Title

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Publication Date
2024-09-01

Load Shifting and Enhancing Energy Savings with Dynamic Ventilation Strategies in Multi-Family Residential Buildings

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Prepared for

2024 ASHRAE Annual Conference
June 2024

Abstract

There is an increasing focus on the time at which energy is used in buildings both to reduce utility costs and carbon emissions in response to time-dependent grid signals. One method to shift electrical load out of peak pricing hours is to use batteries, but they have high first costs and also incur an energy penalty due to round trip efficiency and other losses. Another method is to use thermal storage to offset heating and cooling. Similarly, mechanical ventilation systems can also be controlled to shift energy use to periods of the day with lower energy, cost, and environmental impacts by varying the ventilation rate while still meeting ventilation code requirements. Mechanical ventilation systems in large multi-family residential buildings are mostly central air systems with either manually balanced dampers or constant airflow regulator (CAR) dampers that aim to provide a constant ventilation airflow rate to each apartment. ASHRAE 62.2 allows for dynamic ventilation rate systems in these buildings as long as the average relative exposure rate and the peak relative exposure rate during occupied periods are no more than 1 and 5, respectively, for any time interval that cannot exceed an hour.

In this study, we used EnergyPlus simulations to examine energy end-use profiles for a large multi-family building under design in San Jose, California. We considered a balanced ventilation system using a central dedicated outdoor air supply (DOAS) system. We tested different load-shifting scenarios with multiple parameters to explore how the ventilation airflow rate can be varied to shift load, while also assessing energy and utility cost impacts. The parameters we assessed in each scenario were: the presence of a centralized ERV system or not; ventilation design sizing; and length of load shifting time period. All dynamic ventilation cases, with and without ERV systems, resulted in energy and operational cost savings relative to the constant ventilation cases when compared to providing the same amount of load shifting using batteries, and all tested strategies met ASHRAE 62.2 requirements. The results show that after accounting for the battery penalty typically associated with load shifting, all dynamic ventilation cases reviewed result in improved energy savings when compared to the constant ventilation strategy.

Key Words

Dynamic Ventilation, Load Shifting, Energy Cost & Savings, Fan Supply Power, Residential Buildings

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Table of Contents

Load Shifting and Enhancing Energy Savings with Dynamic Ventilation Strategies in Multi-Family Residential Buildings

Introduction

Mechanical ventilation systems control indoor air quality (IAQ) by diluting or removing indoor air contaminants. However, these ventilation systems lead to energy consumption and operational costs, especially during peak grid hours of the day. The ability to shift electrical loads is becoming increasingly important to reduce both operational costs and carbon emissions. One method to shift load is to use batteries during peak hours and avoid these high utility rate periods. However, using batteries not only leads to high first costs but also has energy penalties due to round-trip efficiency losses, and parasitic loads required for battery systems (such as thermal management systems). They also have relatively short equipment lives compared to other building systems, incurring substantial costs and disruption during replacement approximately every 10-15 years. Other methods for shifting load rely on systems with substantial thermal energy storage. However, it is also possible to shift load and foster energy efficiency by varying ventilation rates dynamically, while sustaining high indoor air quality for occupants.

The design and operation of mechanical ventilation systems are regulated by building codes and standards that set ventilation and IAQ requirements. However, many building codes only consider continuous ventilation at a rate based on the size and occupancy of the buildings. However, ANSI / ASHRAE Standard 62.2-2022 allows for both constant and dynamic ventilation rate systems. Mechanical ventilation systems can be designed to provide time-varying ventilation rates as long as the average relative exposure and the peak relative exposure during occupied periods are no more than 1 and 5, respectively, for any time-step length not exceeding one hour (ASHRAE 2022). Relative exposure rate evaluates the contaminant exposure of the intermittent ventilation strategy relative to the constant ventilation strategy (ASHRAE 2022). The ventilation system can realize load shifting by over-ventilating a space with an economizer during high utility price periods while under-ventilating for all other times, which yields energy and cost savings without requiring the use of batteries. Previous studies have developed intermittent ventilation patterns equivalent to constant ventilation levels (M. H. Sherman 2004). They have also demonstrated the possibility of using a dynamic control strategy for residential mechanical ventilation that provides indoor air quality benefits at reduced energy costs (Max H. Sherman and Walker 2011). However, the load-shifting potential and energy penalties of dynamic ventilation strategies compared to the batteries have not been evaluated.

