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Disclaimer

Energy and IAQ implications of Alternative Minimum Ventilation Rates in California Retail and School Buildings

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ABSTRACT

For a stand-alone retail building, a primary school, and a secondary school in each of the 16 California climate zones, the EnergyPlus building energy simulation model was used to estimate how minimum mechanical ventilation rates (VRs) affect energy use and indoor air concentrations of an indoor-generated contaminant. The modeling indicates large changes in heating energy use, but only moderate changes in total building energy use, as minimum VRs in the retail building are changed. For example, predicted state-wide heating energy consumption in the retail building decreases by more than 50% and total building energy consumption decreases by approximately 10% as the minimum VR decreases from the Title 24 requirement to no mechanical ventilation. The primary and secondary schools have notably higher internal heat gains than in the retail building models, resulting in significantly reduced demand for heating. The school heating energy use was correspondingly less sensitive to changes in the minimum VR. The modeling indicates that minimum VRs influence HVAC energy and total energy use in schools by only a few percent. For both the retail building and the school buildings, minimum VRs substantially affected the predicted annual-average indoor concentrations of an indoor generated contaminant, with larger effects in schools. The shape of the curves relating contaminant concentrations with VRs illustrate the importance of avoiding particularly low VRs.

INTRODUCTION

This report adds to our prior analysis of the energy and IAQ implication of minimum ventilation rates (VRs) in offices [1] , by presenting an analysis for a stand- alone retail building, primary school, and secondary school.

Increases in VRs generally increase building energy use but also reduce indoor air contaminant concentrations that are emitted from indoor sources. Minimum VRs specified in standards such as California's Title-24 building energy efficiency standards [2] aim to strike a balance between the energy use associated with providing ventilation and the indoor air quality (IAQ) improvements that ventilation provides.

A building's VR impacts energy use because outdoor air often requires heating and possibly humidification, or cooling and possibly dehumidification, before it is supplied to indoor spaces. Several previous studies have shown that modifying the minimum indoor VR in commercial buildings significantly affects cooling energy in warmer climate zones and heating energy in cooler zones. Based on simulations of the full U.S. commercial building stock [3], an estimated 6.6% of total building site energy, corresponding to about 16.5% of HVAC energy, is used to condition ventilation air that is supplied mechanically. Conditioning of the additional ventilation provided by infiltration uses additional energy. Analyses by the U.S. Environmental Protection Agency [4] found that raising minimum VRs from 2.5 to 10 liters per second (L/s) per person in U.S. offices increased HVAC energy costs by 2%-10%. This percentage increased significantly when occupant densities were high or economizers were present [4]. Haves et al [5] used a model of a big-box store to assess the energy-savings effectiveness of reducing the minimum VR. This study analyzed minimum VRs that were reduced by 50% for each of seven store models. On average, gas heating energy usage decreased by 60%, and electricity usage decreased by 1.3%, resulting in an overall 7% reduction in average total building energy use. However, no prior studies were identified that estimated the energy use associated with different minimum

VRs specifically in commercial buildings in California. This study estimates the statewide HVAC energy use and IAQ implications of the minimum Title-24 VR for retail buildings and schools for six alternative minimum VRs. Studies using building models based on building energy standards from ASHRAE that typically differ from models of California commercial buildings with respect to modeled envelope and glazing performance, prescribed VRs, and to a limited extent, HVAC system requirements. The models used in this study were based on models that were developed originally to be compliant to ASHRAE Standard 90.1 -2004 [6]; however no changes were made to envelope or glazing performance.

The alternative minimum VRs analyzed in this study are expected to directly affect indoor contaminant concentrations and therefore to affect indoor air quality (IAQ). Prior analyses by Parthasarathy et al. [7] provide the foundation for the current assessment of the IAQ implications of minimum VRs in commercial buildings. Through mass balance modeling and risk analyses, prior studies [7, 8] found that ventilation primarily helps limit health risks from indoor-generated gaseous contaminants, particularly volatile organic compounds that are emitted from furniture, building materials, and many indoor sources that are common in buildings. In comparison, inorganic gaseous contaminants are not a primary concern indoors because many commercial buildings have minimal indoor sources.

This work did not consider the impact of VR on exposure to particles. Modeling in prior studies [9, 10] found that indoor particle concentrations are not highly affected by minimum VRs because particles are present in outdoor air as well as being emitted from indoor sources. In addition, the high removal rates of particles by filters and substantial loss of particles by deposition on indoor surfaces lessen the influence of VRs on indoor concentrations of particles.

METHODS

Overview

The EnergyPlus building energy simulation program [11] was used to estimate how energy use and indoor concentrations of a generic indoor-generated contaminant in school and retail buildings, are impacted by alternatives to the current Title-24 prescribed minimum VRs. The methods employed in this analysis are very similar to those employed for our prior analysis of the effects of minimum VRs on energy use and contaminant concentrations in offices [1].

Building models

The building models used in this study are based on the Department of Energy (DOE) building reference models [12] for stand-alone retail, primary school and secondary school. The DOE reference building models comply with ASHRAE building energy standard 90.1 [6]. Alternative, more recently published building models, were considered [13], however these models do not make use of EnergyPlus's HVAC system auto-sizing features, and so would have required extensive changes to be used with the California climate zone weather files. Envelope and heating, ventilating, and air conditioning (HVAC) systems were modeled as per the published reference building models. Prior modeling efforts for offices [1] found that transitioning the envelope to a Title 24-compliant envelope was time intensive, and had a limited impact on the energy use of ventilation. Data from the California End Use Survey (CEUS) [14] indicate that the majority of both secondary and primary schools in California did not make use of economizers, to reflect this fact, the economizers were deactivated on these two models. Figures 1-3 show graphical representations of the three study buildings. Table **1** gives a breakdown of building floor area and the installed HVAC systems.

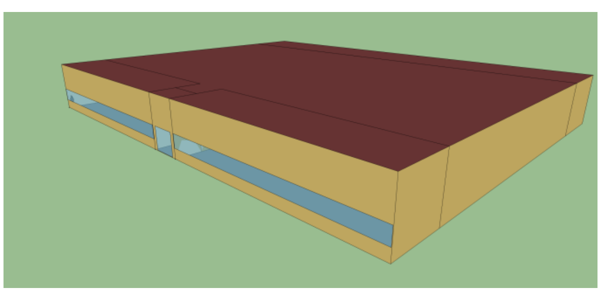

Figure 1. Graphical representation of retail building.

