Title
Smart Ventilation for Advanced California Homes

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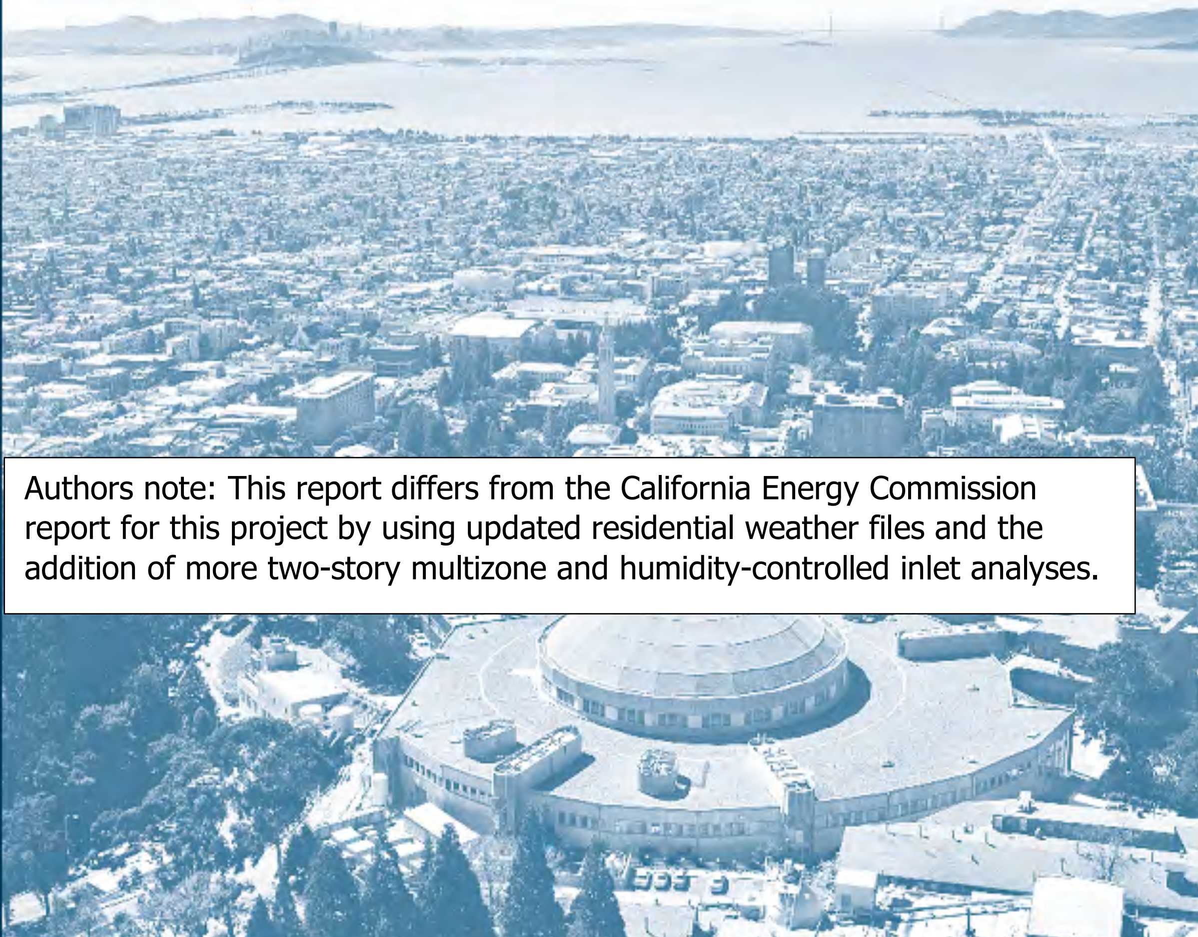

Authors note: This report differs from the California Energy Commission report for this project by using updated residential weather files and the addition of more two-story multizone and humidity-controlled inlet analyses.

Disclaimer

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ABSTRACT

This project investigated smart ventilation approaches to minimize energy use for providing indoor air quality (IAQ) in high performance new California homes. Evaluation criteria included annual ventilation-related energy, peak energy and time-of-use savings, and the indoor air quality relative to a minimally code-compliant ventilation system. The simulations used CONTAM's air flow and contaminant transport model, combined with the EnergyPlus building loads model. House types representing the default California Energy Code compliance homes were investigated for four California climate zones, covering a wide range of climate types. Both single and multi-zone smart ventilation controls were investigated. Contaminant sources included contaminants emitted continuously and varying with time, temperature and relative humidity, episodic emissions from occupant activities and outdoor particles. Single-zone ventilation controls that varied ventilation depending on outdoor temperatures were able to consistently save half of ventilation-related energy without compromising long-term IAQ. Ventilation strategies that tracked occupancy were less successful, because this work included generic contaminants with constant background emission rates. Energy performance for occupancy controls improved with a one-hour pre-occupancy flush out strategy. The addition of zoning ventilation controls did not offer significant IAQ to energy improvements compared to non-zonal versions of the same ventilation system type. The best controls had HVAC energy savings of 10-20%, with individual cases reaching up to 40% savings. However, these savings cannot be achieved without worsening personal exposures for at least one contaminant. A metric is needed to assess the competing changes in exposure to different contaminants in order to determine the net-health impacts of a control strategy. Controls that directly sensed contaminants and controlled them to acceptable levels showed that the California OEHHA limit for formaldehyde completely dominates system performance, with homes not able to meet the limit even with continuous operation of a fan sized to twice the current code minimum.

Keywords: Smart ventilation, controls, indoor air quality, multi-zone, contaminant sensing

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EXECUTIVE SUMMARY

Introduction or Background

New California homes are becoming more energy efficient due to increasing stringency of building codes and California home builders' ability to develop high performance homes. High performance new homes in California are intended to be "net-zero" meaning that they only use as much energy as they can generate with renewable energy sources. For existing homes, there is a need to upgrade them to perform much better than they do at present – using many of the same approaches used in new construction: better air sealing, insulation, windows, appliances and lighting. In addition to energy performance, homes must also be comfortable, durable and healthy places to live. In dwellings sealed for energy performance, a mechanical ventilation system is key to providing good indoor air quality. The building code requires minimum ventilation levels in new homes constructed in California. As space conditioning, lighting and some other energy end-uses in homes have been substantially reduced, the energy required for ventilation and IAQ has not received equal attention. The result is that in most new California homes, ventilation makes up an increasingly large fraction of the total HVAC load and annual energy use. As net-zero becomes code-required in the state, we will need new strategies to reduce ventilation energy use at a reasonable cost.

Balanced ventilation systems with heat recovery are the only approach currently available on the market that reduce the energy associated with providing ventilation and IAQ in dwellings. These are commonly expensive systems (>$1,000), with substantial challenges involved in good installation and in ongoing maintenance. Smart ventilation is the low-cost (<$300) alternative to these more expensive strategies.

The vast majority of new California homes are ventilated by simple fans that operate continuously and without heat recovery. The idea behind smart ventilation is to introduce controls for ventilation systems that can be applied to simpler, lower cost systems, as well as more advanced systems. The key concept behind smart ventilation is to allow ventilation to occur at different times of the day, week or year (e.g., depending on outdoor temperatures or if the home is occupied), or to take account for operation of other house fans (e.g., kitchen, bathroom and dryer exhausts) such that the occupant's exposure to contaminants is the same, or lower, than for a non-controlled system. In addition to energy savings, smart systems can be designed to respond to signals from utilities to reduce ventilation-related loads at times of peak demand, thus ensuring greater grid reliability. Unlike a simple on-off device, however, a smart ventilation system is designed to operate more at off-peak times to offset the on-peak reductions so that occupants do not have to pay a price in terms of health. In other words, a smart ventilation system is only smart if it gives us the benefit of reduced energy use and peak demand without compromising healthy indoor air.

The competitive market has no incentive to develop smarter ventilation systems, because there is currently no way for builders or contractors to put a quantitative value on the ventilation/energy tradeoff or to get credit for improved IAQ in the codes and standards arena; thus, it is difficult to use smart ventilation for competitive marketing. This project is essential to provide the information required by the California Energy Commission and other policy makers to evaluate different options for future standards, particularly those related to ZNE homes. The results of this study will facilitate competitive-sector development of compliant technologies and regulated-sector development of programs. Much of the core research and development for this project is pure public-benefit work, and requires ratepayer support. This is enhanced by additional the public-benefit funding provided by match funding from the U.S. DOE.

Project Purpose

The research has three technical objectives. These objectives are intended to provide the technical material suitable for use by building controls and ventilation manufacturers so that they can produce smart ventilation systems and by codes and standards bodies (specifically Title 24 in California and ASHRAE Standard 62.2 for a national audience) so that credit can be given for these approaches. The objectives are:

Objective 1. Revise IAQ metrics: Methods of assessing IAQ metrics were developed that go beyond simple fixed continuous ventilation rates. New approaches developed in this study include exposure to key contaminants as well as controls to minimize energy use and reduce peak demand. These metrics are specifically applicable to ZNE homes, which will be more air-tight and have smaller heating, ventilation, and air-conditioning systems than current California construction. Because of their small heating and cooling loads, ZNE homes often do not have central air handlers and are zonally conditioned from both a thermal and air-quality perspective so new metrics were developed to assess zonal approaches to IAQ and ventilation. These new metrics were used both internally within this project and may also form the basis for future codes and standards revisions.

Objective 2. Demonstrate that smart ventilation systems can provide acceptable IAQ in ZNE homes. This study used simulation techniques to estimate the energy use and IAQ of homes with different smart ventilation approaches to show that energy can be saved while enhancing IAQ. These demonstrations will give codes and standard developers the technical basis to allow for smart ventilation approaches and for equipment manufacturers to develop smart ventilation products.

Objective 3. Determine how best to design ventilation systems for ZNE homes. Previous studies have shown that optimum smart ventilation strategies depend on climate, building type and other parameters. This study investigated approaches specific to California climates and housing types to determine the best strategies for California homes. It also added the potential for occupancy and contaminant sensing so that ventilation can be reduced when it is not needed.

The results of this project are important for occupants because it is essential that energy efficient homes are also healthy homes and that the well-being of occupants is not compromised in our efforts to reduce energy use. Without smart ventilation, the options are to either lower health levels or to leave energy savings on the table – neither of which are desirable. Smart ventilation has the capability to actually enhance or improve IAQ while still saving energy. Lastly, developing metrics that define smart ventilation and controls that address these metrics are essential from a consumer protection point of view. There are already ventilation products on the market that claim to be smart by saving energy, but they do not also preserve IAQ. Having a sound technical basis, such as that developed in this study, is essential to address this issue.

Project Approach

The development of smart ventilation control strategies were based on: a combination of our previous experience from other projects; an in-depth literature review of residential ventilation controls (that includes existing ventilation energy standards for demand control ventilation from several European countries); analysis of occupancy patterns and occupant-generated contaminants (e.g., from breathing, cooking and bathing); and studies of measured contaminants in homes (in particular the HENGH study of contaminants in new California homes). The various strategies were assessed analytically using computer simulations combining the CONTAM airflow and pollutant transport with the EnergyPlus building loads model. Both of these models have had extensive use in the buildings industry over several decades, but considerable effort was required to get them to work together in a way suitable for the purposes of this study. The metrics used to assess the ventilation control strategies and to form a basis for the tested control strategies are a combination of current methods and new approaches tailored to the specifics of time-variant ventilation and zonal ventilation. The output of the simulations were analyzed to determine energy use (in both site energy that would appear on a utility bill and Time Dependent Valuation (TDV) energy that is used to show compliance in the California State Energy code[1]. The TDV assessment weights the energy used depending on when it is used, with greater weight applied to times of high demand. The energy use associated with ventilation was separated from other building envelope loads to estimate the fraction of ventilation energy savings. The energy use was compared to a reference: a continuously operating system that meets the current California Energy Code minimum requirements. The exposure of occupants to contaminants was also modeled to ensure that any recommended strategies delivered IAQ at least as good as a continuously operating ventilation system.

The project had four main technical tasks:

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[1] This project used the hourly 2019 TDV factors that are used in the CBECC-Res simulation program in residential code compliance calculations.

1. Literature review. This task investigated previous research on smart ventilation-related topics to form a basis for the development of metrics and control strategies.
2. Development of IAQ Metrics. This task examined different methods for evaluating indoor air quality including the CO_2 and humidity-based demand control system used in Europe as well as health-based metrics such as Exposure Limit Values and Disability Adjusted Life Years (DALYs) that combine mortality and morbidity into a single metric.
3. Single zone technology evaluation. This task performed simulation to assess the energy use and IAQ of single-zone smart ventilation approaches.
4. Multi zone technology evaluation. Building on the results of the previous task, this task expanded to include multi-zone ventilation and direct contaminant sensing approaches.

The greatest challenges were:

1) Developing new metrics for ventilation system control – particularly for zonal and direct contaminant control. Several difficult questions needed to be answered, such as: do all zones need to be in compliance and as occupants move from zone to zone how to keep track of exposures? Or, for contaminants, what level should they be controlled to: the maximum allowed by health community standards, or what is typically found in California homes as measured in the HENGH study?

2) Model development: getting CONTAM and EnergyPlus to act as a single air flow, contaminant transport and energy modeling system and converting EnergyPlus operation from simple load calculations into actual energy balances.

3) Ensuring that potential smart ventilation controls had some level of practical application – at least in the near (less than five year) time horizon. Examples of this would be the limited concentration and time resolution of existing pollutant measurement equipment. For most of the zonal controls, it also required the assumption of some sort of perfect device for knowing when occupants move from zone to zone that does not currently exist – which led to the use of simplified approaches to zonal controls.

A project technical advisory committee (TAC) was formed that included representatives from the California Energy Commission (CEC), California Air Resources Board, ventilation equipment manufacturers interested in smart ventilation, the National Institute of Standards and Technology, the California Building Industry Association, the Home Ventilating Institute, and our partners the US DOE and Aereco. The TAC has made supportive suggestions and comments throughout the study. Some key issues were: ensuring that the energy predictions were similar to those used in California Energy Code compliance software (CBECC-Res), how to group rooms into zones for zonal control, ensuring that controls meet acute exposure limits as well as addressing long-term chronic exposure, discussing how systems might be certified for a product directory, as well as simulation details – such as what furnace efficiency to use as a default.

A project website has been created that was used to track project progress and to allow public access to the project results when the project is complete: svach.lbl.gov.

Project Results

This project has successfully demonstrated the potential energy savings for smart ventilation approaches and identified the control strategies that offer the best modeled energy savings across a range of California climates and house types. The key IAQ metric used in this study for evaluating if smart controls provided the same or better IAQ than non-smart systems was the equivalence principle. This metric ensures that the annual exposure to a pollutant is the same as for a home without smart controls. Other metrics were developed for control purposes. These included limiting exceedance of acute contaminant concentrations and using concentrations averaged over different time periods for contaminant-based controls.

The most effective control for **single-zone** applications varied the ventilation system air flow depending on outdoor temperature – with a seasonal variation of higher ventilation rates in milder weather and lower ones when the energy cost to ventilate is higher. This control reduced site ventilation energy use weighted by construction starts per climate zone by about 50%, while TDV weighted average ventilation energy reductions were higher, up to roughly 60%. Because the controls were designed to err on the side of greater ventilation, on average they resulted in better IAQ. These same controls led to peak demand reductions during the 2-6pm period on the hottest days of the up to 300 watts. More than 90% of site energy savings were for heating end-uses, while TDV energy savings were split more evenly between heating and cooling. Occupancy-based controls that accounted for contaminants released by building materials and furnishings during unoccupied times were generally ineffective, with very low energy savings. All temperature and occupancy controls were also tested with auxiliary fan sensing capability (i.e., accounting for the use of other exhaust devices in the home, like bathroom or kitchen fans). Auxiliary fan sensing increased energy savings in all cases, from roughly 5 to 15%.

Multi-zone smart controls did not clearly offer substantial energy savings in new homes compared to non-zoned approaches. The ability to target individual zones for ventilation was offset by the introduction of outdoor particles, and by the need to account for contaminants generated independent of occupancy (e.g., formaldehyde). A method must be developed to balance these competing changes in exposure to determine the net-health impacts of a control strategy. The zonal controls offered some additional energy savings potential, but they consistently compromised IAQ for at least one contaminant. A key barrier to the use of zonal controls is that current occupancy sensing equipment does not perform adequately to track occupants throughout the zones of a dwelling. Furthermore, the ability of homes to be effectively zoned from an

IAQ perspective is limited by opening of interior doors, operation of HVAC equipment, and movement of occupants between zones.