This research explores how multiple parameters, such as design sizing as well as under- and over-ventilation rates, can be adjusted within the limits of meeting peak and average relative exposure rates to shift energy loads from grid peak periods to off-peak hours. The study analyzes the load shifted for each case and the associated change in annual energy use. We put this in the context of the energy penalty of achieving the same amount of load-shifting using batteries. We also explore how load-shifting strategies can be implemented in multi-family residential buildings.

Methodology

Building & Systems

Our study uses EnergyPlus simulations to examine the effect of load shifting on the whole building energy consumption. We leveraged an existing model of a proposed new construction project originally developed as part of a California Energy Commission-funded research project. This was the 995 E. Santa Clara St. Senior Apartments located in San Jose, California with a total floor area of 6596 square meters (71000 square feet). The building is oriented about 59 degrees off of the North cardinal direction with an overall window-to-wall ratio (WWR) of 16%. The first floor consists of office spaces, shared areas, and support. Floors two through six are residential apartment units where there are 69 single-bedroom, approximately 57 square meters (616 square feet), and five two-bedroom, approximately 78 square meters (840 square feet), units. Figure 1 showcases the modeled case study building in OpenStudio. We considered each apartment unit as a single thermal zone with 1 and 2.5-person occupants for the one- and two-bedroom apartment units, respectively. Since we did not model interior walls, we assumed thermal mass objects that would account for the thermal effects of both the interior walls as well as the furniture. For all scenarios, we used the same geometry, thermal zone layout, and thermal mass assumptions.

This building relies solely on electricity as its energy source, with a time-of-use (TOU) electricity price structure that increases to approx. 0.45 c/kWh between 4-9pm each day, from 0.39 c/kWh at other times. The ventilation system is a central dedicated outdoor air supply (DOAS) system and a single packaged terminal heat pump (PTHP) provides heating and cooling to each apartment unit. The rated heating and cooling capacities are 2403 W and 2432 W to account for the minimum equipment sizes across the various heating and cooling equipment used in the project. The heating and cooling coefficients of performance (COP)s are 3.1 and 3.23, respectively. Similarly, 21 °C (70 °F) and 24 °C (75 °F) are the heating and cooling thermostat setpoints for all hours of the day and each apartment. We also assessed the effect of an energy recovery ventilation system (ERV) for heat recovery in this study. It consists of a generic air-to-air heat exchanger, a supply air fan, and an exhaust air fan (DOE 2023). One set of simulations considers an ERV system including centralized exhaust ducting from each apartment back to the DOAS air handler. The other set of simulations considers the same building and systems without ERV.

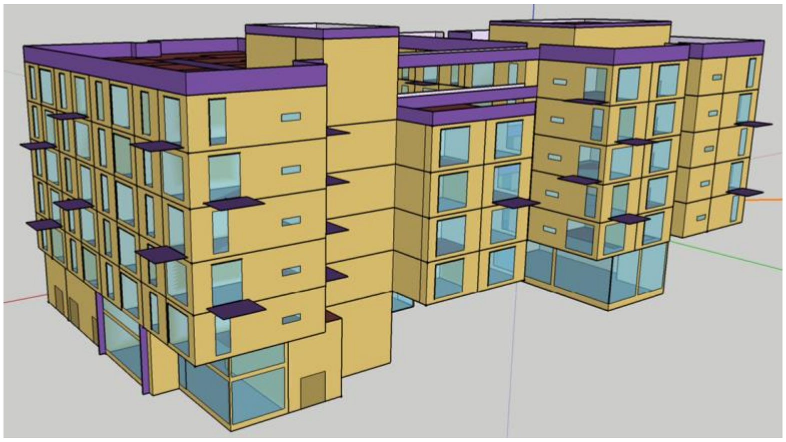

Figure 1: Schematic of the multi-family building located in San Jose, California used in this case study.

