Energy Savings Estimates for Occupancy- and Temperature-based Smart Ventilation Control Approaches in Single-family California Homes

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ABSTRACT

As homes become more air-tight in response to energy efficiency concerns and changes in building codes, new ventilation solutions are needed in order to provide for a healthy indoor environment while minimizing energy use. This is especially true in the state of California, whose 2019 Title 24 Standard encourages tight envelopes through prescriptive air sealing and performance requirements, and requires whole-house mechanical ventilation in all new homes. One such solution employs a real-time assessment of the indoor environment and dynamic operation of a ventilation system. In this study, we investigated the energy savings benefits and indoor air quality improvement available with such a "smart" control strategy for ventilation in four very different California climate zones. We simulated annual operation of multiple control strategies on detailed models of two representative Title 24-compliant prototype homes in California. We did this through co-simulation of the EnergyPlus building energy software and CONTAM, an airflow and indoor air quality simulation software, and an automated Python-based parametric analysis of control variables. All simulations employed the assumption of a single well-mixed zone and the equivalent ventilation method outlined in ASHRAE Standard 62.2-2016. Results show several interesting trends which we hope will help inform standards-development teams, home builders, consumers, and smart ventilation equipment manufacturers in their approach to dealing with dynamically controlled ventilation. In general, control strategies which included optimization based on sensing of outdoor air temperature vastly outperformed strategies which did not. Among these, a temperature cutoff strategy performed nearly as well as more complex variable airflow and variable-exposure-target strategies. Control strategies based solely on occupancy were among the worst performing. Other issues require more investigation such as the acceptability of a seasonal shifting strategy over a daily shifting strategy, and the use of a maximum exposure limit. This work serves as the foundation for ongoing work on multi-zone control and control based on individual pollutant measurements.

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INTRODUCTION

In the past few decades, the buildings community has become increasingly aware of the health effects associated with exposure to airborne pollutants inside residences. At the same time, energy efficiency concerns in buildings are driving increased levels of airtightness and thus less natural air exchange between indoor and outdoor environments. California's 2016 Title 24 Building Energy Efficiency Standards explicitly require caulking, gasketing, and weather stripping of building penetrations for energy concerns in Section 110.7, and include a performance-based compliance pathway in Section 150.1 that is very difficult to achieve with a leaky envelope. This creates the possibility of indoor pollutants in efficient California homes being significantly higher than their older, leakier counterparts, and dedicated ventilation systems becoming imperative.

Furthermore, increased ventilation at times of day and times of year when outdoor conditions are favorable is increasingly being understood as a viable means of providing energy-efficient thermal control (e.g. Turner et al. 2013, Turner et al 2014, Turner and Walker 2014) whether through passive cooling via natural ventilation, economizer action, or (as this study explores) modulation of dedicated ventilation in response to outdoor temperatures.

With these motivations, we analyzed potential solutions that provide occupant pollutant exposure that is equivalent to a continuous IAQ fan, while minimizing the energy penalty associated with conditioning ventilation air. Specifically, we look at smart[1] ventilation strategies that involve modulation of ventilation fan states and speeds throughout the course of a day or year in response to various signals. These signals can include things such as outdoor air temperature, occupancy detection, predicted exposure levels and the operation of auxiliary ventilation devices such as bathroom fans. A thorough review of smart ventilation strategies that have been previously studied can be found in Guyot et al. (2017).

Scope

We limited the scope of our study to advanced homes in the State of California, defined as homes conforming to the 2016 Title 24 energy efficiency standard. We studied homes with dedicated mechanical ventilation and did not explore natural ventilation strategies. Furthermore, we limited the scope of our study to smart ventilation strategies which do not require direct sensing of individual pollutants of interest. Thus all IAQ considerations are made through employment of the concept of relative exposure to a continuously emitted generic pollutant. In the next phase of our work, we will look at strategies which involve sensing of individual pollutants. Lastly, all homes are considered well-mixed zones for the current work. Multi-zone approaches will be studied in detail in a subsequent phase.

Objectives

We pursued three objectives in this work:

1. Provide guidance on the type of signals which should be available in homes with advanced ventilation controls
2. Provide guidance to the buildings community and the State of California on the most effective means of controlling ventilation fans in high-performing California homes
3. Determine the energy savings available with different control strategies

[1] We use the term "smart" to refer to systems that meet the internationally agreed upon definition from the IEA Information Center on energy efficient ventilation: the Air Infiltration and Ventilation Center (Durier et al. (2018)).