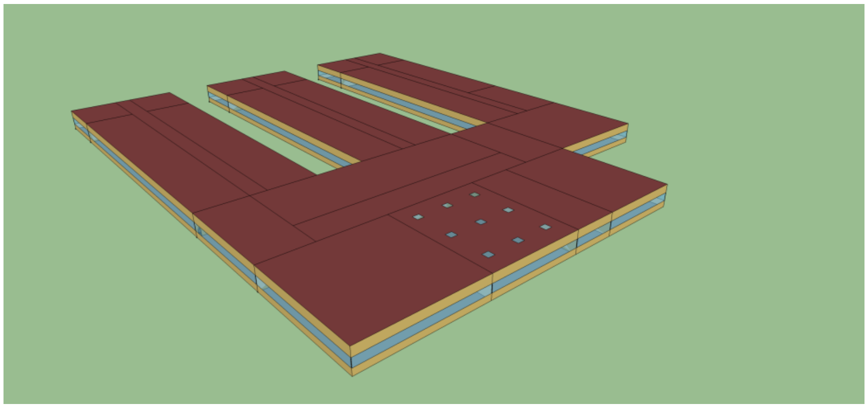

Figure 2. Graphical representation of primary school building.

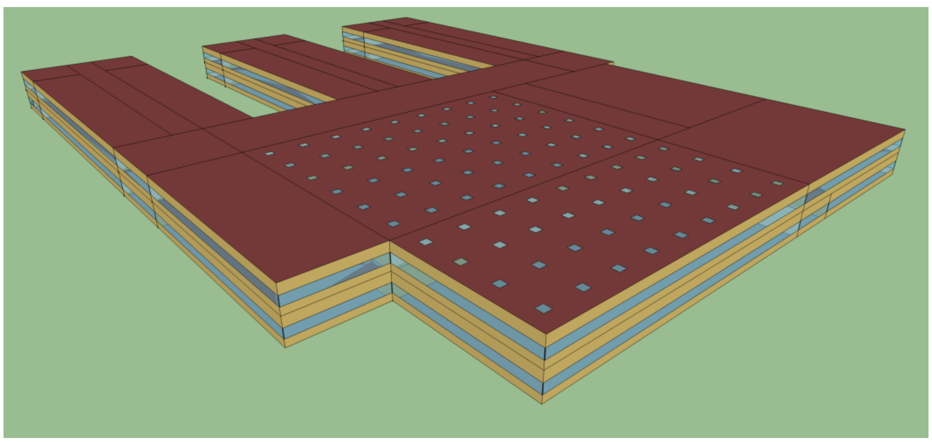

Figure 3. Graphical representation of secondary school building.

Table 1. Building model descriptions

Building	**Building floor area**	**HVAC**
Primary school	6871m^2	Variable Air Volume (VAV) and Constant Air Volume (CAV), Packaged Single Zone Air Conditioner (PSZ-AC) in gym, kitchen and café, no economizer.
Secondary school	19592 m^2	VAV and CAV, PSZ-AC in gym, auditorium, kitchen and café, no economizer.
Retail	2294 m^2	PSZ-AC, gas furnace, economizer for main retail area.

Minimum VR scenarios

Minimum VRs were simulated under seven different VR scenarios; the California Title-24 prescribed minimum VR and six alternative minimum VRs that are 100%, 50%, and 30% above and below the Title-24-prescribed minimum VR. Simulations were repeated for each of the 16 California climate zones. Infiltration was modeled using the ZoneInfiltration:DesignFlowRate object in EnergyPlus, with a flow rate per exterior surface area of 0.302 liters/s-m^2, as per the reference models. This infiltration rate is reduced by 50% when the HVAC system is in operation, as per the original model.

Title-24 based prescribed minimum VRs differ by building type. We applied minimum VRs for the retail store based on a rate per floor area of 1.02 l/s-m^2 (0.2 cfm/ft^2). For the school buildings we applied a rate per floor area, that was approximately equivalent to a per person rate of 7.1 liters per second per person (15 cfm per person). The resulting VRs per floor area (0.76 l/s-m^2 or 0.15 cfm/ft^2) is the same as the Title-24 requirement for “all others” building types, including schools and classrooms. A more detailed discussion of why this was necessary can be found in the later discussion of EnergyPlus modeling issues. The resulting target VRs are listed in Table **2**.

Table 2. Target ventilation rates in the classroom and main retail areas

	Primary school min. VR l/s-m^2, main retail area	Secondary school min. VR l/s-m^2, main retail area	Retail min. VR l/s-m^2, main retail area
0% of Title-24 (n100)	0.00	0.00	0.00
50% of Title-24 (n50)	0.38	0.38	0.51
70% of Title-24 (n30)	0.53	0.53	0.71
100% of Title-24 (Title-24)	0.76	0.76	1.02
130% Title-24 (p30)	0.99	0.99	1.32
150% Title-24 (p50)	1.14	1.14	1.52
200% Title-24 (p100)	1.52	1.52	2.03

In the schools, VRs in non-classroom spaces including office areas and corridors varied proportionally with the VRs in the classrooms. The VRs in the gym, cafeteria, bathrooms and mechanical plant area did not change with VR scenario. Cafeteria and gymnasium VRs per person were be based on the reference rate of 10 l/s per person, bathroom VRs were 25 l/s per person, and the VRs in the mechanical plant rooms were 0.25 l/s.m^2 based on ASHRAE standards [6]. In the retail building, minimum VRs throughout the building (including the office and point of sale areas), were varied for each scenario, in common with the main retail area.

Calculation of contaminant concentrations

Zone contaminant concentrations were modeled assuming a continuous indoor-contaminant emission rate of 3.45E-05 liters/h-m^2, based on reported formaldehyde emission rates in commercial buildings [15]. The modeling of contaminant concentrations was performed using EnergyPlus's ZoneAirContaminantBalance generic contaminant object. No contaminant depositional losses and low outdoor contaminant concentrations were assumed. Because reported indoor contaminant concentrations are normalized to the concentration with the Title 24 VR, the magnitude of the emission rate is of little importance.

Contaminant concentrations are expected to vary spatially from zone to zone and temporally throughout the day. Also the occupancy of the three buildings varied throughout the day. To present a single contaminant concentration metric indicative of the occupants' exposures to the simulated contaminant, results are given as the occupant-weighted, average annual contaminant concentration during occupancy (C_{AWE}).

The C_{AWE} is calculated in two steps; first we calculated a weighted hourly concentration (C_{WE}) for each time step as per Equation 1. This gives a spatially averaged concentration during the hourly time step.

$$C_{WE} = \frac{\sum_0^n C_i O_i}{\sum_0^n O_i} \qquad \textit{Equation 1}$$

where, C_i is the zone contaminant concentration, O_i is the zone occupancy, and n is the zone number.

To provide a single concentration metric for the year, Equation 2 gives the annual average weighted concentration.

$$C_{AWE} = \frac{\sum_{t=0}^{t=x} C_{WE} \times O_t}{\sum_{t=0}^{t=x} O_t} \qquad \textit{Equation 2}$$

where O_t is total building occupancy at a given time step.

Weighting of results by climate zone

We estimated building stock floor area in each of the 16 climate zones for the three new building types (retail, primary and secondary schools) using 2011 census population data [16], electricity use data from the CEUS [14], and aggregated electricity use data from utilities [17]. The building stock areas were used to translate predicted energy use in each climate zone, into statewide energy use, for each of the seven VR scenarios. Weighting factors were used to estimate statewide average values of energy utilization index (EUI), i.e., energy use per unit floor area, and average statewide contaminant concentrations. Weighting factors are reported for each building category individually in Table 3.