Determination of Maximum & Minimum Ventilation Rates

The initial constant ventilation air flow rate for each apartment in the building is determined using Equation 1a or 1b from ASHRAE 62.2 - 2022 (ASHRAE 2022).

$$Q_{\mathrm{tot}} = 0.15 * A_{\mathrm{floor}} + 3.5 * (N_{\mathrm{br}} + 1) \qquad (1a)$$

where Q_{tot} is the required ventilation rate in L/s, A_{floor} is the area of the apartment unit in square meters, and N_{br} is the total number of bedrooms in the apartment unit.

$$Q_{\mathrm{tot}} = 0.03 * A_{\mathrm{floor}} + 7.5 * (N_{\mathrm{br}} + 1) \qquad (1b)$$

where Q_{tot} is the required ventilation rate in cubic feet per minute (cfm), A_{floor} is the area of the apartment unit in square feet, and N_{br} is the total number of bedrooms in the apartment unit.

Equation 1 results in a ventilation rate of 16 L/s (35 cfm) for one-bedroom apartments and 23 L/s (48 cfm) for two-bedroom apartments. However, we use 24 L/s (50 cfm) for both units following typical practice in this region for this building type to up-size the ventilation rate to match the typical flow rate for residential bathroom exhaust fans. In order to meet this constant ventilation rate requirement, we need to be able to supply both higher flow rates (over-ventilate) and lower flow rates (under-ventilate) while providing time-varying ventilation or shifting loads. We consider three under-ventilation rates 14 L/s (30 cfm), 16 L/s (35 cfm), and 19 L/s (40 cfm). These three under-ventilation rates are tested with two oversizing factors of 110% and 120% for duct sizing that can supply an airflow rate of 26 L/s (55 cfm) and 28 L/s (60 cfm), respectively. To meet the average and peak relative exposure rate requirements, we can only under-ventilate for certain hours in a day. In addition to the time-varying ventilation rates with their respective time periods, we also simulate the required constant ventilation rate of 24 L/s (50 cfm) with the system sized for 24 L/s (50 cfm), 26 L/s (55 cfm), and 28 L/s (60 cfm). The resulting design fan power for these system sizes are 2.7 kW, 2.9 kW, and 3.2 kW, respectively. In all, a set of nine scenarios is simulated for both an ERV and a no-ERV case. Table 1 summarizes all nine scenarios that consist of constant ventilation rates with three oversizing factors and three under-ventilation rates with two oversizing factors.

Scenario	System Sizing (L/s)	System Sizing (cfm)	Const. Vent or Over Vent | Under Vent (L/s)	Const. Vent or Over Vent | Under Vent (cfm)	Load Shift Period (hour)
1	24	50	24	50	-
2	26	55	24	50	-
3	26	55	26 | 14	55 | 30	4
4	26	55	26 | 16	55 | 35	5
5	26	55	26 | 19	55 | 40	7
6	28	60	24	50	-
7	28	60	28 | 14	60 | 30	6
8	28	60	28 | 16	60 | 35	8
9	28	60	28 | 19	60 | 40	10

Table 2: Nine Scenarios Simulated for Both ERV and no ERV Systems.