Contaminant control approaches are completely dominated by the difficulty in achieving the OEHHA limit for formaldehyde. Our systems ventilated at their maximum flow rates and still did not achieve the 9 $\mu g/m^3$ OEHHA limit and also doubled energy use. In the future use of other concentration limits should be investigated, e.g., target the 20th percentile lowest concentrations measured in homes.

The next steps in developing this technology will be to create real-world prototypes and to perform pilot studies to evaluate them in occupied homes. We also need to find ways that these energy savings can be reflected in building codes and standards, which do not typically include detailed ventilation airflow calculations. This work is being undertaken by LBNL in collaboration with the US DOE Building America Program.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Throughout this project presentations have been given on smart ventilation at industry conferences, writing papers for technical journals, collaborating with ventilation equipment manufacturers and working with the international ventilation community to share project results and discuss relevant topics. The reaction has been overwhelmingly positive with a typical reaction being: "When can I buy one of these devices?" Since before this project started, LBNL has been actively promoting smart ventilation and it is a topic of great interest in the industry and is now being routinely discussed. A project website has been developed (svach.lbl.gov) that covers the background to smart ventilation, a general discussion of this topic as well as details of this current project.

The results of this project have been shared with the research community, as well as building design and construction industry professionals through the publication of four journal articles and six conference papers. Further articles will be published shortly and results presented at more industry conferences and workshops in the future.

Part of the US DOE co-funding of this project was collaboration with the International Energy Agency Annex 5: the Air Infiltration and Ventilation Center to lead a project on smart ventilation that included other international researchers, and to create an international definition of smart ventilation. This definition goes beyond the energy and IAQ issues covered in this study, and it forms a useful basis for defining smart ventilation systems that the industry needs if it is to progress.

At industry trade shows many manufacturers of ventilation equipment they have expressed interested in the concept of smart ventilation. In order to be more viable in the marketplace several things are needed:

1. A definition of smart ventilation. This is required so that manufacturers of smart ventilation systems get credit for their systems. There are already products on the market claiming to be smart that are not. These products make IAQ worse in

order to save energy and an accepted definitions of smart ventilation allows these claims to be debunked.

2. Credit in building energy codes and standards, such as Title 24 in California, ASHRAE Standard 62.2, and Residential Energy Savings Network (RESNET) ratings. This is one of the vital next steps after this project. LBNL plans to work with California Energy Commission staff to help make changes to California Building Energy codes, with ASHRAE to make appropriate updates to Standard 62.2 (the PI for this project is the current Chair of ASHRAE 62.2), RESNET and other entities to make this happen. This includes possible product certification through organizations such as the Home Ventilating Institute (who were members of the project Technical Advisory Committee). This effort could be extended to include credits from utility programs for grid interactive ventilation that allows ventilation loads to be shed at times of peak demand (additional research efforts are currently being pursued with utilities (in California and elsewhere in the country) and the US DOE on this topic).
3. Pilot field studies demonstrating smart ventilation systems in homes. This addresses issues beyond the control strategies developed in this study to engineering sensors, control panels, Wi-Fi devices, etc. that are required for full product development. The US DOE Building America Program will perform field studies over the next three years led by LBNL in partnership with Building America teams, and equipment manufacturers.

Potential Benefits

When building or renovating homes to be "high performance" it is essential that performance includes healthy safe homes and not just homes with low energy use. Furthermore, in order to enable energy savings from air tightening strategies, the use of mechanical systems is vital. To make this work even better the energy impact of this mechanical ventilation needs to be minimized. This project addresses these issues by developing smart ventilation approaches that are important to ratepayers because they:

1. Maintain health, odor and moisture requirements for indoor air. This is not only desirable from an occupant's perspective, but also has substantial benefits from public health cost savings.
2. Save roughly half of the energy required to mechanically ventilate a home. This corresponds to a reduction in average site ventilation energy use by about 413 - 505 kWh/year for the homes and HVAC systems simulated in this work. This is equivalent to about 12 - 15% of whole house HVAC energy. In TDV this is increased to about 1,615 - 2,743 kWh/year. These savings can be significantly increased, by roughly 5-15%, through sensing operation of other fans (kitchen/bath/laundry exhaust and economizers).

3. Enable peak demand reductions up to about 300W for a period of 2 hours that help to ensure grid reliability at peak times. Moreover, it comes at no penalty/cost to occupants, because the smart ventilation controls are specifically designed to recover from any extended period of lower ventilation to ensure that occupant exposures are not increased.
4. Enable lower-cost approaches to high-performance ventilation. A typical implementation of smart ventilation would be an add-on control to a simple exhaust fan to give it performance close to much more complex and expensive systems, such as heat recovery ventilators. This can be applied not just to new construction but also to existing homes and retrofits – thus significantly expanding the market for providing more ratepayers with good IAQ and energy savings.

This project lays the groundwork for future research projects that develop physical prototypes and use them in pilot studies in homes.

CHAPTER 1: Introduction

Ventilation is the intentional exchange of outside air with the air inside a conditioned space. Its purpose is to displace pollutants of indoor origin such as human bioeffluents, emissions from consumer products and building materials, products of combustion, by-products from cooking and other sources. Ventilation also contributes to a building's energy balance, and thus can be either a driver of energy consumption, or a means of reducing energy use when outdoor conditions are favorable.

Research on how best to ventilate buildings is motivated by several factors. First, increased recognition and awareness of the substantial public health burden that results from exposure to contaminants of concern in indoor environments. Logue et al. (2011) estimated the number of disability-adjusted life years[2] (DALYs) lost per 100,000 people in U.S. residences as a result of exposure to indoor pollutants on the order of 1,000 from fine particulate matter alone, and on the order of 10-100 for both formaldehyde and acrolein. For comparison, about 11 people per 100,000 are killed in automobile accidents every year in the US[3] corresponding to about 19 DALYs per 100,000 people[4]. Second, these exposures are becoming even more important in the context of energy efficiency requirements in building codes and voluntary standards that require substantial air leakage reductions, compared with homes of the past. For example, in many U.S. climates, the International Energy Conservation Code (IECC) requires an envelope leakage rate of 3 ACH_{50} (ICC, 2012), and select voluntary programs, such as Passive House, require extreme airtightness at <0.6 ACH_{50}. New California homes are typically in the range of 4-6 ACH_{50} (Chan, Kim, Less, Singer, & Walker, 2018). Typical values for new homes even a decade ago were in the range of 6-10 ACH_{50}, while older, existing homes range from 10-30 ACH_{50} (Chan, Joh, & Sherman, 2013).

In this context, codes and standards have begun to require mechanical ventilation in residences. Airflow requirements vary, but most standards in the U.S. are based on versions of the ASHRAE 62.2 ventilation standard. All new homes in California have been required to provide whole house dilution ventilation since 2008 (California Energy Commission, 2008). Similar requirements exist in the IECC and in select state energy

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[2] https://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/

[3] https://www.iihs.org/topics/fatality-statistics/detail/state-by-state#yearly-snapshot

[4] Based on ratios of injury to fatality DALYs in Taino et al. 2014

codes and voluntary programs (e.g., State of Washington Energy Code). Without dedicated ventilation systems, concentrations of indoor pollutants in advanced California homes would be significantly higher than their older, leakier counterparts.

Third, increasing ventilation at times when outdoor conditions are favorable is increasingly being understood as a viable means of providing energy-efficient thermal control. Strategies include passive cooling via natural ventilation, the use of economizers, and (as this study explores) modulation of dedicated ventilation in response to outdoor temperatures.

Finally, stress on the electric power grid is a major concern as mechanical cooling and renewable energy saturation increases in California homes and businesses. Ventilation loads are greatest at times of day, and times of the year, when the grid is already stressed the most, or when rapid ramping of supply is needed (late afternoon and evening). Shifting ventilation to times of lower grid demand may provide substantial benefit.

Given these motivations, this study explores possible approaches to providing ventilation that both ensures acceptable indoor air quality, and minimizes the energy penalty associated with conditioning ventilation air. The concept of *relative exposure* was used in this study (and commonly used in other applications, such as ASHRAE Standard 62.2). Relative exposure is a unitless number found by determining the ratio of exposure to the exposure from a reference case. For this study the reference case is a continuously emitted, indoor generic pollutant. A relative exposure less than or equal to one ensures that that the exposure from a smart ventilation system is equivalent to or better than a non-smart system: i.e., a continuous fan sized to the ASHRAE 62.2 ventilation standard.

This project focused on "smart" ventilation strategies that involve modulating ventilation rates throughout the course of a day or year. These strategies may respond to outdoor air temperature, occupancy detection, predicted exposures, and the operation of auxiliary ventilation devices such as bathroom fans. A thorough review of available smart ventilation strategies that have been previously studied can be found in I. Walker, Sherman, Clark, & Guyot (2017).

Past work has used related approaches to develop and assess smart ventilation controls in homes in a variety of climates. A controller named RIVEC (short for **R**esidential **I**ntegrated **Ve**ntilation **C**ontroller) was developed and briefly field-tested in California that used occupancy, auxiliary fan sensing, grid signals and timer-based temperature controls (I. S. Walker, Sherman, & Dickerhoff, 2012). Less, Walker, & Tang (2014) studied the effects of several temperature-based control strategies that used cut-off temperatures below which IAQ fans were turned off (fan airflow were increased during all other hours). Smart controls for humidity control in hot and warm-humid climates were developed for similar homes in Less, Walker, & Ticci (2016). Less & Walker (2017) examined the performance of occupancy and auxiliary fan smart controls in Zero

Energy Ready homes across US DOE climate regions. Work at the Florida Solar Energy Center (Martin, Fenaughty, & Parker, 2018) has developed a multi-parameter smart ventilation controller using outdoor temperature and moisture levels, paired with pre-calculated seasonal ventilation targets. Lubliner et al. (2016) reported on limited field-testing of an occupancy-based smart controller deployed in a Deep Energy Retrofit home in the Pacific Northwest.

Consumer building products are emerging on the market that provide some form of ventilation control based on measured temperature and humidity, but which do not track relative exposure to preserve IAQ, and are not compliant with codes and standards. An incomplete descriptive list of these products is provided in Appendix T of Appendix A, including summaries of cost, sensor options and control schemas. Products are diverse, costing between $50 and $300. They include a variety of either indoor or outdoor (or both) temperature and/or humidity sensors, and many are limited to use with certain fan types, or are embedded within certain fan technologies. Some controllers have hot-humid climate control features, but lack cold climate features. This brief review suggests that products are available and can be economically integrated with systems, sensors and varied control features; what they lack are optimized controls that maintain compliance with ventilation codes and standards.

While past work has explored smart controls broadly in U.S. climates, this study considers only advanced homes in the State of California, defined as homes that conform to the 2016 Title 24 energy efficiency standard. This study looks only at homes with dedicated mechanical ventilation, and does not explore natural ventilation strategies. All of the analyses use detailed annual simulations of reference buildings with thermal and airflow characteristics of homes built to the 2016 Title 24 standard, under a variety of different ventilation control strategies.

The project had the following technical tasks:

1. Literature review. This task investigated previous research on smart ventilation-related topics to form a basis for the development of metrics and control strategies.
2. Development of IAQ Metrics. This task examined different methods for evaluating indoor air quality including the CO_2 and humidity-based demand control system used in Europe as well as health-based metrics such as Exposure Limit Values and Disability Adjust Life Years (DALYs).
3. Single zone technology evaluation. This task performed simulation to assess the energy use and IAQ of single-zone smart ventilation approaches.
4. Multi zone technology evaluation. Building on the results of the previous task, this task expanded to include multi-zone ventilation and direct contaminant sensing approaches.

The technology evaluation tasks used Contam/EnergyPlus co-simulation environment developed specifically for this project.

Smart ventilation is an enabling technology that saves energy in a whole-building context and facilitates other energy-saving technologies. For example, smart ventilation can shift the ventilation load so that much less energy is required for conditioning, a smaller air conditioner might be needed, and peak demand would be reduced—all without negative health or comfort impacts.

Reducing infiltration in existing buildings is a high-payoff state goal that will require installation of smart ventilation systems. The CEC-funded RESAVE study (http://resave.lbl.gov) estimated that tightening California homes and providing adequate ventilation could save approximately $1 billion in annual energy costs. The health costs of air-tightness without adequate ventilation are harder to estimate well but would be substantially higher than the energy savings and thus would be a barrier to air-tightening, seriously limiting the state's ability to approach ZNE homes. This project will provide information that can be used by utility and other programs addressing home energy retrofits to ensure that they meet IAQ requirements. If IAQ requirements are not met, then these infiltration-related savings will not be realized, which will make it very difficult, if not impossible, to meet the state's ZNE targets. Reducing infiltration in new construction is an important step in getting to the state's 2020 goal but faces the real and perceived barrier of IAQ risk. The outputs of this project reduce that barrier and thus facilitate improved energy efficiency.

One aspect of ZNE that can be problematic for utilities is that heating and cooling loads typically coincide with periods of peak demand for the electricity grid. A smart ventilation system can help offset this peak by shifting ventilation loads to off-peak hours. Previous LBNL studies have indicated that simple timer controls to avoid ventilation on summer afternoons or winter nights can save about 40% of peak ventilation load (about 15% of the heating and cooling load for a conventional home and a higher fraction for a ZNE home) (Turner and Walker 2012a). It should be possible to reduce potential grid reliability problems and reduce peak loads further with smart ventilation systems that can respond to utility peak demand/load-shed signals. As part of this study the peak-load reduction was examined as well as overall energy use impacts of the various control strategies.

As noted above, if good IAQ is not achieved or maintained in California homes, substantial health care costs would be borne by California utility ratepayers. Exact values are difficult to determine, but IAQ studies generally show that health-related costs are greater than energy related costs, so health costs would likely exceed the $1 billion estimate above from the RESAVE study.

Having smart ventilation systems will provide additional qualitative benefits by allowing ratepayers greater control over their ventilation and IAQ systems than is currently possible. Smart ventilation will also be more accessible to the Internet of Things and to future high-tech developments and thus is a very reasonable technology approach to consider.

Concern about adverse IAQ impacts is a major barrier to industry and others, such as utilities, wishing to enhance energy efficiency. There has been, and likely will continue to be, a concern that reducing infiltration will cause health problems and reduce building durability. The results of this project will reduce those barriers by providing authoritative information about how to achieve acceptable IAQ with reduced infiltration.

Other high-performance-home stakeholders are interested in the results of this study because they face challenges similar to those faced by the Commission, i.e., how to demonstrate that good IAQ is provided while energy use is reduced through air tightening. Weatherization programs at federal, state, local, and utility levels often limit air-tightening measures based on perceived IAQ issues. LBNL is a partner in the US DOE Building America program, which has several teams, partners, and builders in California as well as builders committed to the US DOE Zero Net Energy program. They all face the challenge of maintaining IAQ while reducing infiltration to meet their energy-saving goals. RESNET rating of homes gives better ratings for tighter homes but also addresses protecting IAQ. Like California, RESNET refers to ASHRAE 62.2 to achieve this goal. LBNL is a member of the RESNET Standards Development Committee and therefore can ensure rapid uptake of the results of this study by RESNET.

CHAPTER 2:
Review of Residential Ventilation Controls and IAQ Metrics

State of the art in residential ventilation controls

More details on the review of the state of the art in home ventilation controls can be found in Guyot et al. (2017), (2018a) and (2018b).