Table 3. Building model weighting factors.

CA Climate zone	Primary school stock area (m^2)	Secondary school stock area (m^2)	Stand-alone retail stock area (m^2)	Primary school weighting factor	Secondary school weighting factor	Stand-alone retail building weighting factor
CZ1	209,562	245,880	538,405	0.01	0.01	0.01
CZ2	613,148	719,410	1,526,300	0.02	0.03	0.03
CZ3	4,410,356	4,406,624	9,170,843	0.16	0.16	0.15
CZ4	1,343,941	1,405,592	2,310,604	0.05	0.05	0.04
CZ5	761,353	210,008	280,980	0.03	0.01	0.00
CZ6	2,112,043	1,813,486	5,617,742	0.08	0.07	0.09
CZ7	1,317,689	2,150,325	3,613,417	0.05	0.08	0.06
CZ8	3,579,969	3,130,880	9,859,505	0.13	0.11	0.16
CZ9	2,252,958	2,698,598	4,981,883	0.08	0.10	0.08
CZ10	2,986,194	3,128,514	6,641,831	0.11	0.11	0.11
CZ11	874,811	738,108	1,302,597	0.03	0.03	0.02
CZ12	3,652,088	3,697,156	7,768,668	0.13	0.13	0.13
CZ13	1,918,548	2,311,265	3,757,210	0.07	0.08	0.06
CZ14	1,457,259	758,385	2,220,708	0.05	0.03	0.04
CZ15	200,038	197,418	489,523	0.01	0.01	0.01
CZ16	61,648	60,841	58,672	0.00	0.00	0.00
State totals	**27,751,605**	**27,672,491**	**60,138,888**	**1**	**1**	**1**

RESULTS

HVAC energy utilization index (EUI)

Figure 4show the HVAC EUI for the stand alone retail building, primary school, secondary school, and at each of the modeled VRs. In the retail building, the gas heating energy increased substantially with increased minimum VRs. In both school buildings, changes in VRs had only a small impact on gas EUI and total HVAC EUI. Eliminating mechanical ventilation modestly increased the energy use for air conditioning in schools.

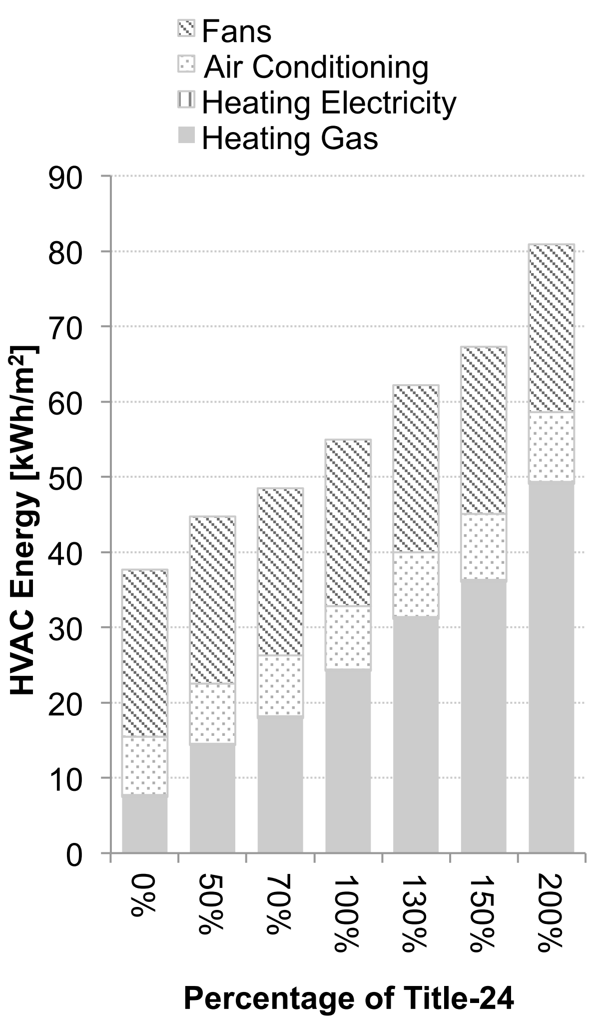

Figure 4. Retail HVAC EUI versus VR.

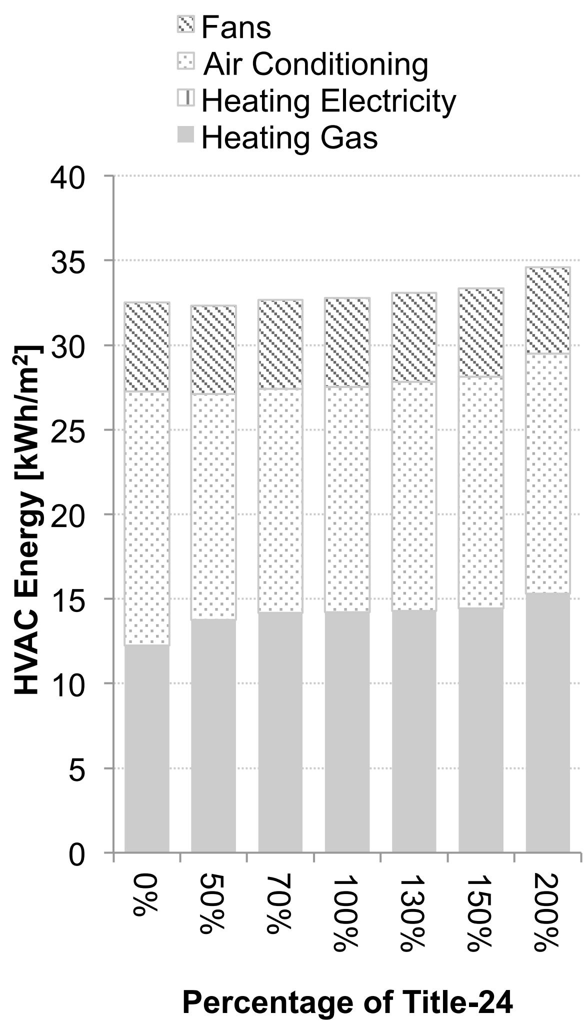

Figure 5. Primary school HVAC EUI versus VR.