Calculating for Relative Exposure Rate & Fan Power

Relative exposure rate evaluates the contaminant exposure of the intermittent ventilation strategy relative to the constant ventilation strategy. We used Equation 2 from ASHRAE 62.2-2022 to calculate the relative exposure rate for each time step to determine the number of hours we can under-ventilate for as well as ensure that the average and peak relative exposure rates remain below 1 and 5, respectively, for every day (ASHRAE 2022).

$$R_i = Q_{\mathrm{tot}}/Q_i + (R_{\mathrm{i\text{-}1}} - Q_{\mathrm{tot}}/Q_i) * e^{-Q_i \triangle t / V_{\mathrm{space}}} \qquad (2)$$

where R_i is the current time step's relative exposure, Q_{tot} is the total ventilation rate, Q_i is the current step's total ventilation rate, and $R_{\mathrm{i\text{-}1}}$ is the prior step's relative exposure.

Equation 3 illustrates the fan part load curve used in this study (DOE 2023). The total design fan power is higher for the ERV cases compared to no ERV cases due to more pressure drop for the DOAS unit and the exhaust air system.

$$FanEfficiencyCurveOutput = C1 + C2 * x + C3 * x^2 + C4 * x^3 \qquad (3)$$

where x is the speed ratio, C1 is 0.0015302446, C2 is 0.0052080574, C3 is 1.1086242, and C4 is -0.11635563.

Results

Before conducting the EnergyPlus simulations, we evaluated the effect of over-ventilation and under-ventilation rates on the fan power and relative exposure rates. Figure 2 illustrates how the time-varying ventilation rates change with both hourly DOAS fan power and relative exposure rates over the course of 48 hours for scenario 4, where the system is sized at 110% to supply an under-ventilation rate of 16 L/s (35 cfm) from 4-9pm and an over-ventilation rate of 26 L/s (55 cfm) during the rest of the day. During these 48 hours, we can use dynamic ventilation to under-ventilate during peak load hours, while meeting the requirement of the average and peak relative exposure rates under 1 and 5, respectively.

Using Equation 2, we calculated the hourly relative exposure rates over a year for all nine scenarios considering both dynamic and constant ventilation rates. Figure 3 gives the distribution and frequency of relative exposure rates over a year for a range of under- and over-ventilation rates. In the constant ventilation cases, the relative exposure remains at 1 as we supply a constant ventilation rate of 24 L/s (50 cfm) and only vary the sizing factor. In all dynamic ventilation scenarios, the distribution of hourly relative exposure rates remains close to 1. Figure 3 illustrates that all scenarios meet ASHRAE 62.2-2022 requirements as the average relative exposure and the peak relative exposure throughout the year are no more than 1 and 5, respectively, for the time-step length of an hour.

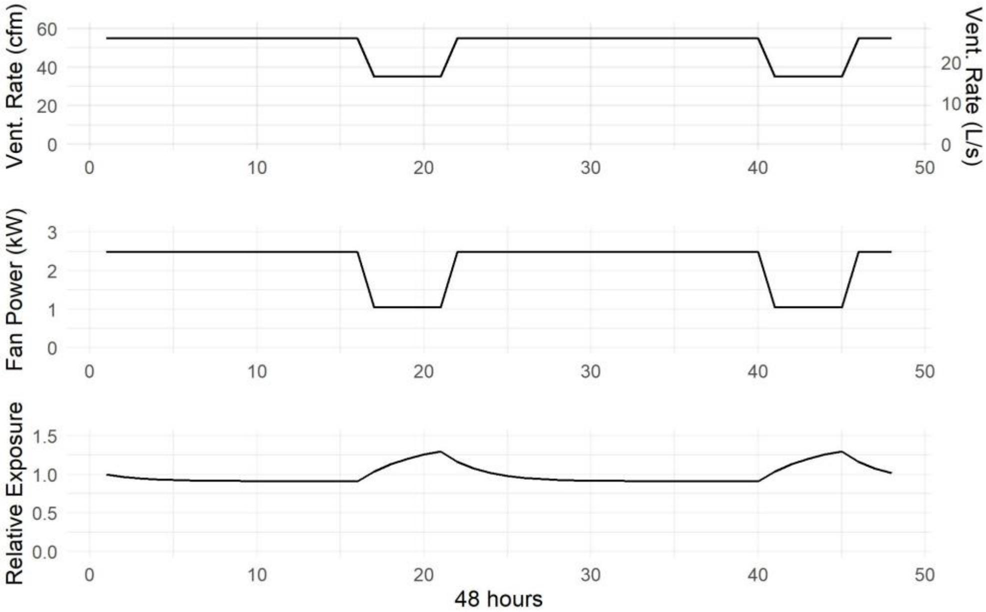

Figure 2: Ventilation rate, fan power, and the resulting relative exposure over 48 hours for scenario 4 e.g. under-ventilating by 36% for 5 hours.