The literature review focused on addressing the following topics:

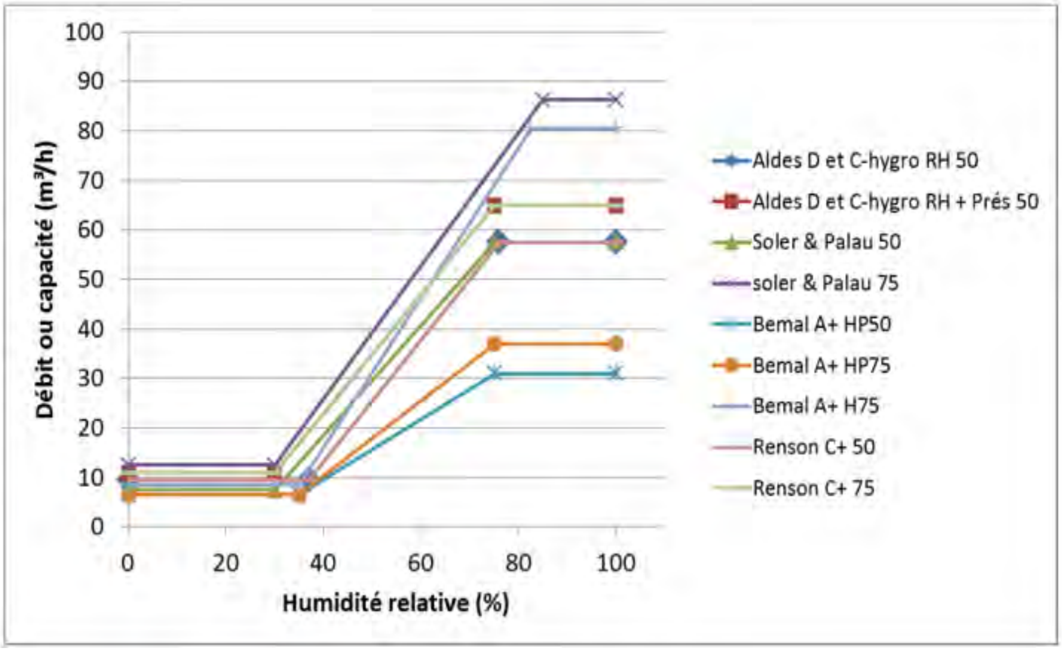
- Suitability of common environmental variables (pollutants of concern, humidity, odors, CO_2, occupancy) for use as input variables in smart ventilation applications
- Availability and reliability of relevant sensors
- Different control strategies used for a smart ventilation approach.

When assessing the results of previous "smart ventilation" studies it must be kept in mind that almost none of these systems attempt to deal with the issue of equivalent exposure – i.e., they do not ensure that the ventilation system does not save energy by under ventilating and exposing occupants to more contaminants. Much of this is tied to the predominance of demand-controlled ventilation approaches that only ventilate for occupant-related contaminants and ignore emissions from building products and other materials in the home, such as formaldehyde. A key aspect of the current study is that all contaminants are included. This is particularly important, because field studies of contaminants in homes (the CEC-sponsored HENGH study by LBNL being the most recent example) have shown that formaldehyde is present at significant concentrations in all homes and definitely needs to be reduced by ventilation – and it is emitted all the time.

Results of the review showed that current "smart" applications focus on demand-controlled ventilation (DCV). Most often demand has been quantified in terms of occupancy, or some other measurable quantity that is usually intended to indirectly estimate occupancy, such as Relative Humidity (RH) or CO_2 concentrations. These DCV systems ignore contaminants not associated with occupants and their behavior, such as formaldehyde emissions from building materials and furnishings. Several countries have developed compliance and certification programs that allow DCV systems to have energy credits for energy code and standard compliance. As a result, DCV systems are readily available on the market; more than 30 compliant DCV systems are available in countries such as Belgium, France, and the Netherlands. These systems commonly use relative humidity controls to vary the size of air inlets in conjunction with the operation of a mechanical exhaust system in the wet rooms (kitchens and bathrooms).

These humidity-controlled air inlets generally have a minimum airflow of around 10 m³/h, a maximum airflow between 50 m³/h and 75 m³/h depending on the type of room considered, and a modulation of airflow between these extremes which follows a linear function of relative humidity in the range 30%—35% to 70%—80%, as shown in Figure 1.

Figure 1: Relationship Between Airflow And Relative Humidity For Air Outlets Used In Nine Current Humidity DCV Systems In Belgium (Caillou, et al. 2014b)



Similar linear functions and step changes have been used in CO_2-based DCV systems. For both the RH and CO_2 based systems, they only function well if there are multiple sensors throughout the home – with the best energy performance if there are sensors in every dry room.

Quantification of demand in terms of individual pollutant loads has rarely been investigated from a research perspective or implemented in homes. The literature review performed for this study found no recorded implementations of smart ventilation where whole house ventilation systems include the air flows from infiltration or mechanical equipment used for source removal such as kitchen hoods and bathroom fans. Measurements of outdoor temperature and TVOCs have been used in a few cases.

Although it is a control strategy investigated in this study, the literature review showed that pollutant sensors are currently not robust or accurate enough to be relied upon for residential ventilation controls. With the rapid development of some sensor technologies this approach may become more viable in the near future.

The regulatory context in which smart ventilation strategies might be implemented most effectively was also assessed. The assessment showed that many countries already have a regulatory structure that is favorable for the development of smart ventilation strategies. These countries have regulations and standards in place that propose "equivalence methods" that offer a path to compliance including the use of smart ventilation strategies. These compliance paths have allowed for the development and availability of demand-control ventilation systems in the marketplace; more than 30 such systems have been approved and are available in countries including Belgium, France, and the Netherlands. It seems likely that the more complex smart ventilation strategies would follow a similar path to market acceptance.

A literature review for studies examining both energy savings and IAQ impacts of smart ventilation approaches found 38 studies of various smart ventilation systems with controls (on either CO_2, humidity, combined CO_2 and TVOC, occupancy, or outdoor temperature) and showed that ventilation energy savings of up to 60% can be obtained without compromising IAQ—and sometimes even improving it. In some cases, the smart ventilation strategies did not reduce energy use (showing an increase in energy use of up to 26%).

Occupant behavior was also examined in the review. The review showed that occupants are rarely aware of the quality of their indoor air, particularly with regard to health issues, and do not necessarily operate ventilation systems when recommended for optimal indoor air quality or energy efficiency – hence automated systems are required. Some studies showed a disparity in concentrations between different rooms of a home, and differences between single-zone and multi-zone modeling in residential buildings, indicating that multi-zone ventilation approaches may yield further energy savings.

The literature review also summarized ongoing developments in smart ventilation strategies and applications, including research into indoor air quality metrics, feedback on the lack of quality in ventilation installations, and source control (filtration and air cleaning) issues.

Valuing IAQ in the marketplace: Metrics and Appraisals

The literature review was combined with other related DOE efforts on development of an IAQ Score to investigate potential metrics for use in the analysis of IAQ and to control ventilation systems. This metrics analysis goes beyond what is required for the simulations in this study to a broader assessment of residential IAQ metrics that could be applied to things like an IAQ score or to other health and durability related residential building codes and standards. The complete metrics review is given in Appendix A.

Metrics

Without the new metrics, codes and standard bodies will not be able to act on many significant IAQ-related building industry changes. There are a couple of recent and developing changes related to IAQ that require new metrics. The first change is the development of smart ventilation strategies and controls that attempt to meet IAQ targets with varying ventilation rates. These smart ventilation strategies employ energy saving strategies that move ventilation around in time to avoid times of higher energy requirements to condition the air, accounting for operation of all mechanical air flow systems in a home—not just the whole dwelling ventilation system—pollutants in outdoor air (such as high ozone or particle levels), and deliberate pollutant removal (such as particle filtration systems). The second change is the emergence of pollutant sensing technologies that will allow specific contaminants to be targeted.

Checklists, Guidelines, and Protocols

Several checklists are currently available for addressing features of homes that may contribute to indoor air quality (IAQ). Many of these lists focus on reducing emissions of contaminants into homes, primarily from building materials, that use third-party assessments of emission rates.

More detailed guidelines and protocols are also available for new and existing homes. For example the American Lung Association provides the Health House Builders Guidelines that contains detailed protocols for building new homes, which include inspecting the site location, foundation, framing, ventilation system, and finishes and furnishings. The EPA's IndoorAirPLUS program, also for new construction, includes specifications for addressing moisture and radon control, pest control, combustion appliance inspections, as well as using low-emitting materials. Like the Health House Builders Guidelines and Indoor AirPLUS, the WELL certification program includes many aspects of healthy buildings beyond air quality. However, WELL primarily focuses on non-residential applications and includes aspects beyond IAQ such as lighting, comfort, and mental health. The LEED for Homes Indoor Air Quality Assessment includes two approaches for establishing better IAQ. The first approach does not have IAQ metrics, instead the building is flushed prior to occupancy. The second approach allows for one-time air sampling and measured levels of contaminants must be below tabulated levels. Listed contaminants include PM2.5, PM10, ozone, CO, TVOC and targeted VOCs.

For existing homes, EPA's Healthy Indoor Environment Protocols for Home Energy Upgrades provide guidance and references to resources on improving or maintaining indoor air quality and indoor environments during home energy upgrades, retrofits, or remodeling. Healthy Indoor Environment Protocols for Home Energy Upgrades provides assessments and actions for controlling harmful contaminants (e.g. Asbestos, combustion emissions, environmental tobacco smoke, lead, ozone, radon, polychlorinated biphenyls), moisture, pests, building materials, and ventilation.

Although these checklists, guidelines, and protocols provide valuable guidance for assessing IAQ, none provide methods for easily comparing new and existing homes, strategically targeting IAQ issues, or performing more detailed evaluations for mitigating risk while optimizing smart ventilation for energy savings.

Mechanical Control Systems

CO_2 as an IAQ metric: Demand Controlled Ventilation (DCV)

DCV systems have been used for many years in commercial HVAC systems for controlling comfort and air quality associated with occupancy. For these systems, measured CO_2 is used as an indicator of occupancy and, quantitatively, of human bioeffluents. When the measured CO_2 exceeds a set threshold, the system circulates air to control comfort and odor-related issues in the building. Although this method is effective for high-occupancy commercial buildings, the use of CO_2 levels as a metric representing occupancy (and bioeffluent emissions) is less applicable to residential applications for the following reasons:

1. Occupant densities are much lower and the available CO_2 signal is much harder to discern from background concentrations. This makes CO_2 much harder to use as an occupancy indicator and a control parameter for operating the ventilation system.
2. Due to the proportionally lower source strengths, there can also be considerable delays between initiation of occupancy and CO_2 levels reaching the control limit for operation of ventilation system.
3. Lower occupancy densities and a larger range of activities mean that occupants are no longer the primary source of pollutants (and thus CO_2 is a less meaningful indicator) that needs to be controlled. A primary example of this is the emissions from building products and materials.
4. The nature and degree of air mixing can be quite different in residential buildings.

Despite these drawbacks, CO_2 concentrations have been used as a ventilation evaluation metric in some European building energy codes, often in conjunction with relative humidity (RH). The metrics differ in detail from country to country but have the general form that limits the concentration and exposure time of CO_2 and/or RH. For example, French regulations use a limit of hourly average CO_2 concentrations of 2000 ppm. Each hour above this limit is weighted by the CO_2 concentration for that hour. These products are summed for the year and cannot exceed 400,000 ppm-h. For RH the limit is set at an hourly average of 75%, and the number of allowable hours above this limit is set at 600 hours in kitchens, 1000 hours in bathrooms and 100 hours in other rooms Both these requirements must be met. Note that the RH regulation is a multi-zone metric because it sets different levels for different rooms. Further details for European DCV metrics can be found in the literature review performed by Guyot et al. (2017).

Equivalent Ventilation

Equivalent ventilation is a key metric for evaluating different ventilation approaches. The central idea behind this technique is that there is a baseline ventilation strategy that can be used as a basis for comparison and that any other ventilation approach should result in the same, or lower, exposure to pollutants. Hence, it would be "equivalent". The only current implementation of this approach is in ASHRAE Standard 62.2-2016. The methods therein were developed by LBNL (Walker et al. (2011)) based on some of the assumptions integral to the ASHRAE Standard, i.e., that the pollutants can be represented by a generic contaminant emitted at a constant rate. The continuous ventilation rate from the ASHRAE standard can then be used as a basis of comparison with time-varying ventilation rates. An equivalent ventilation system is one that produces the same (or lower) exposure to this generic contaminant averaged over a year.

This basic approach only applies (as most residential ventilation requirements) to chronic exposures. However, the calculation procedure has been adapted to limit peak contaminant levels and avoid acute exposures. This is particularly useful for ventilation control strategies that are occupancy-based and the equivalency principle can be adapted such that it is evaluated only during times of occupancy. This equivalency approach can also be used with time-varying emission rates, e.g., a reduced emission rate can be stipulated during unoccupied times, and studies are underway to investigate this approach. Although this equivalency metric is for ventilation rather than IAQ directly, the principles and adaptations discussed here will also be useful for direct IAQ metrics.

This equivalency metric has been used by LBNL in the development of controllers that allows for time-varying ventilation rates to:

- shift ventilation to times of lower indoor-outdoor temperature difference (or humidity difference)
- account for operation of kitchen, bath and clothes dryer and economizer fans
- pre-calculate required fan sizes and temperature cutoffs for outdoor temperature-controlled ventilation
- ventilate less during unoccupied times
- pre-ventilate for pre-cooling energy conservation and peak demand reduction
- include the use of passive ventilation systems
- avoid exposure to acute pollutant levels

IEA-EBC Annex 68

The purpose of Annex 68 is to provide a scientific basis for the design and operational strategies of low-energy residential buildings, while maintaining high IAQ standards by controlling sources, sinks and flows of heat, air, moisture, and pollutants when buildings are occupied. Additionally, Annex 68 aims to collect and provide data about properties for transport, retention and emission of chemical substances in new and recycled building materials under the influence of heat and moisture transfer.

Based on the above results, sixteen target pollutants were selected as potential short-term and long-term exposure risks in low-energy residential buildings: acetaldehyde, acrolein, ɑ-pinene, benzene, carbon dioxide, formaldehyde, naphthalene, nitrogen dioxide, PM10, PM2.5, radon, styrene, toluene, trichloroethylene, TVOC, and mold.

Two methods are recommended for incorporation into an IAQ metric to assess the health risk of these sixteen pollutants. The first method compares measured exposure concentrations to existing exposure standards or Exposure Limit Values (ELVs). ELVs correspond to concentration thresholds above which exposure presents a potential health concern. ELVs are often based on Toxicity Reference Values (TRVs) and Guideline Values for Indoor Air (IAGV). TRVs are based on animal experiments and applying a safety factor of at least 100, while IAGVs are determined from epidemiological studies examining correlation between health symptoms observed in a population of individuals exposed to the compound indoors. Although ELVs can easily be communicated to building contractors, the combined effect of multiple pollutants is currently unknown and averaging or multiplying risks can lead to further uncertainty.

The second recommended method is evaluating the direct health impacts of the pollution through the estimation of Disability-Adjusted Life Years (DALYs) lost. Details for this method are described in Logue et al. (2011). The major advantage of using DALYs over ELVs is that individual pollutants can be summed to estimate a combined effect of exposure. However, this approach is easier to communicate to policy and decision makers than building contractors or building occupants.

Development of new metrics

Due to the limitations described in the previous sections, new metrics are required for comparing IAQ in residential buildings across the range of existing housing stock. These new metrics must be applicable to the entire housing stock, which includes new and old homes of varying energy efficiency, and enable the use and valuation of new technologies and ventilation approaches. The metrics must also be expanded beyond a simple airflow requirement or DCV systems.

Key Aspects of IAQ

Health

The IAQ Health Metric should focus on identifying home features and characteristics that cause contamination or may help to manage IAQ, and on evaluating the chronic hazards associated with contaminants. Standard metrics such as ELVs and DALYs could be used as quantitative tools for quantifying the potential harm of pollutant intake.

For example, previous studies (Logue et al. 2011) investigated health impacts to prioritize pollutants. Logue et al. (2011) used DALYs to identify the most important pollutants in homes. PM2.5, NO_2, Formaldehyde, acrolein, ozone, radon, and secondhand smoke are the highest-risk pollutants. Based on these results, the metrics could suggest the use of low-formaldehyde building products or a good range hood to remove particles from cooking. Pollutants associated with the behavior of occupants, such as smoking, will not be considered by the metric. However, tobacco contaminated materials will be considered, as they are now a part of the asset.

Acute health issues (such as CO poisoning) are beyond the scope of this metric, as they are rare, difficult to predict, and sometimes the result of occupant behavior as opposed to inherent characteristics of the building. However, chronic conditions caused by acute exposure such as allergies or asthma will be included. Also, there may be some ways to include acute issues in metrics. For example, a home ventilation system with a high flow "boost" mode might be able to respond to extreme heat, moisture, and bioeffluents in a tight energy efficient home during times of high occupancy (e.g., birthday parties). The inclusion of some aspect of this flexibility to deal with extreme events would be very useful in an IAQ metric.