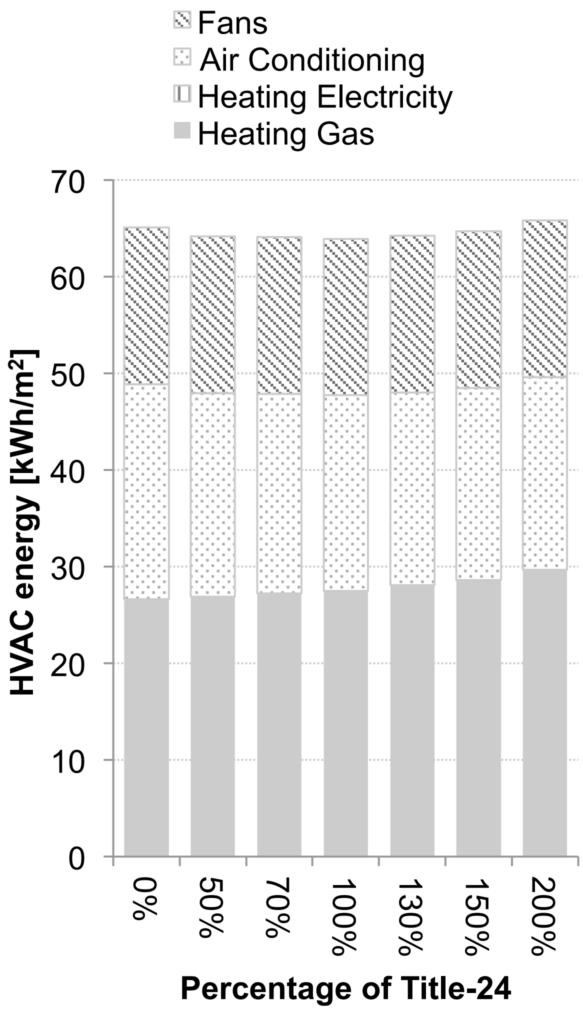

Figure 6. Secondary school HVAC EUI versus VR.

Total building state wide EUI by end use

Figures 7 – 9 provide the total building statewide EUI, at the modeled VRs, for the stand-alone retail building, primary school, and secondary school. Only in the case of the retail building do the changes in minimum VRs significantly impact statewide energy use for those buildings. Relative to the reference Title 24 VR, eliminating mechanical ventilation in the retail building reduces building energy use by approximately 10% and doubling mechanical ventilation increases building energy use by approximately 7%.

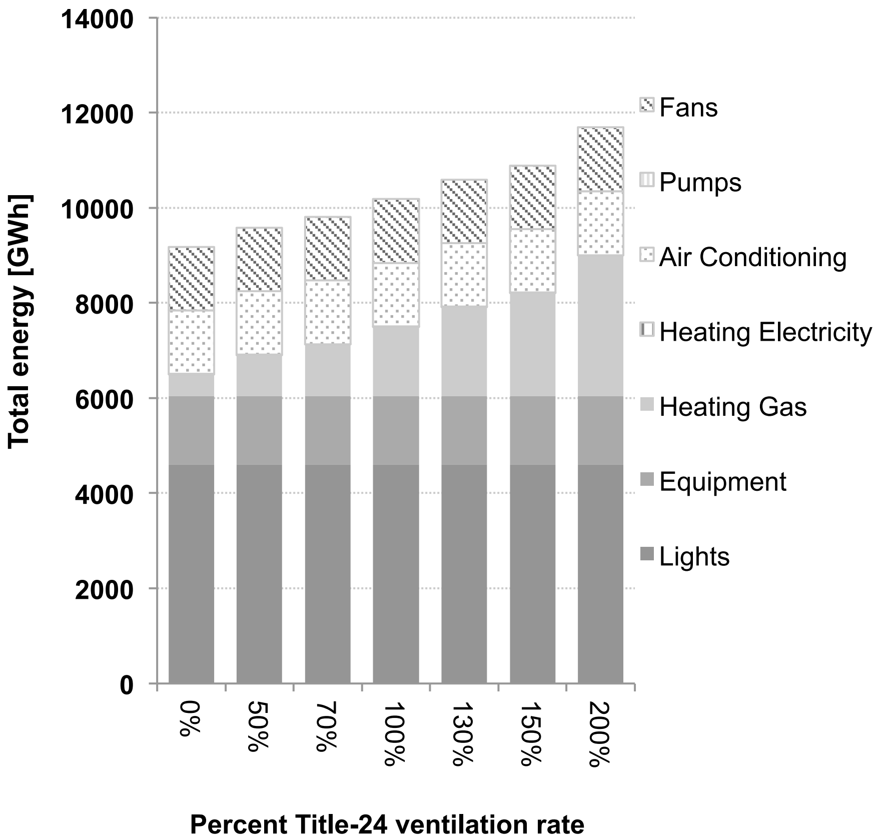

Figure 7. Retail total energy use as a function of VR.

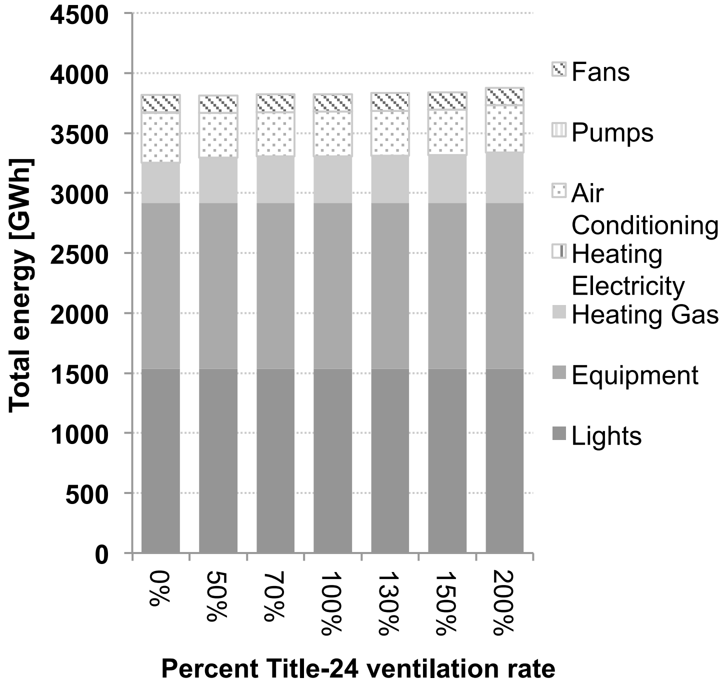

Figure 8. Primary school total energy use as a function of VR.

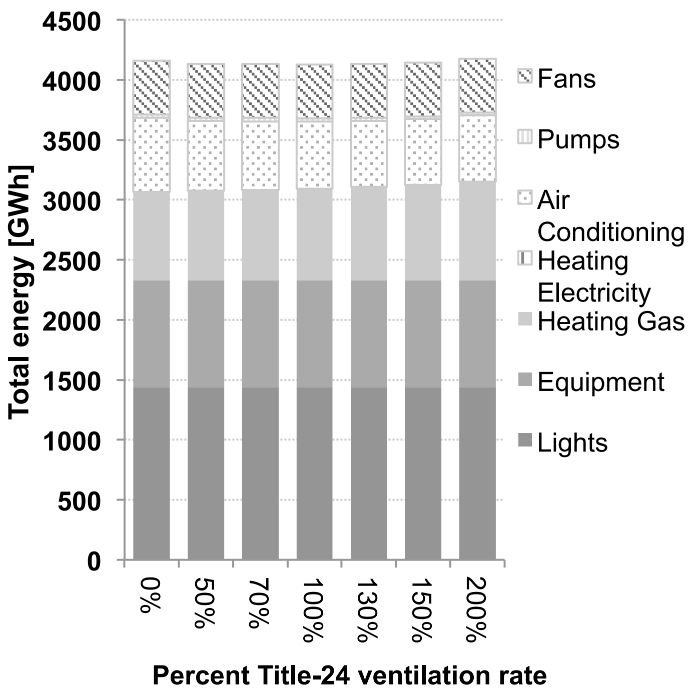

Figure 9. Secondary school total energy use as a function of VR.