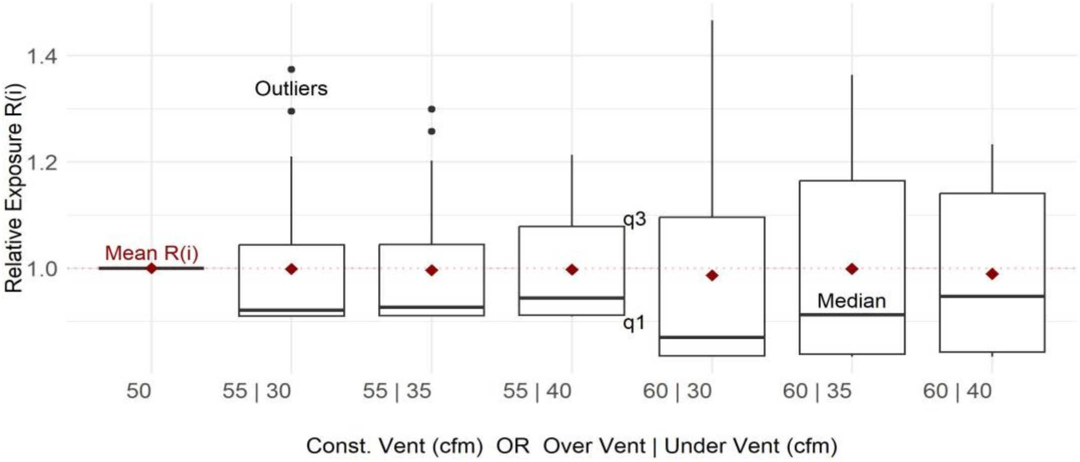

Figure 3: Boxplot of annual hourly relative exposure rates for all 9 scenarios, highlighting that they all meet ASHRAE 62.2 requirements of mean R(i) < 1 & max R(i) < 5.

In addition to calculating relative exposure, we evaluated the total load, including fan, heating, and cooling, that can be shifted for each dynamic ventilation strategy. Figure 4 reports the daily average load shifted in kWh that can be shifted every day if we under-ventilate by a certain percentage for a defined number of hours. The daily average load shifted is determined by multiplying the hourly energy use by the number of hours we can under-ventilate for. For example, in the case of an ERV with a 110% sizing factor, the ventilation system can under-ventilate by 36% for five hours to shift a total of 36.18 kWh of fan, heating, and cooling energy daily. Similarly, in the case of no ERV with a 120% sizing factor, homes can be under-ventilated by 42% for eight hours to shift 68.23 kWh of total energy every day.