Moisture

Health hazards associated with moisture (specifically excessive moisture as a substrate with a food source for microorganisms and mold potential) are well established. However, it is difficult to predict how much (quantitatively) home features increase or decrease the risk of mold growth. Additionally, the risk of moisture and mold through certain asset deficiencies or conditions is not clearly quantified. For example, having high relative humidity may lead to moisture and mold issues, but the threshold may vary greatly between homes.

Often a home will have exhaust fans to remove cooking and bathing moisture, but human respiration (and perspiration) moisture is removed by general household ventilation or the operation of dehumidification systems. For comfort and perceived IAQ, the metric will include humidification during the winter in cold dry climates. Although the IAQ metrics will not address all aspects of comfort (such as radiant thermal issues or drafts), comfort associated with IAQ will be included.

Odor

Odor, as well as moisture, is commonly associated with perceived IAQ. Presently, data and quantitative methods for evaluating odor in residential buildings are not readily available because individual human odor response is highly variable. Some guidance for addressing odor are available for commercial buildings, specifically related to ventilation and airflow requirements based on human and environmental bioeffluents, and could be extrapolated to develop an IAQ Odor Metric for residential buildings.

Historically, odor was often the basis for setting ventilation air-flow requirements – based on human and environmental bioeffluents. Additionally, because odor is classically dealt with by dilution using uncontaminated (or less contaminated) air or source reduction, there may be opportunities to use technologies such as carbon filtration (that can also be used for VOC control) to control odor rather then only using dilution.

A key audience for IAQ metrics for existing homes will be home appraisers. Once the value of good IAQ is included in a home appraisal it will be easier for the IAQ industry to get homeowners to act and move away from only addressing acute issues, thereby drawing attention to chronic health and other IAQ issues. Appraisers report specific interest in IAQ related issues such as: tobacco odors, pet odors, and signs of moisture damage, etc. Therefore it will be important to include these in IAQ metrics for evaluating existing homes. Appraisers also report that it would be easier to discuss and value IAQ in homes if there were a rating system.

Multizone Approaches

As new homes become tighter and high-efficiency heating and cooling systems move away from central forced air, homes are becoming more zonal in terms of their airflow and thermal loads. It is becoming increasingly popular to use zoned systems to condition energy efficient homes – in particular mini-split heat pumps. New homes are also getting tighter with a resulting reduction in natural infiltration airflows. This results in less air mixing inside homes and presents an opportunity to remove pollutants from the rooms where they are generated that can use less airflow compared to whole-house dilution approaches. One example would be bedroom ventilation at night – where an isolated bedroom with a closed door can be ventilated to control for odors, moisture and bioeffluents, enabling lower rates of ventilation in the rest of the home.

Some ventilation standards in Europe and Canada have an implied zonal approach in which they require specific airflows to individual rooms (often accomplished with a ducted balanced/HRV system). A metric that allowed the assessment of this approach compared to the single zone approach could be valuable if US (and California) ventilation standards were to use a zonal approach. A zonal metric would also enable technology development where pollutants known to be common to specific home locations (particles in kitchens, moisture in bathrooms, etc.) could be managed in those locations, or providing pollutant control in occupied rooms. An example of this might be a particle filtration system in a kitchen or a dehumidifier in a bathroom or bedroom.

IAQ Score – An Example Metric

One metric that was investigated is the idea of a home IAQ Score that is also being developed by LBNL for the US DOE Building America Program. Home energy scores have provided an important tool in the market place for assessing a buildings energy performance. Energy scores have allowed the market to place a value on energy efficiency and have allowed home buyers to identify homes that will have lower utility bills and less of an environmental impact. A similar tool for IAQ would allow homeowners to identify homes that have a lower health/irritant impact. An IAQ score would also provide a driver for homebuilders to design healthier homes since an IAQ score would likely have a market value and application in real estate transactions.

The overarching goal of the IAQ score is to create an asset-rating tool for a home with respect to its indoor air quality. As an *asset* rating it will necessarily assume certain baseline conditions, such as occupant behavior, and thus does not predict the actual IAQ of the actual home. The development of the IAQ score for homes is being supported by the US DOE Building America program.

To create a numerical score, the individual IAQ hazards and mitigation strategies for a home are identified. The various hazards add to the score and the mitigation strategies subtract from the score. Different hazards have different IAQ impacts and are given numerical values reflecting these differences. These can be summed to give a total hazard score for the home if there are no mitigation strategies in place.

Mitigation strategies impact the score in several ways. Firstly they are evaluated for their potential effectiveness for on each hazard – i.e., what is the risk reduction if the mitigation strategy is implemented as intended. Few mitigation strategies will affect all hazards in a home. For example, a kitchen range hood has a strong impact on cooking-related contaminants, but much less impact on formaldehyde from building contents. They are then assessed for their effectiveness. For example, a exhaust fan whose air flow is verified will be more effective than one that is not, or an automated range hood that does not require the occupant to operate it would be more effective than a manually operated hood. There will be negative and positive adjustments to the score for other aspects of mitigation strategies:

- Usability: How easy and intuitive is it to use or implement the measure?
- Durability: Is the measure likely to retain its utility and performance over time?
- Robustness: How commonly does the system work when implemented as intended?
- Maintenance: How much effort is required to maintain the measure?

This way, no measurements or diagnostics are require to obtain a score for a home, but homes that do have confirmed performance will get a better score.

Appraisals

For an IAQ assessment – whether it is an actual score or a more general approach to evaluating the health and durability aspects of homes a key point of view to be considered is that of the real estate industry – specifically how homes are appraised. To gain perspective on how the industry views IAQ and how they might receive an IAQ score appraisers from California, Colorado, Florida, and Kentucky were interviewed and this discussion summarizes the interview results.

While efforts to quantify incremental property values conferred by high-performance features go back at least to the early 1980s, the vast majority of activity has taken place within the past five years. There have been scores of studies and an array of disjointed policy efforts to engage and compel the appraisal industry to consider building performance in their valuations. Federal agencies and others in the "high-performance homes" community have had little to show for all these years of work, largely due to lack of understanding of the appraisal practice as well as market and business conventions and constraints.

Many players have engaged in efforts to promote improved property valuation practices regarding green and high-performance features. These include the Appraisal Foundation, The Appraisal Institute, Colorado Energy Office, Earth Advantage, EcoBroker, Elevate Energy, Fannie Mae, Federal Housing Administration, Home Innovation Research Labs, The Institute for Market Transformation, Northwest Energy Efficiency Alliance, National Association of Homebuilders, National Association of State Energy Officials, National Association of Appraisers, RESNET, USEPA, USDOE and some of its National Laboratories, the U.S. Green Buildings Council, and the Vermont Green Homes Alliance. Many activities have resulted, ranging from trainings, to data-gathering instruments, and the emergence of a literature attempting (largely through Hedonic Pricing techniques) to statistically isolate the effects of green/high-performance characteristics on home values. In some cases, the results of studies have been analytically flawed, overgeneralized, and oversold.

Leading efforts to date have focused largely on energy, and to a lesser degree water and other "green" factors such as building materials. Little to no effort has been spent on indoor air quality, primarily due to lack of interest on the part of homebuyers (as perceived by appraisers), and, to a lesser degree, due to difficulty in quantification.

Appraisers (both residential and non-residential) utilize three well-established methods of valuation, often used in tandem or in combination.

<u>The Cashflow method</u> entails defining value as a multiple of income and expenses. While typically used only for non-residential "income" properties, it has been applied to assessing the incremental value of energy features in homes. This does not appear to be relevant for IAQ issues.

<u>The Comparable Sales method</u> requires finding "like" homes that have been recently sold and analyzing those outcomes, with adjustments up or down for differences in the subject property. Lacking IAQ data or scores that can be correlated with large numbers of home sales, makes this approach viable only when there are large numbers of homes receiving IAQ scores and, if those data are publicly disclosed, sales data can be correlated with scores.

<u>The Cost Basis method</u> sets value equal to cost, with adjustments. This method is perhaps the most promising angle for IAQ if the costs of remediation can be identified and incorporated into the sales transaction/negotiation process. One appraiser

suggested that training home inspectors (who are already in the building) to estimate these costs may be one way to achieve this.

Aside from the actual valuation methods, appraisals also serve an important role in assembling qualitative and quantitative documentation. This is where IAQ information could most readily make its mark.

Over the course of a 5-year Memorandum of Understanding, the US DOE has collaborated with The Appraisal Foundation (TAF) to produce several reports. The first defines "competency" as it pertains to appraisers' ability to incorporate green and high-performance building considerations into their valuation assignments (Black *et al.,* 2015). This document references IAQ a number of times and points to various resources. A subsequent document in the series (Curry *et al.,* 2016) focuses on specific applications in residential settings. This document goes into slightly more detail on IAQ--including examples of issues to be on the lookout for and types of tests and reports to look for—and refers to the Information Atlas for appraisers (created by LBNL) for more information.[5]

Recent work for DOE (Mills 2015) identified a high-level set of barriers to the incorporation of IAQ and other home performance considerations into residential valuations, along with recommendations. The following discussion includes observations on how these considerations might apply in the case of the proposed IAQ score.

Highly limited awareness and interest; sometimes aversion

Issue: The IAQ issue is hardly on the radar of appraisers, and they do not generally perceive homebuyers as caring about it. One very seasoned appraiser stated that "I have actually never had a Realtor, a builder, a developer, a buyer, or a seller express any concern to me about valuing the indoor air quality of a property."

Recommendations: While "IAQ" may not be a familiar concept to appraisers, many, in practice, actually do observe relevant factors in a home (tobacco odors, pet odors, and signs of moisture damage, etc.). One interviewee mentioned a recently listed home in a very hot market that was well priced but had serious cat odors – 30 prospective buyers passed on the offering because of this. Some appraisers of course operate in areas where radon testing and mitigation are required. In these cases, they are more keenly aware of the need for assessment.

All interviewees said that a scoring system would help back them up in terms of logging these otherwise nebulous and subjective issues. To be usable by appraisers, such information must have a high level of geographic specificity. Realtors are important 'trade allies' in this regard, as they are a key source of information to appraisers.

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[5] https://sites.google.com/site/appraisinghpbuildings/key-topics/indoor-environmental-quality

Competency

Issue: Few appraisers are literate on matters of IAQ research, risk weightings, or mitigation technologies and have correspondingly few, if any, techniques for including IAQ in the valuation process.

Recommendations: It will be important to create appraiser-specific trainings to introduce an IAQ score or score and establish related literacy in IAQ concepts and third-party reports. Appraisers will need to understand this information and be comfortable adopting the findings.

Time/budget pressures and process commoditization

Issue: Financial regulations implemented in the wake of the 2008 housing market meltdown resulted in the entry of new "middle-men" into the appraisal process, along with efforts to automate and commoditize the appraisal process. Appraisers' fees have been cut in about half in the process (appraisers take home maybe $100-$150 per typical appraisal and spend less than an hour at the property), and appraisers' discretion has also been reduced as the process has become more commoditized.

Recommendations: Transaction costs associated with IAQ score documents must be reduced to an absolute minimum. Entities creating appraisal templates and protocols should be engaged and compelled to recognize the relevance of this information. Financial incentives to help appraisers justify the added time to consider IAQ would no doubt increase their use of the information.

Risk aversion

Issue: Appraisers are cautious about extending the scope of their practices, partly due to aforementioned time/budget pressures, but also due to professional liability considerations and reputational risks such as those that "bit" appraisers when they were taken to task for being part of the housing bubble. As a result, attributing additional value to a property is something they are more cautious about than previously.

Recommendations: The credibility of the score, those applying it, and associated documentation will be key to appraisers' comfort level.

Getting scores into the MLS (there is already an extensive "Green MLS" movement) would be a good way to ensure that appraisers can readily find the scores through an information channel with which they are familiar.

Appraisers like the idea of considering particularly sensitive populations (allergies, asthma, children). However, they cautioned that having "modified scores or indices" for different groups could easily make the report difficult to absorb. A more elegant solution would be if certain thresholds (e.g. scores 80 and above) can be flagged as thresholds of acceptability for certain sensitive populations.

CHAPTER 3:
Single Zone Smart Ventilation Controls

Appendix B is a detailed report discussing the single zone smart ventilation work. The following is a summary that highlights the most important details.

Introduction

The single zone task had three objectives:

1. Provide guidance to the building community, and the State of California, on the most effective means of sizing and controlling ventilation fans in high-performing California homes.
2. Estimate the energy savings available with different Smart Ventilation controls.
3. Assess the effects of Smart Ventilation controls on occupant exposure to pollutants of indoor origin.

Method

The IAQ analysis uses the concept of *relative exposure*. This is an approach for assessing the IAQ performance of variable ventilation strategies (Max H. Sherman, Mortensen, & Walker, 2011; Max H. Sherman, Walker, & Logue, 2012). Relative exposure assesses the relative concentration of a generic pollutant emitted at a constant rate indoors, with no outdoor sources and no non-ventilation removal processes (e.g., deposition, filtration, etc.). The metric compares the concentration of that pollutant under time-varying versus continuous ventilation schemes. Over short time periods (i.e., about the time needed to replace all the air in the building), a relative exposure of 1 means the two ventilation rates are equal. Averaged over longer periods (e.g., annually), a value of 1 means the two ventilation strategies provide equivalent pollutant exposure—even though the instantaneous ventilation rates may vary dramatically. Values less than one reflect over-ventilation relative to the reference airflow rate (lower pollutant exposure), while values above one reflect under-ventilation (higher pollutant exposure).

Relative exposure is the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard. The standard requires that exposure be estimated at each time step of the assessed period, which in this study was once every 5-minutes. Annually, the arithmetic mean 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 value of one implies that the annual mean occupied exposure to the generic contaminant is the same as would have occurred if the house were ventilated continuously at the whole house target airflow (Qtotal) calculated in 62.2-2016. These cases are said to be "equivalent".

Two different relative exposure values were used in this study, and they differ only in terms of which house airflow estimate they use. First, is the *controller relative exposure*, calculated using the airflow estimate available to the house's ventilation control system. This is the best information that a real controller could use to estimate exposure and control a ventilation fan. Second is the *real relative exposure*, calculated using the total airflow for the home that includes natural infiltration through envelop leaks.

These relative dose and exposure calculations are used to determine when the fan being controlled is turned on or off in such a way as to achieve equivalent exposure over a year of operation. The fan on/off decision is made once every 5-minutes, which aligns with the overall simulation time step of 5-minutes. The SVC strategies analyzed in this work also turn the ventilation fan on or off in response to one or more of three different signals: outdoor temperature, occupancy, and auxiliary fan operation. In response to these signals, a ventilation fan is modulated to provide more ventilation when advantageous and less when not. The relative dose and exposure are tracked at all times – whether the ventilation fan is running or not.

To determine the energy savings from different smart ventilation strategies, the first step was to determine the energy used to condition the ventilation air that was added by installing a continuous fan sized to the ASHRAE 62.2-2016. This was done by simulating homes with no mechanical ventilation, and then simulating the same house with constant mechanical ventilation – the difference being the energy used to ventilate the home. This allows comparison of the energy used in different smart ventilation scenarios to determine their energy savings. These energy estimates include fan energy, as well as space conditioning energy required to treat the incoming air due to mechanical ventilation and natural infiltration.

In order to allow for time-varying ventilation fan capacities must exceed the minimum code requirements because of the need to ventilate at higher rates at some times to make up for lower ventilation at other times. This whole house ventilation fan is referred to as the IAQ fan in this report.

Smart Control Descriptions

The smart control approaches are summarized in Table 1.