Total EUI by climate zone (CZ)

Figures 10 – 12 provide the total state wide energy use at the modeled VRs for the stand alone retail building, primary school, and secondary school, broken down by climate zone. Results show that changes in minimum VRs have the greatest effect on HVAC energy use in the Climate Zones with colder winters (CZs 1, 2 and 16). In the school buildings there is a trend in several of the climates that as VRs are increased from zero up to an intermediate VR, HVAC energy use decreases. This reduction in energy use is assumed to be the result of free ventilation cooling. This same trend was shown for offices without economizer controls [1]. In the hottest climate, CZ15, total HVAC energy use increases with each incremental step up in the minimum VR.

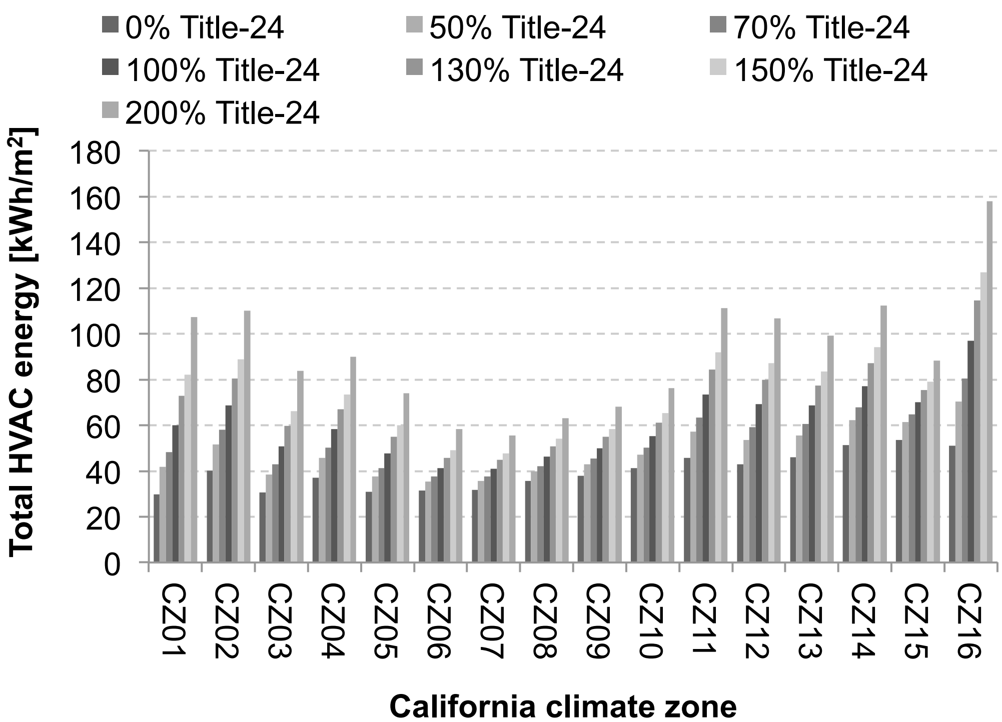

Figure 10. Retail EUI energy use by climate zone and VR.

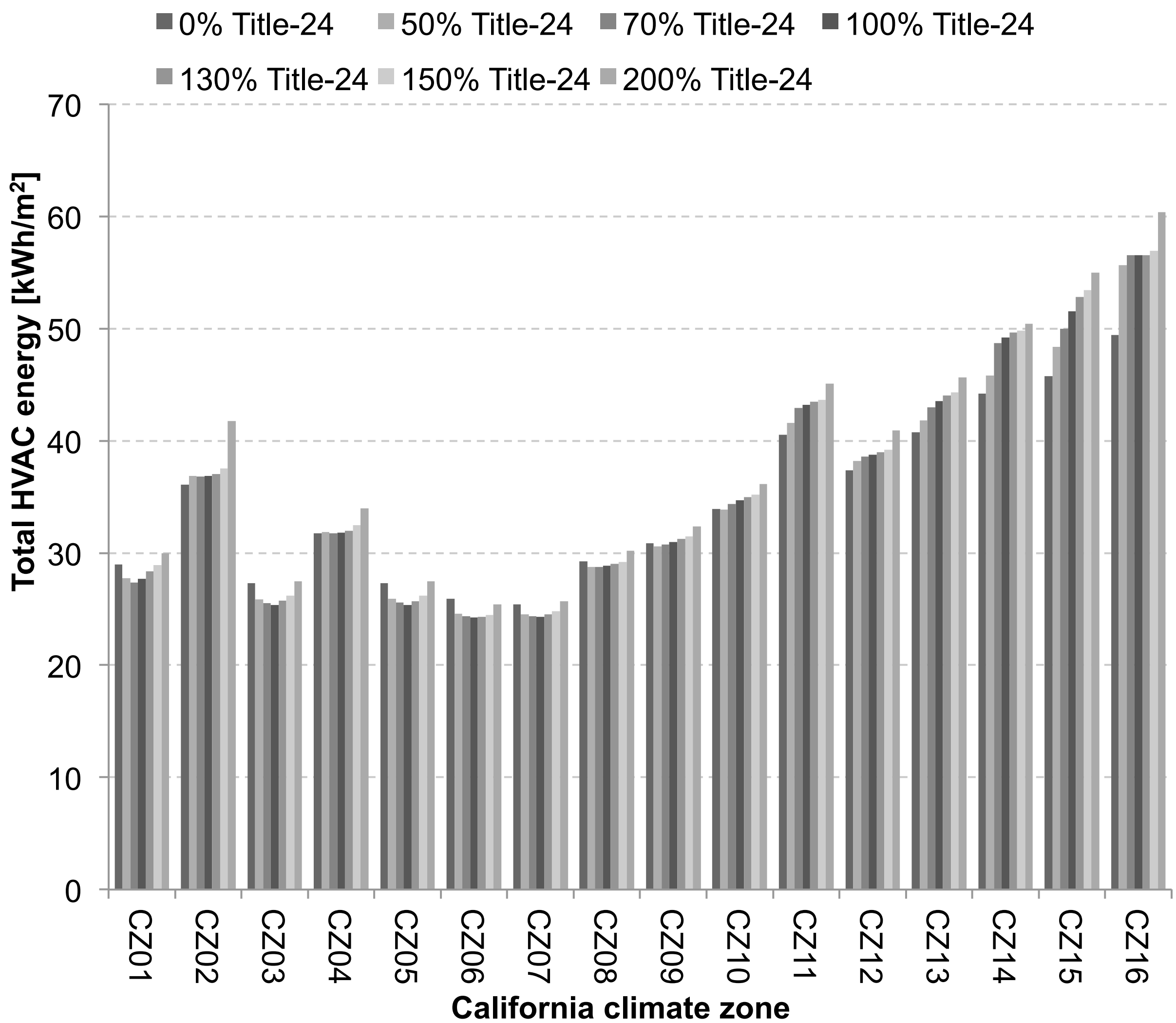

Figure 11. Primary school EUI energy use by climate zone and VR.