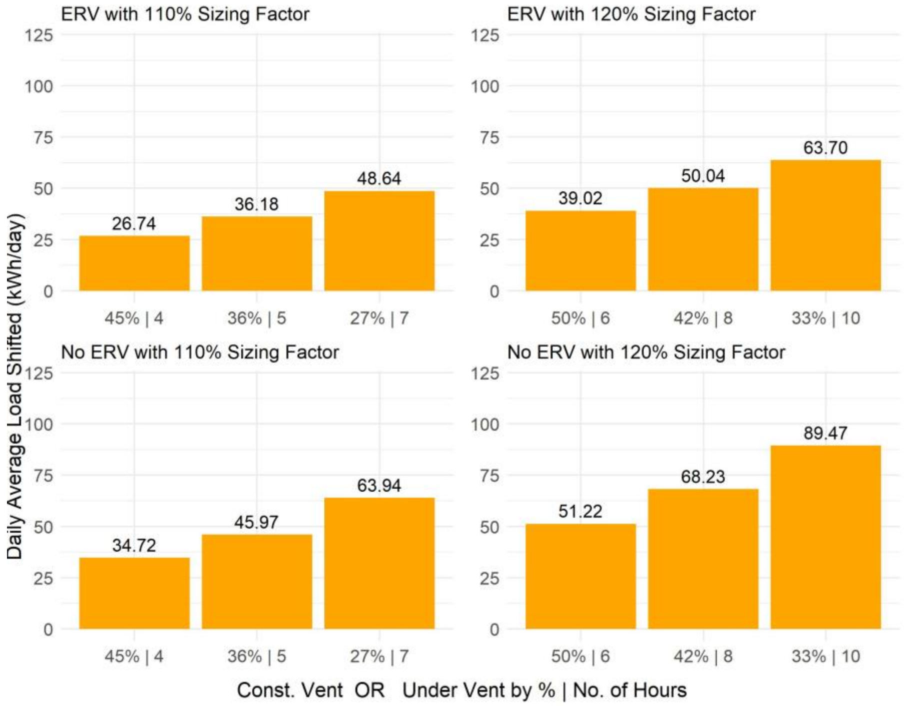

Figure 4: Daily average load shifted, including fan, heating, and cooling, relative to system sizing.

After we conducted all EnergyPlus simulations, the hourly results for fan, heating, and cooling energy were processed as total energy consumption over a year for the entire building. Figure 5 reports the relative energy consumption in kWh per year compared to case 1, where we supply a constant ventilation rate of 50 cfm with the ventilation system sized at 100%. For ERV with a 110% sizing factor, the constant ventilation case sized at 110% reports energy savings as the fan system operates more efficiently compared to the system sized at 100% for 50 cfm due to slightly oversized ductwork and other components. These energy savings increase when the oversize factor is increased to 120%. For the cases without ERV, energy savings for the constant ventilation cases follow a similar trend but are comparatively lower due to a lack of heat recovery, particularly in colder periods of the year.

In the case of an ERV system, all the dynamic ventilation scenarios report annual energy savings compared to a 100% sizing, constant ventilation case, largely due to the effect of oversizing the ventilation system. Even though there is an energy penalty to over- and under-ventilate, the total energy usage for time-varying ventilation remains less than that for the constant ventilation case sized at 100%. For ERV with a 110% sizing factor, the energy savings in dynamic ventilation strategies increase with the decrease in under-ventilation rates and an increase in the number of hours that we under-ventilate for. A similar trend is noted for ERV with a 120% sizing factor but with higher energy savings due to an increase in the oversize factor. For both no ERV systems, the energy losses decrease with the decrease in under-ventilation rates and an increase in the number of hours that we under-ventilate for.

Note here that in all dynamic ventilation strategies, the time period for under-ventilation starts at 4 pm and extends for the full load shift length. For example, if we under-ventilate for eight hours, the time period would start at 4 pm and end at 12 am. We chose to under-ventilate at night (during typically cooler temperatures) as it is a heating-dominated building annually. Moreover, in California, the grid is also dirtier at night due to far lower renewable power generation from solar PV during those hours. Since a system without ERV cannot recover heat, its energy consumption is more sensitive to outdoor temperatures and shifting ventilation to different times can change overall energy consumption substantially. This effect is much smaller for a system with ERV. Overall, the ventilation load-shifting strategies result in energy savings for a system with ERV, but in an energy penalty for systems without ERV, primarily due to higher heating energy penalty. However, this effect is very time and weather dependent, and these results show the effect of one fixed time period per scenario throughout the entire year.