THEORETICAL BACKGROUND

The analysis presented in this work is made possible by the concept of *relative exposure*. This is an approach for assessing the IAQ consequences of variable ventilation strategies (Sherman, Mortensen, & Walker, 2011; Sherman, Walker, & Logue, 2012) and is now the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard.. Relative exposure tracks real-time exposure to a generic pollutant emitted at a constant rate indoors, relative to a constant-ventilation-rate scenario, according to Equation 1.

$$\boldsymbol{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t/V_{space}}} \tag{1}$$

In cases where there is no real-time and scheduled ventilation, then Equation 2 is used.

$$\boldsymbol{R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \tag{2}$$

At a given time step, a relative exposure equal to 1 means the two ventilation rates are equal. When averaged over a period of time (e.g., annually), a value of 1 means the two ventilation strategies provide equivalent pollutant exposure. Annually, the arithmetic average of the relative exposure during occupied hours must be less than or equal to one in order to satisfy ASHRAE 62.2-2016 requirements. A more detailed explanation of how relative exposure is calculated in this work is given in ASHRAE 62.2-2016, Appendix C.

Closely related to relative exposure is the concept of *relative dose*, which is mentioned throughout this work. Relative dose is simply the integrated relative exposure over the time period of interest, normalized by that of a constant-ventilation scenario. Relative dose is calculated using Equation 3:

$$\boldsymbol{d_i = R_i * \left(1 - e^{\frac{\Delta t}{24}}\right) + d_{i-1} * e^{\frac{\Delta t}{24}}} \tag{3}$$

METHODS

In order to study the energy and indoor air quality (IAQ) benefits and consequences of smart ventilation strategies, we first created a combined energy-IAQ model of two representative California home types, at three different air-tightness levels, in four very different California climates: Arcata (CZ1), Blue Canyon (CZ16), Oakland (CZ3), and Riverside (CZ10). CONTAM models (Dols and Polidoro 2015) were created to assess the IAQ portion of the problem by modeling the air flow mass balance including inter-zonal air flow, mechanical air flow and infiltration, and contaminant transport. EnergyPlus models were used to assess the thermal and systems portion of the problem by modeling the building envelope; HVAC system and controls; occupants and building energy use.

Using an automated parametric modeling approach, we co-simulated these two simulation platforms across the homes, climates and control strategies of interest. At each timestep, CONTAM sent environmental data (wind speed, direction and outdoor temperature), and system operation data (mechanical system flows) to EnergyPlus. The EnergyPlus Energy Management System (EMS) was used to manage this interchange and to implement required calculations and control strategies.

Smart Ventilation Strategies

We assessed several control strategies, which we describe briefly now. These can be broadly categorized as occupancy-based controls and temperature-based controls. Occupancy controls require knowledge of occupancy presence, and temperature controls require knowledge of outdoor temperature. In response to these signals, a ventilation fan is modulated to provide more ventilation when advantageous and less when not, subject to the requirement that annual relative exposure averages 1.0 or less. The following sections describe control strategies which respond to each of these signals.

We assessed three occupancy-based control strategies:

1. Unocc: Ventilation is stopped completely when the residence is unoccupied, subject to a constraint of maximum relative exposure of 5 to ensure acute exposure concerns are satisfied upon occupant return.
2. Reduc: Similar to the first strategy, ventilation is reduced but not curtailed completely while the residence is unoccupied. This decreases the length of the "recovery" period necessary when occupants return.
3. Flush: This is identical to Unocc strategy, with the exception that ventilation is increased to its maximum for a period of time immediately prior to occupants returning. This also reduces the recovery period and peak exposure.

We also assessed six temperature-based controls:

1. Lockout: Ventilation is simply turned off for the hottest hours in the summer and coldest hours in the winter, and then increased at other times of the day to ensure daily and yearly relative dose of one.
2. Seasonal: Based on an annual shift in ventilation rather than a diurnal shift. Seasonal exposure targets are established that generally reduce ventilation during the heating season and increase ventilation during the cooling season. These are designed to average 1.0 annually.
3. Cutoff: On top of the seasonal control (above), ventillation is further modulated during the hottest times of the summer and coldest hours of the winter by continuously sensing outdoor temperature and setting a high relative exposure target when temperature is above (or below for heating) a pre-defined cutoff temperatures.
4. Running Median (MedRE): Ventilation is curtailed in the winter when outdoor temperature is below a continuously adjusted running median temperature calculated over a period of several days, and increased when it is above. An opposite pattern is used in the summer.
5. VarRE: Relative exposure targets are continuously varied in proportion to outdoor temperature.
6. VarQ: Ventilation flow rate is continuously varied in proportion to outdoor temperature.