Table 1: Summary Of Single-zone Smart Control Strategies

Control Name	***Description***
Lockout	Turns IAQ fan off during the hottest hours of the day in the cooling season and during the coldest hours of the day in the heating season. Lockout hours (4-, 6- and 8-hours) are pre-calculated using weather files. Fans are oversized to run continuously outside of lockout hours to ensure daily exposure ≤0.97.
Running Median (MedRe)	Compares current outside temperature against the running median outside temperature, and selects either a high exposure target (reduced airflow) or a low exposure target (increased airflow). During heating season, ventilation is reduced when below the median and increased when above the median. Opposite in cooling season.
Seasonal (Season)	Reduces ventilation rates in the heating season and increases them in the cooling season. Exposure targets for each season are pre-calculated using a weighted average to ensure that annual exposure will be ≤0.97.
Cutoff	Uses the exposure targets from the Seasonal controller, and adds cut-off temperatures for each season selected by parametric optimization, with a low and high exposure target. Reduces ventilation during the heating season, with a focus on the coldest hours, while still ventilating at high rates during mild weather. Vice versa in cooling season.
Variable Airflow (VarQ)	Ventilation fan airflow is continuously varied proportional to outdoor temperature. Airflow is scaled using the ratio of the current indoor-outdoor temperature difference, compared with the seasonal maximum temperature difference. The seasonal maximum values are selected using parametric optimization to ensure maximum energy savings, with annual exposure ≤0.97.
Variable Exposure (VarRe)	Target exposure is continuously varied proportional to outside temperature. Exposure varies between the minimum value (highest airflow) and a maximum value (lowest airflow) for each season. High exposure target is selected using parametric optimization to ensure maximum energy savings, with annual exposure ≤0.97.
Occupancy (Occ)	IAQ fan is turned off when the home is unoccupied, and ventilation rate is increased when occupants return home to account for background contaminant emissions. Daily-integrated exposure is maintained ≤0.97. Three versions are assessed:

Control Name	***Description***
	• Fan off when unoccupied • Fan at 35% flow when unoccupied • Pre-ventilate the home 1-hour before occupancy
Auxiliary Fans (AuxFans)	This option senses the operation of other exhaust devices in the home, and it includes these flows in the controller airflow estimate, which reduces IAQ fan runtime and overall ventilation rates. This controller was added onto each of the other control types to assess combined control performance.

Simulation Approach & Protocols

The simulated homes match the specifications of the two CEC single-family prototype units (Nittler & Wilcox, 2006), whose properties are made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 energy code. Detailed models were created of two prototype homes: a 1-story 2,100 ft^2 prototype home and a 2-story 2,700 ft^2 prototype home, with forced air space conditioning systems. The HVAC equipment was sized using the auto-size feature in EnergyPlus. Thermostat schedules were set to meet those specified in the 2016 ACM. The ventilation systems are compliant with ASHRAE 62.2-2016 that includes infiltration credits and sub-additivity adjustment for unbalanced exhausts[6]. Exhaust systems were used as the reference as they are by far the most popular method of complying with ventilation requirements in the state[7]. The total ventilation rate requirement for the single story home is 93 cfm and 119 cfm for the two story home.

Several deliberate deviations were made from the Title 24 prescriptive path prototypes; whole house economizer fans that are present in the prototype homes were not included and HVAC equipment efficiencies were improved. Duct leakage was not

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[6] This fan sizing is not the same as that adopted in the 2019 Title 24 building energy code cycle. The newly adopted Title 24 fan sizing method uses the same calculation procedures as the ASHRAE 62.2-2016, but for all homes with envelope leakage 2 ACH_{50} and greater, a default of 2 ACH_{50} is used in fan sizing calculations. For homes that are below 2 ACH_{50}, the newly adopted fan sizing method requires use of the small leakage value in calculating the fan airflow. So, for homes ≤2 ACH_{50}, the methods are identical, and in leakier homes, the adopted sizing procedure leads to larger fan airflows than are required by ASHRAE 62.2-2016.

[7] 64 of the 70 homes in the recent HENGH field study of new California homes (Chan et al. 2018) had exhaust systems.

modeled because advanced homes were assumed to have all ducts within conditioned space, consistent with Title-24 2016 prescriptive path option C. Similarly, automatic window controls for optimizing ventilation cooling were not included. Equipment efficiency was increased beyond prescriptive minimums to SEER 16 A/C (COP of 3.95) and 92 AFUE gas furnaces in order to align with standard new construction practice encountered in HENGH field study and based on TAC feedback. Three envelope leakage levels were used: 1, 3 and 5 ACH_{50} to represent a range of new construction airtightness. For the tight 1 ACH_{50} home the ventilation system that was controlled using smart ventilation strategies was a balanced system, for the other homes a simple exhaust fan was used.

Climate zones were selected that represented the range of climatic conditions in California: Arcata (CZ1) on the north coast, Blue Canyon (CZ16) – the coldest climate zone, temperate Oakland (CZ3), and Riverside (CZ10) in the central valley that represents a location with greatest growth in new construction. Because residential compliance weather files were not available for Energy Plus, we developed customized EnergyPlus weather files using the weather data contained in the CBECC-Res weather files used to demonstrate residential compliance with the building energy code.

The energy and IAQ modeling was performed using a Contam/EnergyPlus co-simulation platform that was developed for this specific project to allow for real-time ventilation controls and based on an approach developed and validated by Dols et al. (Dols, Emmerich, & Polidoro, 2016).

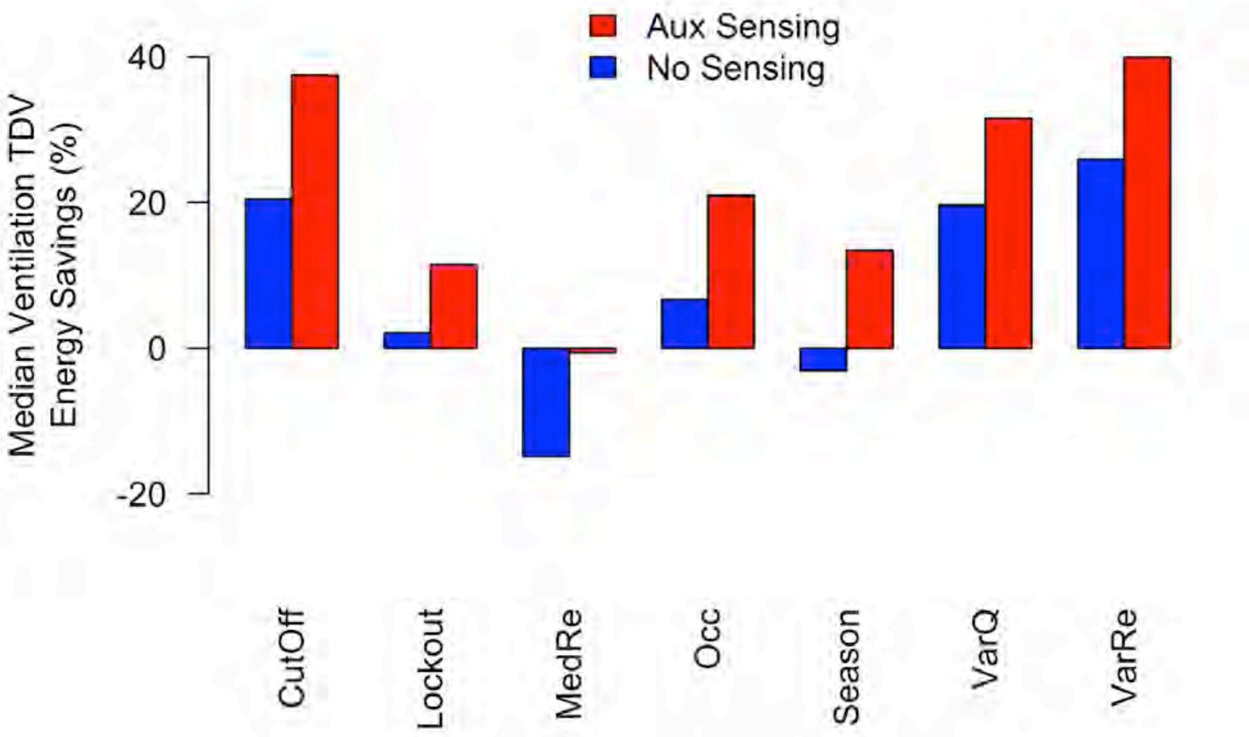
All energy assessments included both site energy and time dependent valuation (TDV) energy, which is a metric used in demonstrating Title 24 compliance that accounts for time-varying impacts of energy consumption. TDV energy weights peak demand periods heavily for electricity consumption, so it partly reflects peak demand reductions. Additional analysis examined a peak period of 2-6 pm in summer. Detailed results across climate zones and house types are presented where possible as well as results weighted for each climate zone by new construction starts to get a single number for statewide potential savings.

Results for single zone smart ventilation

Controller performance varied substantially by climate zone, airtightness and house prototype, therefore this report does not provide simple state-wide estimates of energy savings, nor does it identify which controllers are best optimized for state-wide use. Instead, guidance is provided on which control approaches are best suited to different climates.

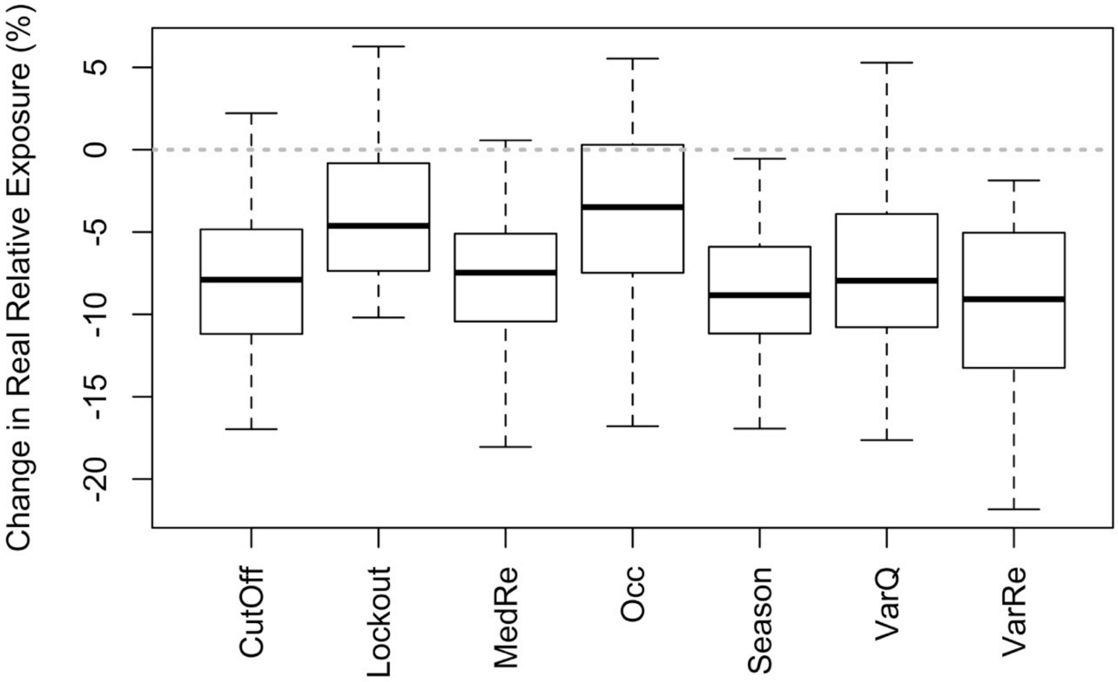
The most successful smart controls shifted ventilation rates seasonally, rather than over the course of the day or month and used parameters pre-calculated using an optimization routine, and they reduced weighted average site ventilation energy use by 41 - 51% (413 - 505 kWh/year; 12 - 15% of whole house HVAC energy), while TDV weighted average ventilation energy reductions were higher, at 36 - 61% (1,615 - 2,743 kWh/year; 6 - 10% of whole house TDV HVAC energy). Figure 2 illustrates the median TDV energy savings of all the simulations for each smart ventilation controller. Auxiliary fan (i.e., kitchen, bathroom and dryer exhausts) sensing increased site energy savings in all cases, from roughly 5 to 15%. This procedure increased the average non-normalized site ventilation savings for the best control types to a range between 50 - 58% (TDV ventilation savings between 48 - 67%). More than 90% of site energy savings were for heating end-uses, while TDV energy savings were split more evenly between heating and cooling. Peak demand during the 2-6 pm period on the hottest days of the year was reduced through use of the smart controls, with peak load reductions of 0- 300 watts. It is possible that specific peak controls could achieve even greater reductions in demand. On average, the smart controls reduced occupant pollutant exposure by 0-10% (improved IAQ), but they increased peak exposure to the occupants, with some controls having much higher peaks than others.

Figure 2: Median Ventilation TDV Energy Savings For Compliant SVC With And Without Auxiliary Fan Sensing.



Smart ventilation and baseline constant fan cases did not provide the same IAQ because control strategies were chosen to be slightly conservative – i.e., to provide a reduction in exposure in almost all cases. **Error! Reference source not found.** illustrates the reductions in exposure for each controller showing that typical reductions were about 5-10%.

Figure 3: Reduction In Real Relative Exposure.



To provide an apples-to-apples assessment of energy savings, the energy use was normalized in each case by the corresponding annual relative exposure. When normalized, weighted average energy savings increased. The best controls achieved weighted average site ventilation energy savings of 56 - 64% (591 - 678 kWh/year; 16 - 19% whole house HVAC savings), and TDV ventilation savings from 51 - 68% (2,180 - 3,004 kWh/year; 9 - 12% whole house HVAC TDV savings).

The best overall controllers used seasonal shifting of ventilation. Use of the smart ventilation controls was much more effective than increasing airtightness while using continuous fans sized to ASHRAE 62.2-2016, because the ventilation standard increases the required IAQ fan airflow, as infiltration is reduced. This limits the benefits of air sealing if infiltration credits are used to determine mechanical ventilation airflow requirements.

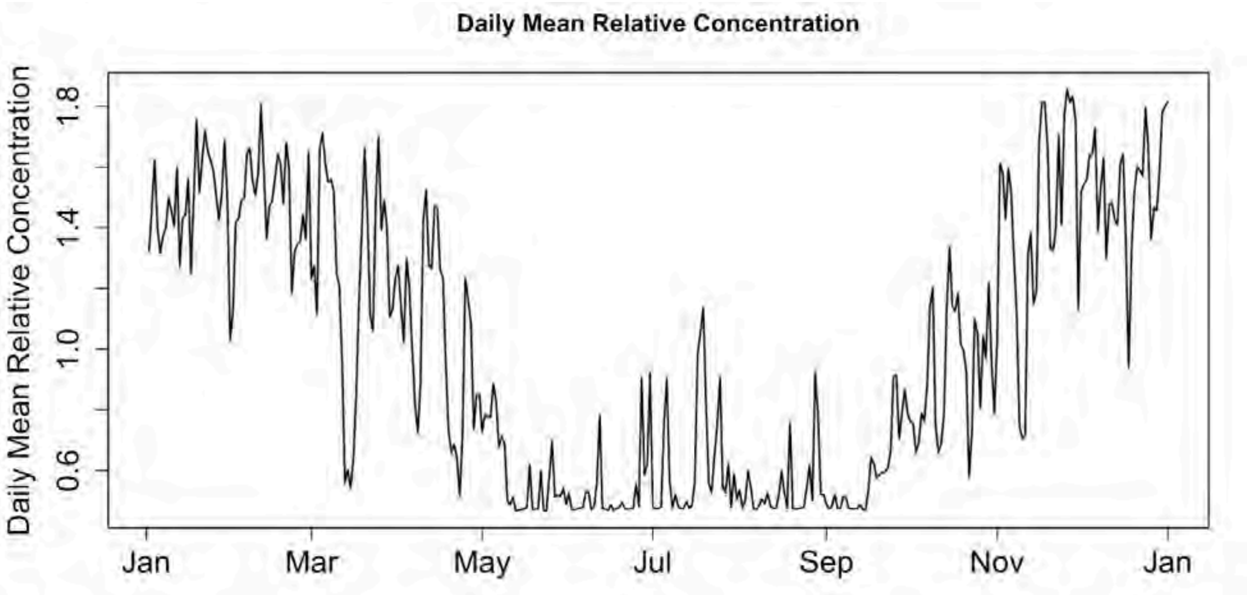
Occupancy-based controls saved energy by reducing the whole house ventilation rate, but these controls were generally ineffective, with very low energy savings. Performance was improved somewhat through use of a 1-hour pre-occupancy flush out period, though savings were still marginal compared to temperature-based controls.

Figure 4 shows the controller relative exposure for one example case. In the mild summer months the controller keeps the relative exposure low—just about 0.5—but allows it to be higher (exceeding 1.5) in cold winter months. This corresponds to more ventilation in the summer and less in the winter.