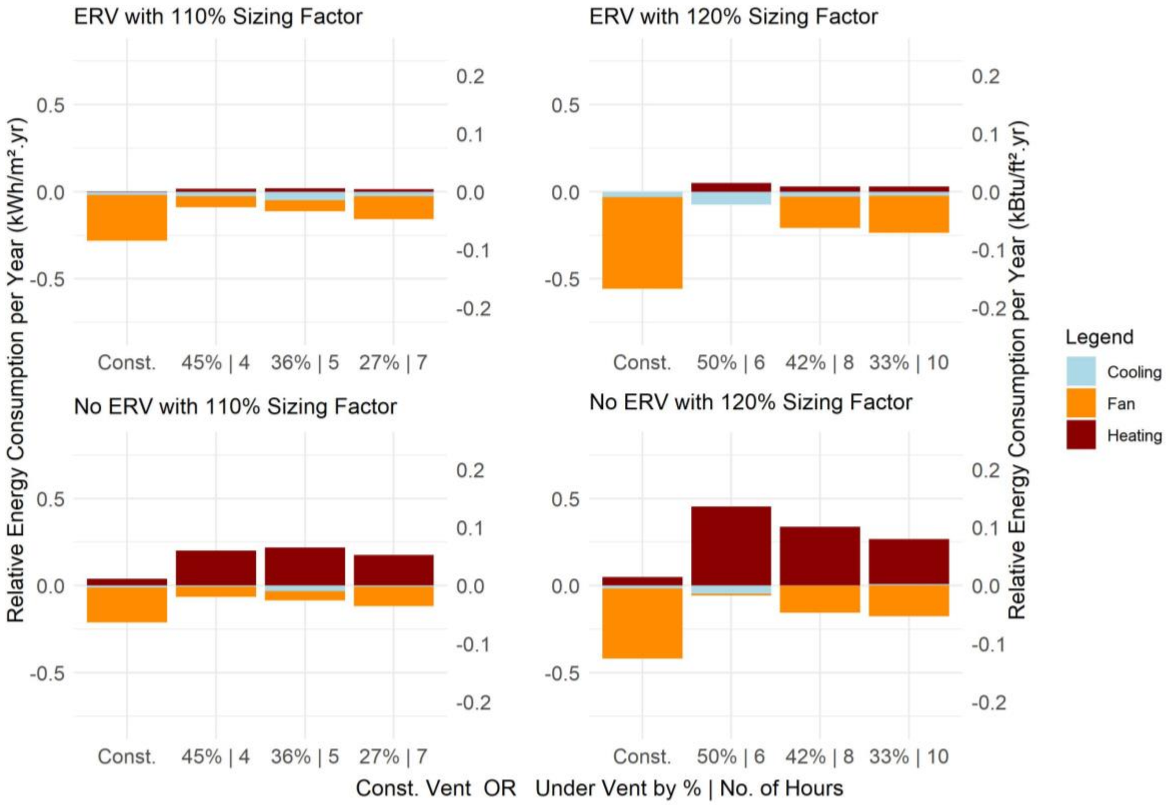

Figure 5: Yearly energy consumption relative to constant ventilation of 50 cfm with a sizing factor of 100%

Discussion

Dynamic ventilation strategies yield energy savings for the design with an ERV system and a slight energy penalty for the design without an ERV system. The results also indicate that energy penalties associated with dynamic ventilation strategies are both time- and temperature-dependent and can have a significant impact when the system cannot recover heat.

Dynamic ventilation strategies yield operational cost savings for the design with an ERV system and a slight cost penalty for design without an ERV system. For example, in the case of ERV, for scenario 4 (5-hour load shift), there are $514/yr utility cost savings associated with the energy savings of using the dynamic ventilation strategy. However, in case of no ERV, for scenario 4 (5-hour load shift), there is a $102/yr utility cost associated with the energy penalty of using the dynamic ventilation strategy.