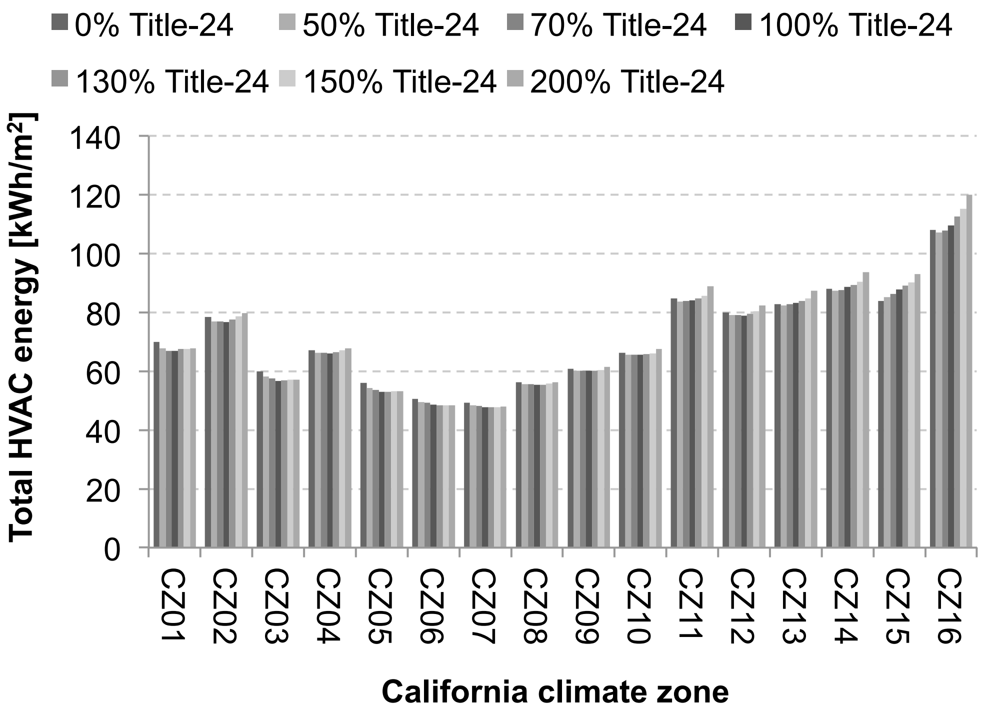

Figure 12. Secondary school EUI energy use by climate zone and VR.

Ventilation Rates and Contaminant Levels

Table 4 gives the average VRs during occupied hours in the main retail area and classrooms, as reported in the EnergyPlus summary table file. VR results are also presented normalized to the results achieved with the reference Title-24 VR (i.e. the "baseline" case in Table 4).

For the school buildings, the observed average VRs, reported in the EnergyPlus summary table file, were approximately 20% higher than the anticipated (i.e., model input) design minimum rates. The normalized VRs show that at the higher VRs, the intended VRs were not being met. For example, for the P100 scenario a normalized VR of 2 (twice the Title 24 requirement) was expected, compared to the reported normalized VR of 1.84. This discrepancy is discussed in more detail in the discussion of modeling issues.

Table 4. Average observed ventilation rates as reported in EnergyPlus summary table files.

	Retail		Primary School		Secondary School	
	Average VR l/s-m^2	Title-24 normalized	Average VR l/s-m^2	Title-24 normalized	Average VR l/s-m^2	Title-24 normalized
n100	0.4	0.32	0.0	0.00	0.0	0.00
n50	0.8	0.66	0.4	0.50	0.5	0.50
n30	1.0	0.80	0.6	0.70	0.6	0.70
Title24 Baseline	1.3	1.00	0.9	1.00	0.9	1.00
p30	1.5	1.20	1.1	1.30	1.2	1.30
p50	1.7	1.32	1.3	1.48	1.4	1.48
p100	2.1	1.60	1.6	1.84	1.7	1.81

In the retail store, average VR's were higher for all VR scenarios compared to the schools, in part due to the higher design VR , and in part due to the use of economizers in the core retail zone of the store. The economizers did not increase VR by as much as was observed in the earlier study in offices [1] . In the retail building model, located in CZ03, using the Title-24 VR scenario, the economizer was in use 95% of the time. However, even during economizer operation, VRs were on average only 34% higher than minimum VR, with peak VR 90% higher than the minimum. The disparity between the average and peak VR during economizer operation relate to the economizer control strategy in the model and to the specific climate conditions. Economizer control was modeled based on a differential air temperature (dry-bulb), with the economizer activated when outdoor air temperature is less than return-air temperature, and de-activated at a maximum outdoor air temperature threshold of 28 ^oC during these periods.

Figure 14 gives the weighted annual average contaminant concentrations, normalized by the concentration with the reference Title-24 VR provided. Results show that the minimum VR has a larger impact on contaminant levels in schools, compared to in the retail building. These results agree with expectation based on the reported VRs in Table 4. Contaminant concentrations in schools increase substantially as VRs decrease below the Title 24 VR.

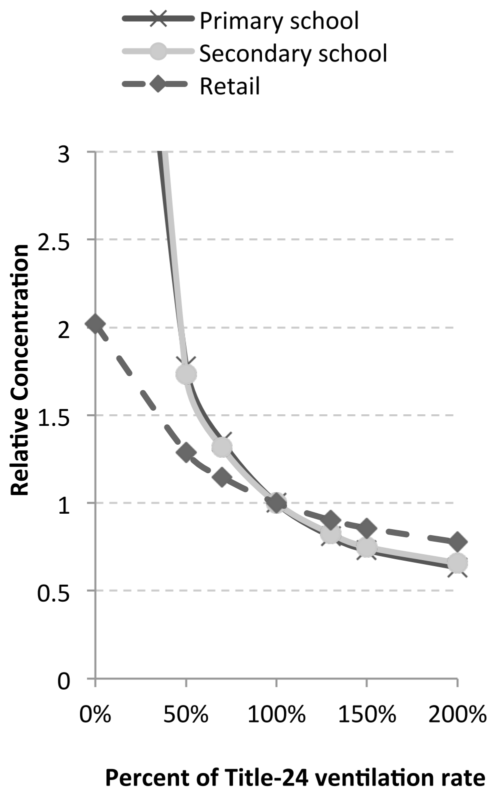

Figure 13. Annual average normalized contaminant concentration as a function of VR.