Use of the smart ventilation controls was much more effective than increasing airtightness while using continuous fans sized to ASHRAE 62.2-2016, because the ventilation standard increases the required IAQ fan airflow, as infiltration is reduced. This limits the benefits of air sealing if infiltration credits are used to determine mechanical ventilation airflow requirements.

Occupancy-based controls saved energy by reducing the whole house ventilation rate, but these controls were generally ineffective, with very low energy savings. Performance was improved somewhat through use of a 1-hour pre-occupancy flush out period, though savings were still marginal compared to temperature-based controls.

Figure 4: Controller Relative Exposure For The VarQ Controller



Current products available for $150 to $300 on the consumer market have the core hardware capabilities to act as smart ventilation controls (fans or wall controllers with integrated temperature and humidity sensors), but very few of the currently available products actually ensure compliance with the ASHRAE ventilation standard, and none use the time-varying ventilation approach from Appendix C of ASHRAE 62.2 to facilitate time-shifting of ventilation flows over more than a 24-hour period. More work is required in order to allow builders and designers to take credit for smart ventilation control strategies in demonstrating compliance with California' Title 24 Building Energy Code. Also, field demonstrations of the energy and IAQ performance of smart ventilation controls are needed in new California homes, before these technologies can be adopted at scale. An adapted version of the varQ control algorithm is being field tested in 12 - 16 dwellings as part of the U.S. DOE Building America program in the years 2020-2022.

CHAPTER 4:
Multi-zone and contaminant controlled smart ventilation

Appendix C is a detailed report discussing the multi-zone and contaminant controlled smart ventilation work. The following is a summary that highlights the most important details.

Introduction

Some homes are not well-mixed, instead exhibiting zonal ventilation and IAQ behavior. These homes either do not use a central Air Handling Unit (AHU) to distribute heating and cooling, or they use smaller equipment that operates less frequently than was previously common in residences.

Some high-performance homes use heat recovery balanced ventilation systems that exhaust air from “wet” rooms (kitchen, bathrooms and laundry) and supply ventilation air to all other locations. This can create a zonal ventilation system.

If zones are reasonably well isolated from one another, then a ventilation system could be controlled to only ventilate occupied zones thus potentially saving on ventilation energy requirements.

Many countries formulate their ventilation requirements in residences around room-by-room airflow requirements. For example, Canada’s CAN/CSA-F326-M91 (2010) standard (CAN/CSA, 2010) requires supply of 10 L/s in master bedrooms and 5 L/s to all other room types, including other bedrooms, living room, dining room, family room, recreation room, kitchen, bathrooms and laundry. It also allows exhaust flows from kitchens, bathrooms and laundry rooms at a continuous rate of 30 L/s in kitchens and in bathrooms (10 L/s each).

This study based the total ventilation rate requirement on ASHRAE 62.2-2016, with a total of 93 cfm for the single story house, 119 cfm for the two story house and 48 cfm for the apartment. The target mechanical ventilation fan flow in each zone was weighted by the fraction of dwelling floor area in that zone. The smart ventilation systems require some oversizing. For most controls the one and two story house used a 180 cfm fan except the varQmz control that used a smaller 138 cfm fan that allowed for better control optimization. For the apartment most controls used a 123 cfm fan except for the optimized varQ control that used an 85 cfm fan and varQmz that used a 57 cfm fan. For all dwelling types, the supplyTracker and occupantTracker did not oversize the fan, they moved the same total flow between rooms, and the occupantVenter that ventilated only occupied zones increased the base fan flow by 50%.

Method

he energy and IAQ implications of zonal ventilation systems and smart controls were explored using a co-simulation approach between EnergyPlus and CONTAM, which extends the previous efforts in single-zone homes.

Simulation Approach and Protocols

The 1- and 2-story single-family CEC prototype dwellings were modeled in the zonal simulations, along with an additional single apartment unit from the CEC multi-family prototype building. The assessment looked at relatively tight envelopes of 0.6, 2 and 3 ACH_{50}) in four CEC climate regions (1, 3, 10 and 16), as well as different zonal ventilation equipment, smart control types, occupancy patterns, and indoor contaminant emissions. The zonal simulations only simulated very airtight dwellings (<3 ACH_{50}). As in the single zone simulations, custom EnergyPlus weather files were developed, using data contained in the CBECC-Res weather files used to demonstrate compliance with the building energy code. All HVAC systems were heat pumps, using electricity for both heating and cooling. The use of heat pumps distinguishes the multi-zone simulations from the single-zone cases, which used gas furnaces for heating. This difference impacts total energy use, savings potential, and time-of-use impacts, which are particularly strong for electricity consumption. Furthermore, temperature-based control parameters that were optimized around energy savings were re-calculated using the heat pump assumption. Two different heat pump system types were analyzed: (1) central forced air with a MERV13 particle filter (as required by 2019 Title 24) that tends to mix air between zones, and (2) distributed systems with no filtration and much less distribution between zones. The apartment dwellings were simulated only at one envelope leakage level—3 ACH_{50}—and all apartment surfaces, aside from one exterior wall, were treated as perfectly sealed from adjacent units in the building and without heat transfer.

Each dwelling was split into four zones (plus an unoccupied attic for the single-family homes): the kitchen, bathrooms, bedrooms and other living spaces. The apartment bedrooms were further divided into adult and child bedroom zones. The 2-story prototype other living spaces were split into a Common zone and a Family Room zone. This division allows us to account for the major difference in locations for pollutant emissions (moisture mostly in wet rooms (kitchens and bathroom) and particles from cooking in the kitchen), as well as occupancy patterns (relatively small amounts of time in kitchens and bathrooms and several hours of continuous occupancy for bedrooms).

Three whole dwelling, non-zoned ventilation systems were simulated for comparison to the zoned systems:

1. Central exhaust located in Other zone
2. Central supply located in Other zone, with MERV13 filtration on supply volume. All supply fan flows were assumed to also have a 3-to-1 recirculation

flow for tempering. This increased the supply fan energy use by a factor of 4 relative to similar size exhaust fans.

3. Balanced system, with exhaust flows from Kitchen and Bathroom zones, and supply flows (with MERV 13 filtration) to Other and Bedroom zones. The supply side of the balanced systems were also assumed to use a 3-to-1 recirculation flow for tempering, again effectively quadrupling the fan energy.

The zoned ventilation systems were all sized proportional to the zone floor area being served:

1. Exhaust fans located in each zone of the dwelling, controlled independently.
2. Supply fans located in each zone of the dwelling, controlled independently
3. Balanced supply/exhaust systems located in each zone of the dwelling. Note, this differs from current ducted systems, which are balanced for the home, but not for each zone in the home. This system will be balanced in each zone.
4. Central exhaust in “wet” zones (Bathroom and Kitchen) with controlled inlets in each “dry” zone (Bedrooms and Common area).

Whole house target and mechanical fan airflows are calculated using the ASHRAE 62.2-2016 ventilation standard, and these whole house flows were divided amongst the zones, proportional to their floor area fractions. Methods for sizing and assessing zonal ventilation systems are not currently included in the ASHRAE standard or in California Title 24 Building Energy Code and this weighting approach represents our best effort at a zonal extension of the approaches currently used in the governing standards.

While the simulation tools use a mass balance to fully account for all air flows and pollutant transport between inside and outside and between zones, it is not practical for a ventilation system controller to know all this information. Therefore, the ventilation equivalence calculations use an estimate for the total zone ventilation flow (combination of zone fan and zone infiltration flows) at any given time together with the target for that zone. For the contaminant-sensing, this simplification is not required and the ventilation system operates in a zone until all contaminants are below pre-set acceptable levels. A third option was also developed that uses the real-time generic contaminant concentration predicted in each zone by CONTAM, and compares this against the whole dwelling steady-state concentration that would occur at the 62.2 target ventilation rate.

To determine acceptable limits for indoor contaminant concentrations levels OEHHA, WHO and EPA long-term and short-term exposure limits were used. For formaldehyde, the OEHHA REL is 7 ppb and the WHO limit is 80 ppb. For comparison, the HENGH 20th percentile is 15 ppb.

Emission rates for moisture, CO_2, formaldehyde and particles were taken from a combination of the literature and derived from measurements in the HENGH field study.

For particles, removal by interior deposition, the building envelope for outdoor particles, and filters was included.

Outdoor contaminant levels come from a variety of sources. CO_2 was treated as constant outdoors at 400 ppm, and outdoor formaldehyde was a constant 3 ppb. Hourly ambient humidity was extracted from the simulation weather file. Hourly outdoor particle data were extracted from U.S. EPA ambient files that correspond to the simulated CA climate regions.

Smart Control Descriptions

Zone occupancy is a key aspect of zonal ventilation control. All zonal controllers used the zone occupancy as a key control input. A typical 9-hour workday/school day absence from 8-5pm Monday – Friday, with continuous weekend occupancy was assumed. A fixed schedule of occupants moving between rooms at different times of day was imposed, together with scripting their activities within the zones (e.g., person one in the kitchen zone cooking, or person two in the bathrooms taking a shower).

The other ventilation controls were similar to those for the single zone, but with metrics and operating strategies adapted for the multi-zone simulation framework. As with the single zone work, in order to isolate the energy used for mechanical ventilation in compliance with Title 24, a baseline with infiltration and auxiliary fans, but no whole dwelling ventilation was simulated, as well as a baseline with a constant flow fan sized to 62.2-2016. The constant flow base cases were run with all fan types, both zonal and non-zonal, including exhaust, supply and balanced fans.

The following smart control strategies were examined:

- **Baseline + IAQ Controls.** Intended to improve IAQ while not affecting energy use, these controls do not modulate the total airflow, instead they change which zone the air is supplied or exhausted from based on the zone's occupancy.
    - **supplyTracker** – For supply and balanced systems the supply air flows are directed to occupied zones. There is no reduction in total system airflow. The total system airflow is directed to each occupied zone in proportion to its floor area. It is possible for a single occupied zone to receive the full dwelling airflow rate. Annual ventilation airflows are unchanged.
    - **occupantTracker** – This is the same as the supply tracker, but also includes exhaust air, such that the exhaust is taken from occupied zones only and the total dwelling air flow is maintained. Annual ventilation airflows are unchanged.
- **Outdoor Temperature Controls.** These controls use measured outdoor temperatures to shift ventilation flows to mild weather periods.
    - **varQ** – For single-point unzoned ventilation systems, the whole dwelling IAQ fan flow rate is varied according to outdoor dry-bulb temperature,

    using pre-optimized temperature scaling factors. This leads to increased annual ventilation flow. This is an adapted version of the varQ controller assessed in the single-zone simulations. The optimization strategy was improved upon compared to the single zone simulations, mostly to improve performance in CZ1. The scaling of ventilation flows with outdoor temperature was allowed to vary independently between the heating and cooling seasons. In the single-zone work, the heating and cooling temperatures used for scaling were a fixed offset from the annual minimum or maximum temperature, in the zonal cases, these offsets were independently optimized.
    - **varQmzSingleZoneOpt** – For multipoint zoned systems, this control has the same airflow as varQ, but zone airflows are directed to occupied zones only. This leads to increased annual ventilation flow.
    - **varQmz** – For multipoint zoned systems, this control has the same calculation procedures as varQ, but temperature scaling parameters are optimized for a two-zone dwelling using assumed occupancy patterns. This approach can decrease annual ventilation flow.
- **Zone Occupancy Controls.** Unlike the above **"tracker"** controls, these controls apportion the whole dwelling flow to each zone and then only vent occupied zones. These controls only work with zonal ventilation systems. These strategies reduce annual ventilation airflow for the dwelling, but make those flows more effective, by delivering outside air to the occupants. Controls use either estimated relative exposure and dose (as calculated in 62.2-2016) or actual contaminant predictions.
    - **zoneExposure** – The controller tracks relative exposure and relative dose in each zone, and operates the IAQ fan to maintain both metrics below 1 during occupied periods, otherwise exposure is controlled to less than 5 to avoid acute exposures.
    - **zoneASHQexposure** – This is the same control strategy as zoneExposure, but instead of using controller estimates of relative exposure and dose, it controls the zone Generic contaminant concentration to be the same as the steady-state zone concentration that would occur at the uncontrolled annual ventilation rate.
    - **occExposure** –Tracks controller estimated relative exposure in each zone and integrated 24-hour relative dose for each occupant. Zones are vented if any person in the zone has an integrated relative dose greater than 1, or if the zone relative exposure is greater than 1. Unoccupied zone relative exposure is controlled to less than 5. This controller ensures that a personal exposure in one zone can be compensated for by increased ventilation in another zone.

    - **occASHQexposure –** This is the same control strategy as occExposure, but instead of using controller estimates of relative exposure and dose, it controls the zone Generic contaminant concentration to be the same as the steady-state zone concentration that would occur at the uncontrolled annual ventilation rate.
    - **occupantVenter –** All zones get a minimum flow rate when unoccupied. Additional airflow is distributed to occupied zones. There is no tracking of controller estimated exposure, dose or contaminants.
- **Contaminant Controls.** These controllers use actual contaminant concentrations in each zone, and the zone ventilation is operated when they exceed health-relevant thresholds. These controls apply to all zonal ventilation types.
    - **contaminantDwelling** – The whole dwelling is vented if any contaminant exceeds health thresholds in any zone.
    - **contaminantZone** – Each individual zone is vented if any contaminant in the zone exceeds health thresholds.
    - **contaminantZoneOcc** - Each individual zone is vented if it is occupied and any contaminant in the zone exceeds health thresholds.
    - **aerecoRH** – exhaust units (in bathrooms and kitchen) and air inlets (in the other "dry" zones) are modulated based on zone humidity levels.

Results for multi-zone and contaminant-controlled ventilation

Direct Contaminant Control

Using measured contaminant concentrations led to consistently increased ventilation rates in the dwellings in order to meet the CA OEHHA formaldehyde 24-hour target of 9 $\mu g/m^3$. None succeeded in meeting the limit, though the increased ventilation reduced personal exposures to the generic contaminant, formaldehyde and CO_2. The increased outside airflow tended to increase particle exposure on average. Because the smart ventilation system fans are doubled in their capacity to enable the time shifting of ventilation, their continuous operation to attempt to control formaldehyde led to ventilation energy use that was typically more than doubled for these controls. The only way for direct contaminant controls to be otherwise effective would be to use a higher limit for formaldehyde.

The aerecoRH controller was developed for heating-dominated climates and is based on increasing ventilation when indoor humidity is high. The scaling of the inlet openings and exhaust flows with zone relative humidity was not optimized for some of the California climates that we assessed. This led to increased ventilation rates compared with the constant fan baseline cases that reduced median non-particle exposures but increased HVAC energy use. CZ16 in the colder dryer mountain regions was the only case where ventilation rates were reduced and energy savings were achieved (median of 19% whole dwelling HVAC savings), but this worsened all personal exposures (from

8 to 78%, depending on the contaminant of interest). The increase in personal exposure was often due to increased particle exposures compared to exhaust systems where the envelope to removes incoming particles at 50% efficiency, or MERV 13 filtration that was assumed for supply and balanced systems. Future development of the aerecoRH controls for US climates will require an optimization effort to identify appropriate methods to scale ventilation with indoor humidity, such that energy savings and adequate IAQ performance are achieved.

HVAC System Type

Two HVAC system types were simulated in the multi-zone dwellings. Ductless mini-split heat pumps were used that control temperatures by zone, and central forced air heat pumps that mix air in the dwelling and do not allow for thermal zoning. HVAC system type had overall marginal impacts on IAQ in most cases, though particle exposures were substantially reduced in CZ10 and 16 for single-family prototypes, as well as in the apartment dwellings which had the highest overall particle exposures. The high efficiency homes studies here required very little HVAC airflow to meet space conditioning loads. Therefore, the mixing from the HPfau forced air systems had no identifiable impacts on personal exposures to contaminants. It is possible that mixing might have contributed to reduced particle exposure during cooking by distributing particles away from cook, but we expect the MERV 13 filtration was the dominant effect. The VRF systems used less energy, both in baseline and in smart control modes, because of their low fan energy use and their improved efficiency from variable capacity and thermal zoning. The HPfau systems had higher energy use, and their savings from smart controls were correspondingly higher.