For both ERV and no ERV systems, all dynamic ventilation cases result in operational energy savings when compared to using a battery to shift the same amount of electrical load as the different dynamic ventilation cases. Since batteries have approximately only 80% round trip efficiency (excluding other parasitic losses, such as thermal management systems), the total energy consumption for all constant ventilation cases increases by 25% of the total load shifted. For example, in case of scenario 4 with no ERV, the energy penalty associated with dynamic ventilation for shifting load for five hours each day is 636 kWh/yr. Meanwhile, the energy penalty associated with using batteries to shift that same load would be 4802 kWh/yr. In this case, we save 4166 kWh/yr with dynamic ventilation instead of using batteries.

Dynamic ventilation strategies perform better than the constant ventilation scenarios with battery usage in terms of energy and cost savings. However, they cannot be implemented in multi-family residential buildings if the ventilation system cannot provide airflow at the required over-ventilation and under-ventilation rates. The building owners would incur some additional costs if the systems need to be sized larger than typical. However, when load shifting is required, doing so using dynamic ventilation instead of batteries would avoid the first costs associated with the battery system.

Also, in practical terms, ventilation rates in multifamily buildings with centralized ventilation systems are typically controlled using either manual balanced dampers or constant airflow regulator (CAR) dampers. Manual balancing dampers are simple devices that enable on-site air balancing. These dampers feature an adjustable quadrant that allows technicians to manually regulate airflow. By turning the quadrant, the damper blades open and close to introduce a variable restriction to provide airflow at the design ventilation rate for each space, at one pressure and flow condition. However, once balanced, the system will not provide exactly the same relative change in airflow through all dampers at other conditions. Zones in the ductwork closer to the air handler will see slightly different ventilation rates than those far down the ductwork from the air handler, and this effect will be greater in larger and more complex ventilation systems. This effect could be mitigated by balancing the system to provide the average of the over- and under-ventilation rates and then measuring the actual airflows achieved in each apartment with the DOAS fan operating at the over- and under-ventilation speeds. The maximum under-ventilation time period could be reduced as needed to ensure that each apartment meets or exceeds ASHRAE 62.2 requirements considering the distribution of actual ventilation rates achieved in each apartment. In contrast to manually balanced dampers, constant air rate (CAR) dampers are more complex devices that automatically regulate airflow in duct systems to a constant level. The passive control element responds to changing duct pressure and requires no sensors or controls (Aldes 2020). Increasing fan speed in an attempt to over-ventilate will simply increase duct static pressure and cause the CAR dampers to adjust and close further while still providing the airflow they were configured to provide. Here, varying the ventilation rate would require configuring the CAR dampers to provide airflow at the over-ventilation rate and turning on and off the ventilation (e.g. run for 45 minutes each hour) to achieve the desired under-ventilation rate. This will yield higher fan energy consumption than truly modulating the fan (as would be possible with manually balanced dampers).

Future Work

Further work is needed to test a dynamic ventilation strategy in a building to better understand the limits of applicability, where a dynamic ventilation strategy is feasible versus an on/off control strategy, and the measured impacts on indoor air quality. In this research, we explored only one building in one climate, and the results would vary substantially in other situations. Using fixed time periods for load shifting in this initial study highlights a clear effect on the overall energy consumption of these systems, particularly those without heat recovery. In addition to testing different climates, varying ventilation rates in response to outdoor temperatures would yield more savings while still providing a load shifting opportunity. Last, it is also possible to respond to dynamic grid signals instead of fixed time periods.

Conclusion

This study used a simulation method to test a variety of scenarios including varying sizing factors, under- and over-ventilation rates to shift energy loads from grid peak to off-peak hours on a multi-family residential building in San Jose, California. The results showed that all dynamic ventilation cases with ERVs result in energy savings, compared to using the constant ventilation strategy with 100% design sizing. All dynamic ventilation cases, in the absence of ERVs, result in energy losses, compared to the constant ventilation case with the same design sizing. However, after accounting for the battery energy penalty that would be incurred by shifting a comparable amount of electrical load, all dynamic ventilation cases, including no ERV, result in energy savings.

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