Figures 15- 17 give the (unweighted) median, inter-quartile, maximum and minimum hourly contaminant concentrations, in the form of a box and whiskers plot. Additionally the single weighted average hourly concentration (C_{WE}) is presented as a dashed line. Contaminant concentrations in these figures are normalized to median concentration at the Title 24 minimum VR. The figures show that in the primary school classrooms, for the n50 scenario (50% of Title 24 VR), the 75th percentile of concentration is approximately 90% times higher than with the reference Title-24 VR supplied, though average weighted concentration is 78% higher. In the secondary school classrooms, reducing VR by 50%, increased average weighted concentration by 96%, and shifted the 75th percentile up by 81%.

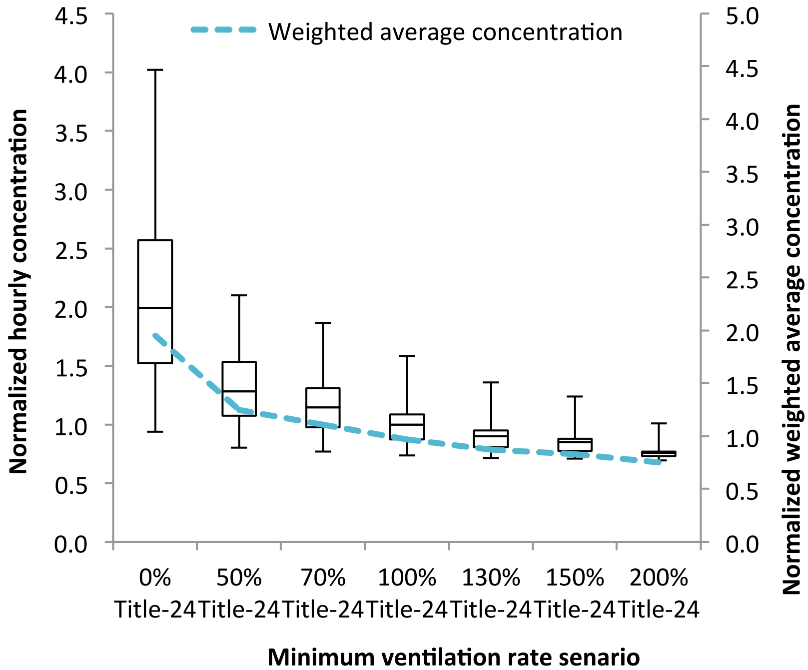

Figure 14. Normalized hourly contaminant concentrations in the retail store as a function of VR.

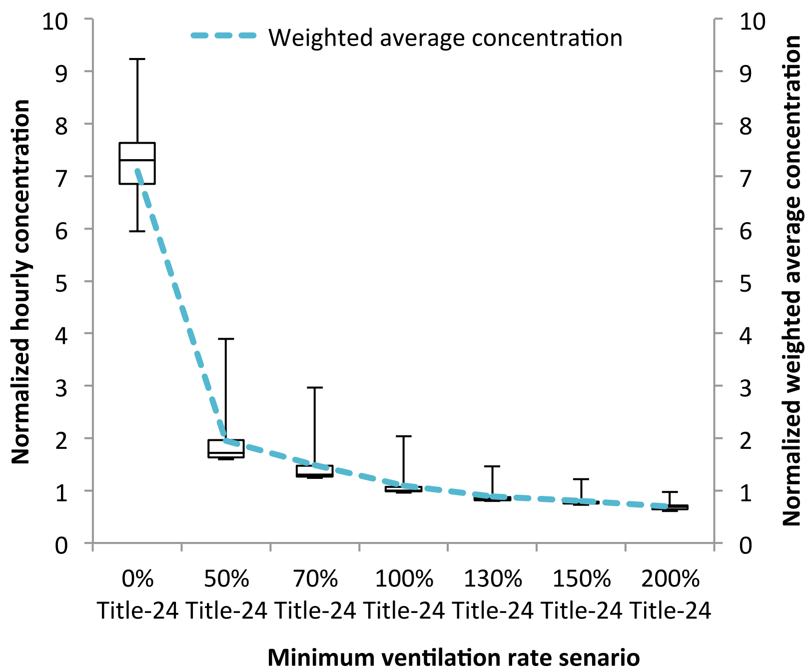

Figure 15. Normalized hourly contaminant concentrations in the primary school as a function of VR.

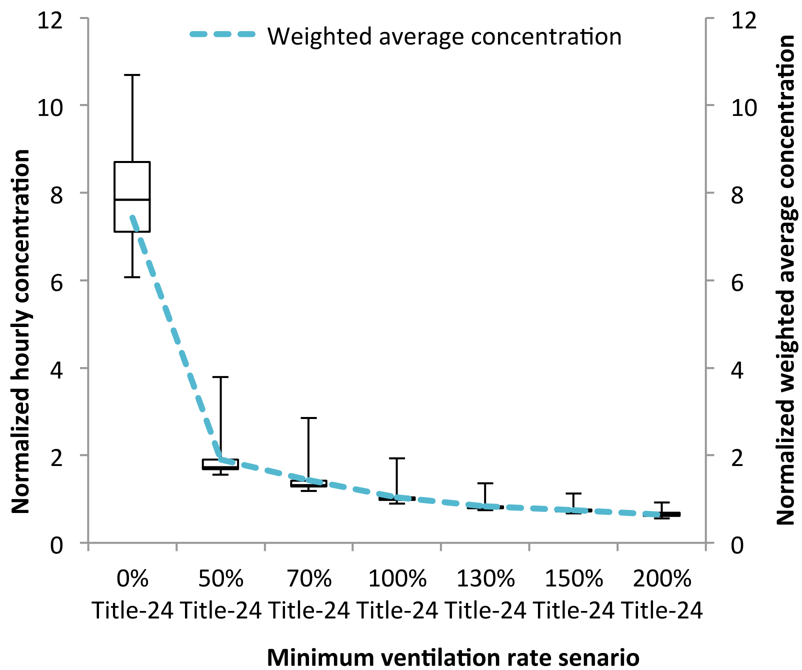

Figure 16. Normalized hourly contaminant concentrations in the secondary school as a function of VR.

DISCUSSION

The EnergyPlus modeling indicated that changes in the prescribed minimum VR has a substantial impact on total HVAC energy use in the retail building, with heating energy highly affected by minimum VR. Total building energy consumption is affected more modestly, for example eliminating mechanical ventilation reduces energy consumption by approximately 10%. However in the school buildings, HVAC and total energy consumption were not significantly affected by changes in the minimum VR.

A reduction in the minimum VRs from the current Title-24 rates to minimum rates of zero, reduced total HVAC EUI's by 31%, 1%, and -2% for the stand alone retail building, primary school, and secondary school, respectively, and reduced gas EUI by 52%, 3% and 2%. These results compare to results from the Benne et al. [3] which found that in the retail category of buildings, reducing the minimum mechanical VR to zero resulted in a 17.7% and 30% reduction in gas EUI for DOE climate zone 3B and 3C, which are the two climate zones in California. In the study by Benne et al., eliminating mechanical ventilation in education buildings reduced the gas EUI by approximately 44%. The Benne study used a group of different types of educational buildings and varied VRs in the whole building, while our modeling maintained VRs unchanged in the gymnasium, cafeteria, bathrooms and mechanical plant area.