The CutOff, VarRe and VarQ strategies all used opimtization routines to establish control settings prior to simulation execution, based on site energy savings.

RESULTS

We first present a summary of annual energy savings available with smart ventilation controls. Figure 1 below shows a summary of the calculated savings for a moderately tight (3ACH50) single-story prototype home with colors designating end use responsible for each portion of the energy consupmtion. Climate zones refer to California Climate Zones, not U.S. DOE national zones.

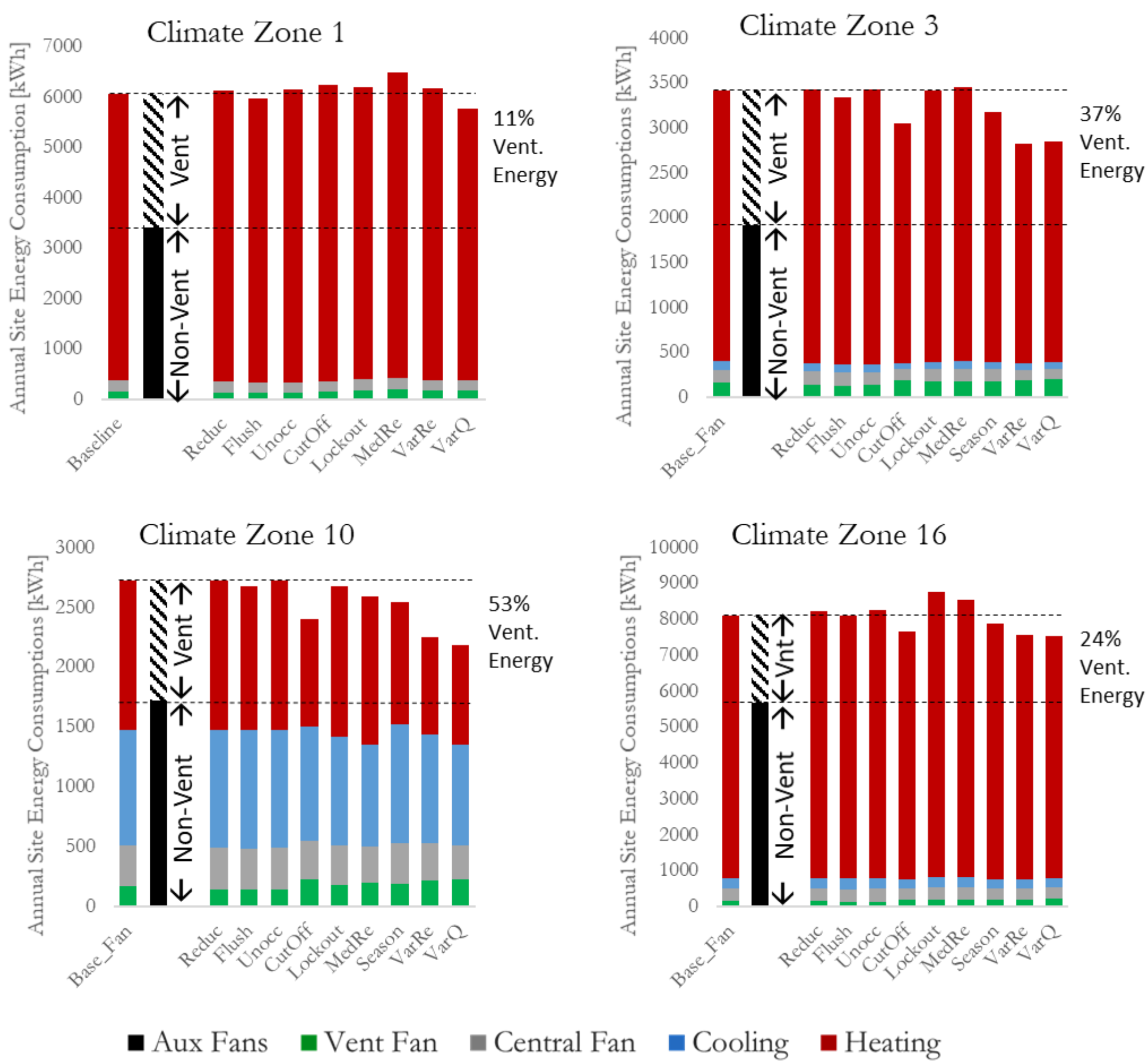

Figure 1 Modeled energy savings with each control strategy analyzed. Reported percentage of ventilation for each California climate zone refers to the percentage of energy associated with whole-house mechanical ventilation that is saved in the best-performaing strategy. Diagonal hatches denote the portion of energy use associated with whole-house mechanical ventilation. Percentages refer to fraction of ventilation energy savings with best performing strategy.

Occupancy-based Controls

A few general trends can be immediately understood from Figure 1. First, according to this simplified analysis, purely occupancy-based strategies seem not to provide much energy savings in any climate. This result is confirmed by other works including a field study (Martin et al. 2018) which failed to realize much savings with occupancy-only controls:

> "For the actual unbalanced exhaust ventilation system operating at the test home, heating and cooling energy savings from the modeled [occupancy-based smart ventilation controls] OSVC are minimal, at only 28 kWh per year, or 1%."

Similarly, Less and Walker (2018) conducted a national study and found:

> "Overall, savings from occupancy-based smart controls were low, because of the recovery period required after occupants return home, during which the airflow is double the 62.2 reference. This recovery is required to maintain equivalence with the ASHRAE standard."