Ventilation System Type

Ventilation system type was a very important factor for the personal contaminant exposures, as well as for the baseline and smart control HVAC energy performance. Balanced fans had the highest ventilation rates and typically the lowest personal pollutant exposures. These were followed by exhaust fans, which tended to have marginally lower exposures than supply fans, with the exception of CO_2, where supply fans outperformed exhaust. Due to their need for recirculated tempering air, the supply and balanced fan types had much higher HVAC energy use. For smart controls that increased total annual outside air flow (e.g., some outside temperature-based controls and the contaminant controls), this higher fan energy almost completely eliminated energy savings. In contrast, for controls that reduced the annual outside air flow (e.g., most zone occupancy controls), the higher energy use of the supply and balanced fan types led to greater savings.

When zoned, changes in exposures were small (<5%) except for supply fans that increased particle concentrations by 9%. This is because the zoned supplies were very effective at delivering outside air (including particles) to the occupied zones. This occurred despite the filtration of supply airflows using MERV13 filters. Exhaust fan types generally had less impact when zoned, because exhaust fans largely distribute outside airflows according to the leakage area in each zone, irrespective of the fan's location in the dwelling. This can be a benefit of this fan type, but it generally makes them a poor candidate for zonal controls. Exhaust fans did provide zonal ventilation benefits when substantial differences in concentrations occurred between zones in the dwelling. These differences occurred in all dwellings due to localized emissions (e.g., cooking, bathing, breathing in closed bedrooms at night), and in the leaky 2-story dwellings where pressure interactions between the ventilation fan and building envelope led to under-ventilated 2nd story zones. In these cases, exhaust fans with zoning provided IAQ benefits. Exhaust fan cases used by far the least annual HVAC energy use, and they performed best for control types that increased annual outside airflows, because the fan energy penalty was dwarfed by the load reductions achieved through temperature-based shifting of ventilation.

These results imply that effective ventilation zoning requires supply or balanced systems, but that the benefits of zoning are unclear, and the energy savings must overcome their much greater mechanical fan energy use.

Dwelling Type

Dwelling prototype impacted both the IAQ and energy results in the zonal simulations and controls. Due to its adiabatic surfaces and internal heat loads, the apartment dwellings were strongly cooling dominated, and increased ventilation often reduced annual energy use, rather than increasing it. This meant that controls targeting reduced ventilation rates actually used more energy, not less. Outside temperature-based controls also failed to deliver energy savings in the apartment dwellings, again because they are so cooling dominated, and controls were not optimized to account for this interaction with internal loads. The apartment dwellings had the highest air change rates, due to their smaller size and fan sizing calculations in ASHRAE 62.2. Occupants in apartments benefitted from these higher air change rates for contaminants that were emitted constantly throughout the dwelling. But for contaminants with indoor sources that were based on occupant activities, the smaller volume of the apartment dwelling led to increased exposures. This was particularly the case for CO_2 and particles. The single-family dwellings had HVAC loads that resulted in energy savings using the smart controls tested in this work. The 2-story dwellings behaved quite differently than the 1-story when envelope leakage was higher (3 ACH_{50}) and unbalanced fan types were used. In these cases, the fan pressure and envelope pressures interacted, leading to generally low outdoor airflow rates and high contaminant concentrations on the 2nd level zones. Occupants spent lots of time in the 2nd story bedroom zone, so the exposures were notably higher in these cases. These leakier 2-story dwellings had substantial IAQ benefits from using zonal ventilation equipment. The 2-story dwellings also had higher annual HVAC energy use, and often had correspondingly higher energy savings through smart controls. These results imply that consideration of energy savings for smart ventilation should definitely distinguish between single-family and multi-family dwellings.

Envelope Leakage

This study focused on dwellings substantially more airtight than typical new California construction. Envelope leakage was a marginally important factor in the outcomes of the zonal ventilation control performance mostly because the ASHRAE 62.2 fan sizing for single-family homes includes envelope leakage and generally acts to have similar combined natural infiltration and mechanical ventilation across a broad range of envelope leakage. Absolute energy savings (kWh) were greatest in the most airtight dwellings, largely because the fans controlled nearly all of the outside airflow in these cases, so the potential savings were greatest. The relative savings (%) were lowest for these cases. The leakier cases (3 ACH_{50}) had correspondingly the lowest absolute savings and the highest relative savings, because infiltration had greater impacts and the baseline fans were smaller. Envelope leakage also impacted personal exposures, particularly in the leakier homes that used unbalanced ventilation equipment, because the interaction of the fan pressure and envelope pressures led to inconsistent ventilation rates between the zones. This was particularly the case in the 2-story dwellings, where the 2nd level zones were stranded with less outside airflow and higher contaminant concentrations. The very tight 2-story dwellings maintained similar ventilation rates between zones, because they were entirely fan pressure dominated.

Climate Zone

Climate zone substantially impacted energy performance, and to a lesser extent personal pollutant exposures. CZ16 showed the highest average personal exposures for the generic contaminant, CO_2 and particles, while having by far the lowest formaldehyde exposures. Low formaldehyde concentrations in CZ16 were driven by the lower emission rate due to lower indoor humidity. CZ16 also had, on average, marginally lower ventilation rates than in the other climate regions, but these differences were not enough to explain the increases in pollutant exposure. Climate zone also dominated the variability in annual HVAC energy use, with the coldest location (CZ16) consistently showing both the highest annual consumption and the greatest absolute energy savings from smart controls. The relative (%) ventilation energy savings were also greatest in CZ16 for controls that used outdoor temperature measurement, but the other control types had much less variability in percent savings between climate regions. For example, the best energy savings strategy (varQmz) saved 60% in CZ16 but only 27% in CZ 10. These results imply that any energy savings attributed to smart ventilation should vary by climate zone.

Number of Control Zones

Many of the zonal smart ventilation controls assessed two zoning configurations—one where each zone in the dwelling was treated independently, and a second where only two zones were considered, bedrooms and non-bedrooms. The second zoning approach is based on what has been observed in homes: namely that bedrooms are the only zones that might regularly have closed doors and be occupied for long periods continuously. The cases with each zone treated independently were able to save more energy, because they further reduced dwelling ventilation rates, but they did this at the expense of increased personal exposures for some contaminants. Given the worsened personal exposure and small increase in energy savings, we recommend that zonal smart ventilation systems use fewer, rather than more zones, which should reduce system costs and complexity. The apartment prototypes behaved distinctly from the single-family cases, but their behavior in response to zoning assumptions is largely irrelevant, because these control types almost universally increased annual HVAC energy use for apartment dwellings, so we do not recommend using these strategies under either zoning configuration. The occupantTracker control improved IAQ when all zones were treated independently, but this was because the occupantTracker control did not attempt to save energy, but instead to only improve IAQ. On top of this, because the occupantTracker ventilated occupied zones more effectively, it tended to increase personal particle exposures while reducing all other exposures.

Multizone and Contaminant Control Summary

Zoned dwellings with zonal ventilation equipment and smart controls form a complex system, which none of the smart controls tested were able to adequately optimize. No controls were able to provide equivalent personal contaminant exposures for all species of contaminants assessed, likely because of the diversity of the pollutant sources (indoor continuous or episodic and outdoors) and of the removal mechanisms (outside air ventilation, deposition, filtration). The most common adverse IAQ impact from otherwise effective zonal ventilation equipment and controls was an increase in personal particle exposures. This occurred because outdoor particles were more effectively delivered to the occupants when using zonal ventilation systems. In contrast, many indoor contaminant exposures were reduced by the localized ventilation patterns.

In Figure 5, we compare the personal generic contaminant relative exposure (x-axis) against the whole dwelling annual HVAC energy savings (y-axis) attributable to the smart ventilation controls in all simulations executed in this work. Plot symbols are colored according to the control type, and plot shapes represent the ventilation system type. The generic contaminant has a somewhat linear relationship with HVAC energy savings, because the generic exposures respond nearly linearly with changes in ventilation rates and associated energy savings. All contaminants responded differently to changes in ventilation rates. For comparison, these same results are plotted along with personal particle exposures in Figure 6 to illustrate the lack of a linear relationship.

Successful controllers would be in the upper-left hand quadrant of Figure 5, indicating positive energy savings and reduced personal exposures. We see that many controls were able to reduce whole dwelling HVAC energy by up to 40% (and by 15-22% on average), but this was done at the expense of worsened personal exposure to contaminants (in this case, the generic indoor contaminant). In many cases, the energy savings exceeded what was achieved using single-zone ventilation equipment and controls. But very few cases both saved energy and provided acceptable or improved IAQ. More commonly, the zonal smart controls either saved energy at the expense of worsened IAQ (higher exposure), or improved IAQ by using more energy (negative energy savings).

Zonal smart ventilation controls were not effective in the multi-family apartment dwellings. This was largely because in all but two scenarios (multi-point and single-point balanced fan types in CZ16), the baseline constant flow fan cases actually provided sufficient ventilation cooling that annual HVAC energy use was decreased, rather than increased by code-compliant ventilation. This rendered most of the zonal smart controls ineffective, as many rely on reducing outside airflow to save energy.

Figure 5: Site Energy Total HVAC Savings (%) and Personal Generic Relative Exposure

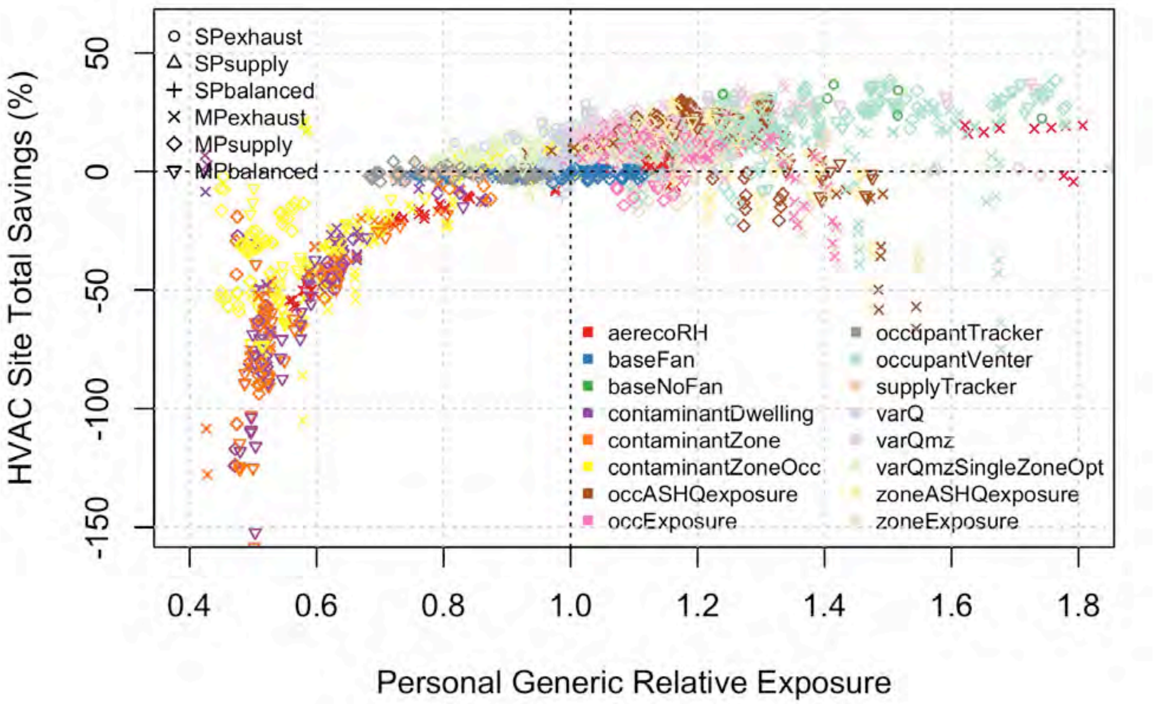


Figure 6: Site Energy Total HVAC Savings (%) and Personal Particles ($PM_{2.5}$) Relative Exposure