The results for the retail store differ markedly from those of the school buildings. However the retail store results are similar to the results observed in the small office building which is of a comparable size [1]. Also, the previously referenced modeling of a retail building by Haves [5] found that heating energy use was highly affected by VR.

In the prior modeling of medium and large offices [1], minimum VRs had a minimal impact on heating electricity (reheat) and heating gas use, as observed in our school buildings. Cooling loads were found to be higher in the larger offices and schools, than in our retail store due to both higher internal gains, and a lower building envelope surface area to floor area ratio. The ratio of the envelope area to floor space impacts the building's thermal conductive losses and gains per unit floor area, which has a direct impact on the thermal energy balance. The differences between our school, retail and office models and the models of Benne et al. are thought to be the main source of the differences in sensitivity of energy use to changes in the minimum VR.

The modeling indicates large increase in indoor contaminant concentrations in schools as VRs decrease below the Title 24 VR prescribed for schools. Available data indicate that VRs in California's elementary level classrooms often fail to meet Title 24 requirements, with the estimated average classroom VR approximately 40% below the Title 24 requirement and many classrooms with much lower VRs [18]. Low VRs in classrooms were also associated with increases in student absence rates [18]. Because classroom HVAC systems in California usually have no economizer, maintaining minimum VRs is particularly critical and, as shown by this modeling, the energy penalty of increasing VRs in classrooms is small.

This analysis is the first to assess the effects of minimum VRs on energy use in retail and school buildings in California. Strengths include the modeling for each California climate zone, the weighting of results to obtain statewide estimates, and the incorporation of calculations of the effects of VRs on indoor concentrations of an indoor-generated contaminant. Limitations include modeling of only one type or retail building and two types of school buildings. The effects of minimum VRs on energy use in large retail buildings or other types or retail buildings might differ considerably from the results in this paper.

This modeling was constrained, to some extent, by limitations in the EnergyPlus program, In the primary and secondary school models, there is a different pupil occupant density in the *corner* and *multi* classrooms. *Multi* and *corner* classrooms share services from common HVAC systems. For the schools, it was found to be necessary to specify minimum VRs by floor area at a common rate for all classrooms, as opposed to specifying a ventilation rate per occupant. EnergyPlus appeared to auto sized the minimum VR requirements incorrectly, unless all the zones serviced by a given HVAC system have the same minimum VR requirement per floor area. This situation differs from the retail model where each zone is serviced by its own HVAC system.

The EnergyPlus program did not provide precisely the desired minimum VRs and there was a significant discrepancy between the summary values of VRs provide by EnergyPlus and the average VRs calculated manually using reported hourly rates. In the school and retail models, there is a discrepancy between the average outdoor air mass flow rate, as reported in the Table summary file of EnergyPlus, and average of the hourly the mass flow rates as reported at the outdoor air inlet node of the roof top HVAC units. Figure 13 gives a single example of the Table-reported average occupied mass flow rate, the target design flow rate and the average mass flow rate at the air inlet nodes. The modeled HVAC system has three packaged air conditioners dedicated to the classrooms, that each provide service to a “pod” of *corner* and *multi* classrooms. There are three pods in the primary and secondary school, each comprising of both multi and corner classrooms. The source of this discrepancy in reported ventilation rates is unknown. Reported minimum VRs in each scenario still scale with ratios that are approximately consistent with our initial objective, therefore this discrepancy is not expected to impact the conclusions of this study.

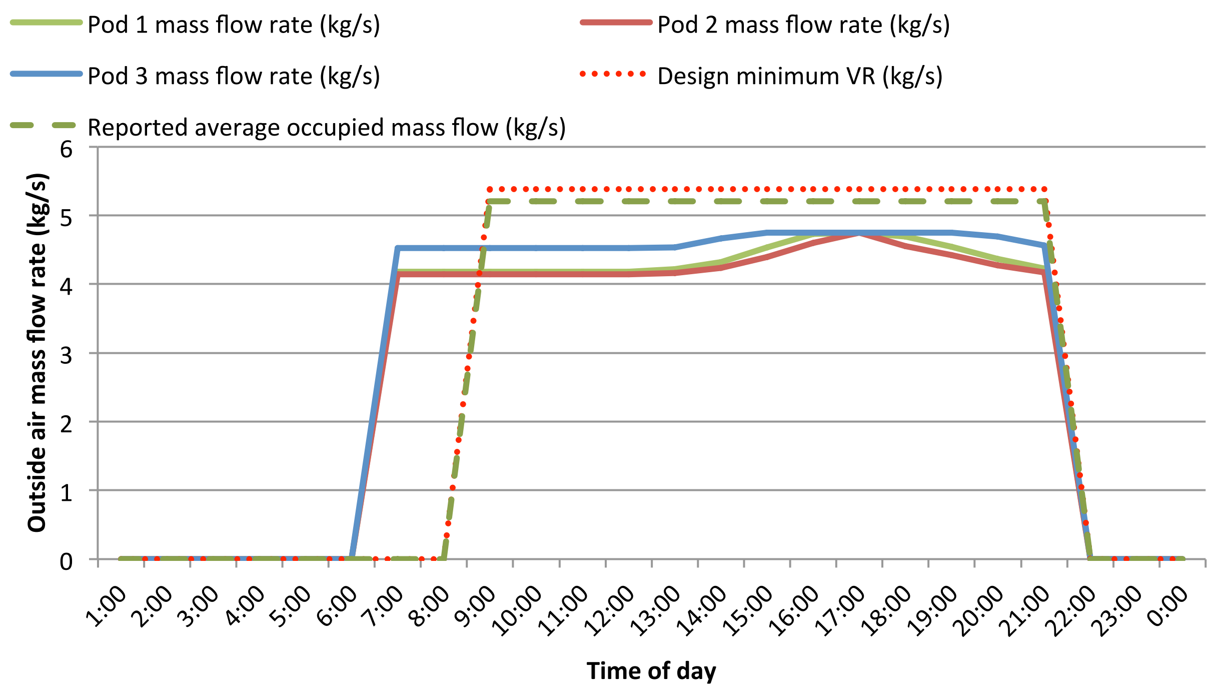

Figure 17. Reported hourly mass flow rates, reported average rate, and reference rate.

CONCLUSIONS

Based on the EnergyPlus modeling, changes in minimum VRs had a large impact on heating energy consumption in the stand-alone retail building. The effects of VRs on total building energy use were more moderate, for example, eliminating all mechanical ventilation, compared to providing the minimum VR specified in Title 24, reduced energy use by approximately 10%. In the schools, the modeling indicates that minimum VRs influence HVAC energy and total building energy use by only a few percent.

For both the retail building and the school buildings, minimum VRs substantially affected the predicted annual average indoor concentrations of an indoor generated contaminant, with larger effects in schools. The shape of the curves relating contaminant concentrations with VRs illustrate the importance of avoiding particularly low VRs.

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