The authors are not aware of any studies demonstrating a means of saving an appreciable amount of energy through smart ventilation control using only an occupancy signal and unbalanced fans with code-compliant controls. This is unfortunate, as smart thermostats, which are rapidly growing in popularity, often have an integrated occupancy sensor, and many cell phone-based apps that control smart thermostats also allow enabling of geo-fencing which can automatically activate controls based on an occupants' proximity to their home.

There are a few reasons for this phenomenon. First and most obvious is that typical occupancy patterns in residences prevent the greatest savings from being realized: In summer months, the typical work day coincides with the times at which one would want to reduce ventilation and thus home are unoccupied, leaving little room for savings through better control. In the winter, occupancy controls time-shift mechanical ventilation from relatively warm daytime hours to colder evening/nighttime hours, thus incrasing heating load. Other reasons are more complex. Next, ASHRAE 62.2-2016 currently makes no explicit allowance for reduction in assumed emissions of the generic pollutant used to control dynamic ventilation strategies when homes are unoccupied, unlike some other building codes (e.g. Danish Enterprise and Construction Authority 2010). Also, unbalanced exhaust flows act in a coupled and non-linear manner with natural infiltration, and the manner in which this phenomenon is accounted for in ASHRAE 62.2-2016 puts dynamic control strategies at an inherent disadvantage from the perspective of an increase the total amount of air to be moved (and therefore energy use). This phenomena is very difficult to explain and thus beyond the scope of this paper but Less and Walker (2017) explain it in detail for the interested reader. Future standard changes may allow for energy savings to be gained through occupancy-only strategies but for now we should not expect much savings through this type of control.

Temperature-based Controls

Another interesting result can be found by comparing the best performing temperature-based strategies. The modeled energy savings for the best-performing strategies of this type are shown in Figure 2:

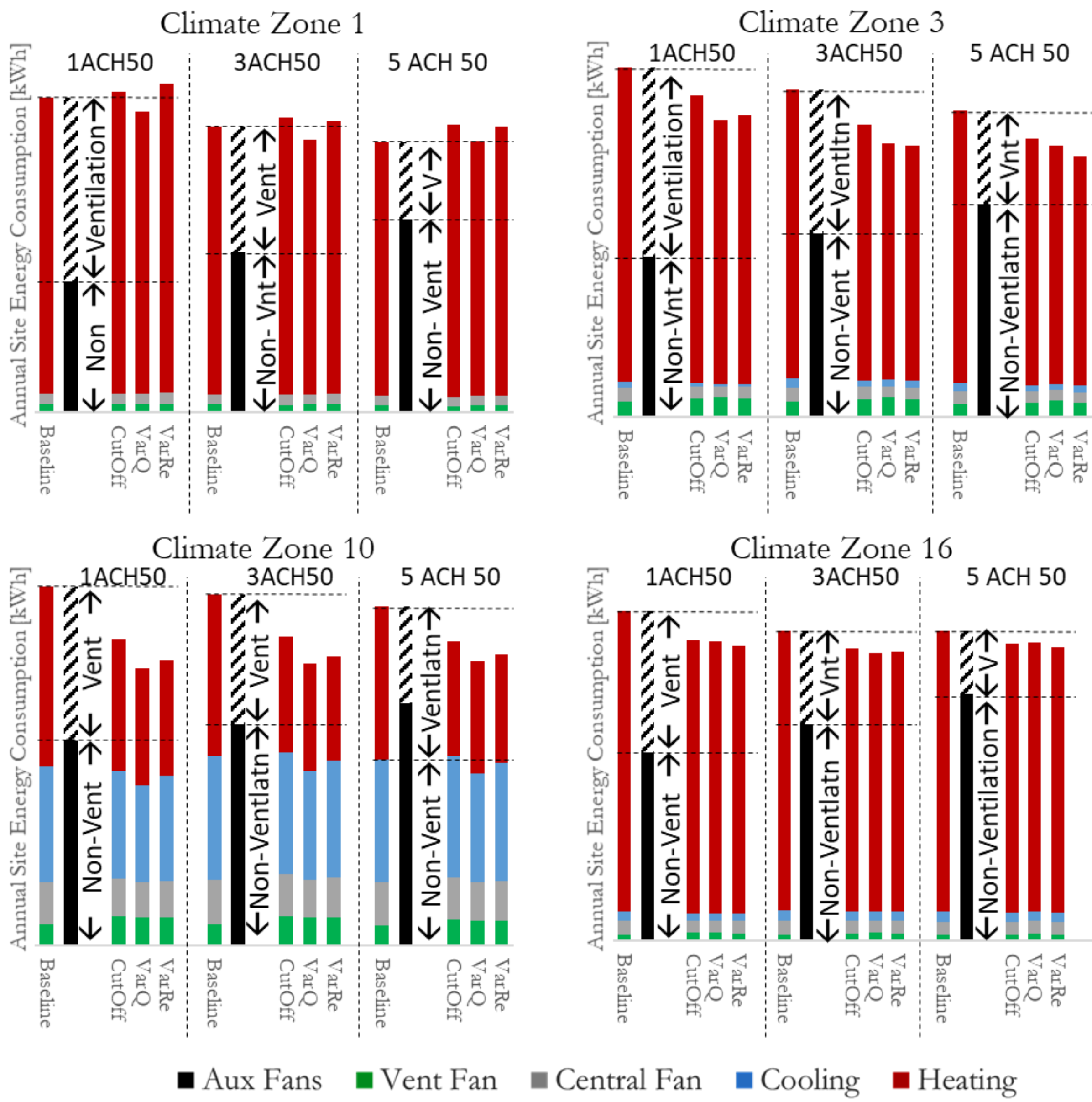

Figure 2 Annual consumption with best performing temperature-based smart ventilation control strategies. All results are for a single-story prototype home. Results are given for three different air-tightness levels as noted. Hatched regions denote energy associated with ventilation. Percentages refer to fraction of ventilation energy savings with best performing strategy.

The three best-performing strategies in Figure 2 require very different hardware. The best performing strategy, "VarQ", involves the continuous modulation of fan speed. This likely requires a variable speed drive on the exhaust fan. While variable speed drives are becoming more prevalent, it is an added expense which builders and homeowners may choose not to include after value engineering. In contrast, the VarRe and Cutoff strategies were simulated with only a single-speed fan and this saved nearly as much energy in all but one climate analyzed.

CONCLUSION

Through a detailed modeling study we investigated nine smart ventilation control strategies for single-family homes. The best controller was able to reduce ventilation energy consumption by a weighted average of 43%. Occupancy controls were shown to provide much smaller benefits than temperature-based controls. Among the temperature control strategies investigated, those not requiring variable speed drives performed nearly as well as those with. Future work will consider control based on individual pollutant sensors, and multi-zone control.

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NOMENCLATURE

R = Relative exposure
Q = Ventilation rate, m^3/s
Δt = Simulation time-step, hours
V = Volume of the space, m^3
d = Relative dose

Subscripts

i = current time step
$i\text{-}1$ = previous time step
tot = Target from ASHRAE 62.2-2016

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