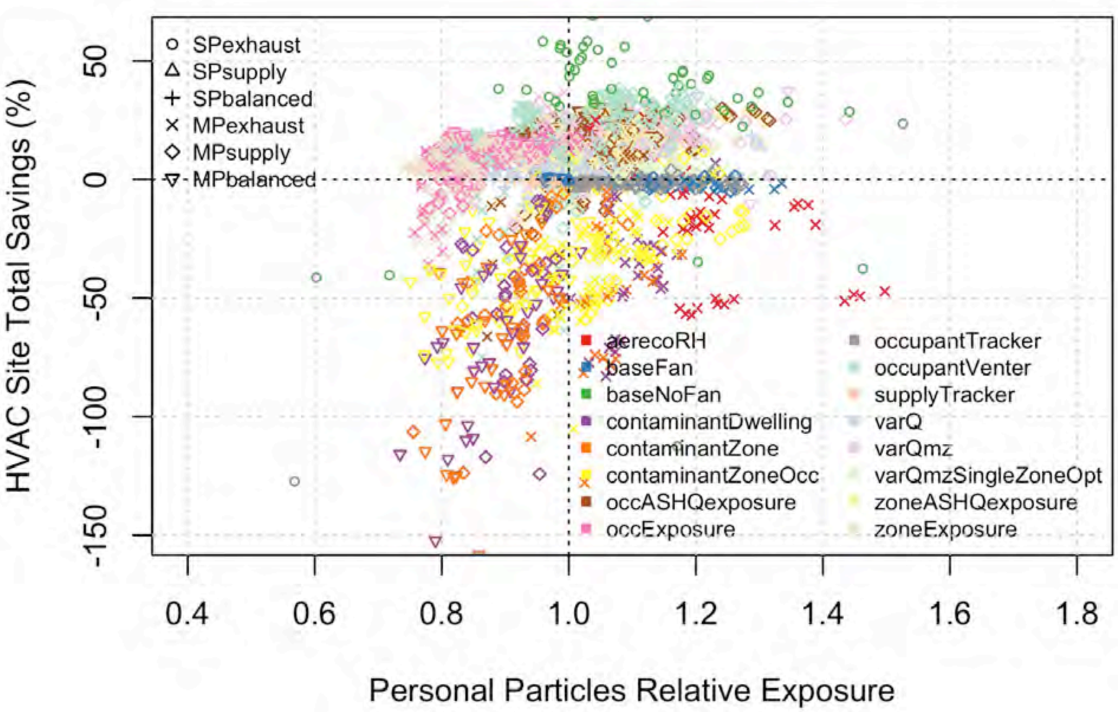


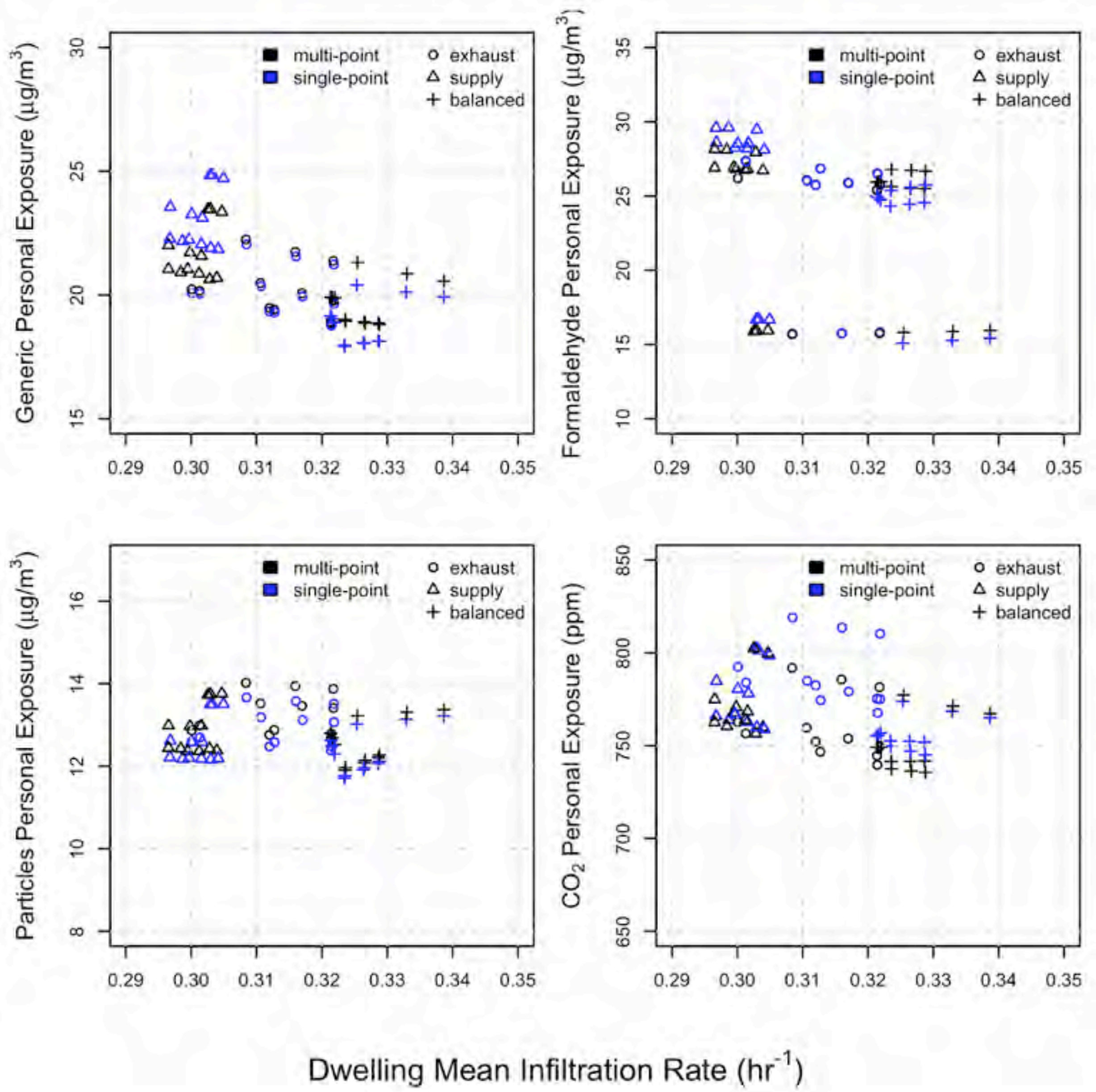
Figure 7 shows the mean dwelling ventilation rates compared with personal exposures to each of the four contaminants of concern. The plot symbols represent the fan type, and the colors indicate whether the ventilation system was single-point (non-zonal) or multi-point (zonal). These tight dwellings with mechanical ventilation have only a narrow range of ventilation rates. Balanced fans had the highest ventilation rates and typically the lowest personal pollutant exposures. These were followed by exhaust fans, which tended to have marginally lower exposures and higher ventilation rates than supply fans. CO_2 was an exception, where supply fans outperformed exhaust. When zoned (black vs. blue in Figure 7), balanced fans worsened pollutant exposures (from 0.1 to 4%, on average) compared with the non-zonal balanced fan cases. When exhaust fans were zoned, they slightly worsened generic and particle exposures (by 0.6 to 2%, on average), while slightly reducing formaldehyde (0.3%) and substantially reducing CO_2 (3.5%) exposures. For zoned supply fans, the personal exposures dropped substantially for the generic contaminant, formaldehyde and CO_2 (by 1 to 4%, on average), and got much worse for particles (9%).

The multi-zone results have generally shown that the increased energy savings potential of occupancy-aware zonal ventilation controls are outweighed by their varied impacts on personal contaminant exposures. Unless a single metric is developed that balances the net-health impacts of these ventilation controls, then it is impossible to distinguish between controls that improved or worsened IAQ and occupant health. The ability to target individual zones for ventilation is offset by the introduction of outdoor particles directly to the occupants, and by the need to account for contaminants generated independently of occupancy (e.g., formaldehyde) that are emitted during unoccupied times. Contaminant control approaches are completely dominated by the difficulty in achieving the OEHHA limit for formaldehyde. Our systems ventilated at their maximum flow rates and still did not achieve the 9 $\mu g/m^3$ OEHHA limit and also doubled ventilation energy use.

Based on this work, two primary questions emerge: (1) Should zonal ventilation equipment be prioritized/encouraged in modern, airtight dwellings; and (2) Do ventilation controls offer substantial energy savings when using zonal equipment and occupancy sensing?

Given the results described above, we do not suggest strong support in the building codes to encourage zonal ventilation systems for whole dwelling ventilation. The only exceptions to this might be for 2-story dwellings with 3 or more ACH_{50} envelope leakage that use a single exhaust fan on the lower level, where the 2nd level was substantially under-ventilated. We also conclude that zonal smart ventilation controls are not yet viable given the current code requirements for equivalent exposure for dynamically controlled ventilation systems. A method must be developed to balance these competing changes in exposure to determine the net-health impacts of a control strategy. On top of this, zonal ventilation systems are expected to be more expensive, complex, and difficult to install and verify correctly for performance and code compliance. Zonal controls add further complexity on top of the zonal equipment.

Figure 7: Ventilation Rate and Personal Contaminant Exposures for Each Fan Type and Zoning Type in 1-story single-family dwellings. Baseline constant flow fan cases.



CHAPTER 5: Technology/Knowledge/Market Transfer Activities

SVACH Website

A website, http://SVACH.lbl.gov was created to inform the interested public on the status of this project and on the results of the work. It serves as a repository for relevant SVACH publications.

Technical Publications

The following Journal articles and conference papers were produced for this project:

Less, B.D., Clark, J., and Walker, I.S. (2019) Energy savings with outdoor temperature-based smart ventilation control strategies in advanced California homes. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2019.04.028

Clark, J., Less, B., Dutton, S., Walker, I. and Sherman, M. (2019). Efficacy of occupancy-based smart ventilation control strategies in energy-efficient homes in the United States. Building and Environment, Vol. 156, https://doi.org/10.1016/j.buildenv.2019.03.002. LBNL 201199

Guyot, G., Sherman, M.H. and Walker, I.S. (2018). Smart ventilation energy and indoor air quality performance in residential buildings: a review. Energy and Buildings. Vol. 163, pp. 416-430. https://doi.org/10.1016/j.enbuild.2017.12.051

Guyot, G., Sherman, M.H. and Walker, I.S. (2018). Performance based approaches for smart ventilation in residential buildings. International Journal of Ventilation. https://doi.org/10.1080/14733315.2018.1435025

Guyot, G. Sherman, M. and Walker, I. 2017. A Review of Pollutants and Sources of Concern and Performance-Based Approaches to Residential Smart Ventilation. AIVC Workshop, Brussels, Belgium March 2017.

Iain Walker and Brennan Less. 2018. "Rethinking Occupancy-Based Ventilation Controls". Proc. 2018 AIVC Conference.

Iain Walker and Brennan Less. 2018. "Reassessing Occupancy-Based Ventilation and IAQ in Homes". Indoor Air extended abstract.

Clark, J, Walker, I., Less, B., Dutton, S., Li, X. and Sherman, M. 2018. Smart Ventilation in Advanced California Homes. ASHRAE Conference Paper, Houston, Summer 2018. ASHRAE, Atlanta, GA.

Presentations for this project have been given at AIVC workshops and the following conferences: Home Performance Coalition, RESNET, Indoor Air, and ASHRAE. LBNL staff have spoken with many ventilation equipment manufacturers at the trade shows associated with these conferences. The result of these discussions is that many more manufacturers are aware of smart ventilation controls and systems, have greater awareness of the technical aspects of smart ventilation (such as maintaining equivalent exposure to contaminants) and are interested in integrating advanced smart controls into their products.

Development of a definition of Smart Ventilation

As part of the US DOE co-funding of this project LBNL worked with the International Energy Agency Annex 5: the Air Infiltration and Ventilation Center to lead a project on smart ventilation that included other international researchers, and to create an international definition of smart ventilation. This definition goes beyond the energy and IAQ issues covered in this study, and it forms a useful basis for defining smart ventilation systems that the industry needs if it is to progress.

"Smart ventilation is a process to continually adjust the ventilation system in time, and optionally by location, to provide the desired IAQ benefits while minimizing energy consumption, utility bills and other non-IAQ costs (such as thermal discomfort or noise). A smart ventilation system adjusts ventilation rates in time or by location in a building to be responsive to one or more of the following: occupancy, outdoor thermal and air quality conditions, electricity grid needs, direct sensing of contaminants, operation of other air moving and air cleaning systems.

In addition, smart ventilation systems can provide information to building owners, occupants, and managers on operational energy consumption and indoor air quality, and signal when systems need maintenance or repair.

Being responsive to occupancy means that a smart ventilation system can adjust ventilation depending on demand and reduce ventilation if the building is unoccupied. Smart ventilation can time-shift ventilation to periods when indoor-outdoor temperature differences are smaller and away from peak outdoor temperatures and humidity, or when indoor-outdoor temperatures are appropriate for ventilative cooling, or when outdoor air quality is acceptable.

Being responsive to electricity grid needs means providing flexibility to electricity demand (including direct signals from utilities) and integration with electric grid control strategies.

Smart ventilation systems can have sensors to detect, for instance, air flow, systems pressures or fan energy use in such a way that systems failures can be detected and repaired, or when system components need maintenance, such as filter replacement."

Technical Advisory Committee

The TAC was chosen specifically to be a major part of the technology/knowledge transfer for the SVACH project. The TAC included representatives from the Energy Commission, California Air Resources Board, ventilation equipment manufacturers interested in smart ventilation, the National Institute of Standards and Technology, the California Building Industry Association, the Home Ventilating Institute, and our partners the US DOE and Aereco. The TAC has made supportive suggestions and comments throughout the study. Some key issues were: ensuring that the energy predictions were similar to those used in California Energy Code compliance software (CBEC Res), how to group rooms into zones for zonal control, ensuring that controls meet acute exposure limits as well as addressing long-term chronic exposure, discussing hoe systems might be certified for a product directory, as well as simulation details – such as what furnace efficiency to use as a default.

Technical Support to 2019 Title 24, part 6.

The project provided limited technical support to the CEC in changes to Title 24 related to residential ventilation for the 2019 code cycle due to scheduling conflicts – input for the 2019 code was required far in advance of completion of this project. Therefore, the advice and recommendations resulting from this project will be discussed with the Energy Commission in the context of future code changes. This effort will be coordinated with potential changes to ASHRAE Standard 62.2 that is used as a reference for the California code. Chapter 6 has more details on these recommendations for Title 24.

CHAPTER 6: Conclusions/Recommendations

Title 24 Next Steps

The 2019 Title 24 has adopted parts of the ASHRAE 62.2-2016 ventilation standard, including the ability to demonstrate compliance for time-varying ventilation using relative exposure (i.e., smart ventilation controls in Normative Appendix C). But there is no current method in the Title 24 to account for the energy savings or to get compliance credit for such systems.

One option would be to incorporate the ability to model dynamic ventilation systems and relative exposure into CBECC-Res, or allow the use of pre-calculated scheduled mechanical ventilation airflows (rather than the current fixed fan airflow). This is required to reflect the diversity of results found across house types, climates and envelope leakage rates in our work. This is also the only way to provide adequate market flexibility for future changes to control schemas by manufacturers, new code requirements, etc.

Another option is to use third-party compliance verification where a particular smart ventilation control approach is simulated using agreed upon assumptions and scenarios and gets an energy use multiplier that can be used in compliance calculations (as is done in European building standards). The Energy Commission would also need to develop requirements or guidelines for manufacturers to use in demonstrating the compliance of their systems with the code requirements. This would include which housing types to model, ventilation system types, climate regions, and other such variables.

The reference case in our simulations was a continuous fan sized to the ASHRAE 62.2-2016 ventilation standard, but the 2019 Title 24 will require that IAQ fans in residences are sized differently. The new Title 24 fan sizing calculations are the same as ASHRAE 62.2-2016, however, rather than use the measured envelope airtightness of the home as an input to the calculations, the envelope airtightness is fixed at 2 ACH_{50} for all homes (homes that are tested below 2 ACH_{50} must use the lower number and increase the required fan size). Overall, this will increase the baseline fan sizes compared with our current simulations. This represents an additional opportunity for smart ventilation controls, because they can demonstrate energy savings relative to a baseline with higher ventilation energy consumption. Energy savings will increase, though improvements in IAQ through smart controls will be reduced or eliminated.

Finally, the superposition models used in ASHRAE 62.2-2016 are biased towards high exposure in constant fan cases using unbalanced fans. This could be fixed in ASHRAE

62.2 itself, but absent that, the Energy Commission could consider amending the calculation procedures used in California. For example, the equation used to estimate whole house airflow for exposure calculations in Normative Appendix C of the Standard could be changed so that it is an identity (i.e., the same forwards-backwards) with the fan sizing equation as outlined in appendix B.

IAQ Metrics

In order for IAQ to have greater value in the buildings industry, it is necessary to go beyond simply specifying air flows and develop metrics and scoring systems that can be used by builders and the real-estate industry. In addition, emerging pollutant sensing technologies have the capability to change the home performance market by introducing more awareness of IAQ. All interviewees said that a scoring system would help support their claims of improved IAQ performance, and the lack of a scoring tool undermines their current efforts to sell improved IAQ and health in homes. To be usable by appraisers, such information must have a high level of geographic specificity. Realtors are important 'trade allies' in this regard, as they are a key source of information to appraisers. Appraisers like the idea of considering particularly sensitive populations (allergies, asthma, children). However, they cautioned that having "modified scores or indices" for different groups could easily make the report difficult to absorb. A more elegant solution would be if certain thresholds (e.g. scores 80 and above) can be flagged as thresholds of acceptability for certain sensitive populations. We also identified the need for a comprehensive metric that balances the net-health impacts of changes in multiple contaminants of concern that typically occur in response to ventilation controls, particularly when using zonal equipment and occupancy sensing. Without this metric, it is impossible for the industry to develop or assess smart ventilation controls that can be consistently said to meet the equivalent exposure requirement currently embedded in ASHRAE 62.2-2016. The most likely candidate for this metric would be an assessment based on Disability Adjusted Life-Years (DALYs).

Single zone smart ventilation

The most successful smart controls shifted ventilation rates seasonally, rather than over the course of the day or month and used parameters pre-calculated using an optimization routine, and they reduced weighted non-normalized average site ventilation energy use by 41 - 51% (413 - 505 kWh/year; 12 - 15% of whole house HVAC energy), while TDV weighted average ventilation energy reductions were 36 - 61% (1,615-2,743 kWh/year; 6-10% of whole house TDV HVAC energy). Auxiliary fan (i.e., kitchen, bathroom and dryer exhausts) sensing increased ventilation site energy savings in all cases, from roughly 5 to 15%. This also increased the average non-normalized site ventilation savings for the best control types to a range between 50 - 58% (TDV ventilation savings between 48 - 67%). More than 90% of site energy savings were for heating end-uses, while TDV energy savings were split fairly evenly between heating and cooling.

Peak demand during the 2-6pm period on the hottest days of the year was reduced through use of the smart controls, with peak load reductions of 0-300 watts. It is possible that specific peak controls could achieve even greater reductions in demand. Other peak periods could be considered in future work.

Occupancy-based controls had very low energy savings because, unlike all previous occupancy-based controls, this work included emissions from building materials. This is critical because material emissions, such as formaldehyde, result in concentrations of concern for health in almost all homes. If occupant schedules are well known, then pre-ventilating strategies can be used to improve occupancy-based energy savings.

Use of the smart ventilation controls was much more effective than increasing airtightness while using continuous fans sized to ASHRAE 62.2-2016. This is because the benefits of air sealing are limited, if infiltration credits are used to determine mechanical ventilation air flow requirements.

Current products available for \$150 to \$300 on the consumer market have the core hardware capabilities to act as smart ventilation controls, but very few of the currently available products actually ensure compliance with the ASHRAE ventilation standard, and none use the time-varying ventilation approach from Appendix C of ASHRAE 62.2 to facilitate time-shifting of ventilation flows over more than a 24-hour period.

Zonal smart ventilation and contaminant controls

Multi-zone smart controls did not clearly offer substantial energy savings in new homes compared to non-zoned approaches. The ability to target individual zones for ventilation was offset by the introduction of outdoor particles, and by the need to account for contaminants generated independent of occupancy (e.g., formaldehyde). A method must be developed to balance these competing changes in exposure to determine the net-health impacts of a control strategy. The zonal controls offered some additional energy savings potential, but they consistently compromised IAQ for at least one contaminant. A key barrier to the use of zonal controls is that current occupancy sensing equipment does not perform adequately to track occupants throughout the zones of a dwelling. Furthermore, the ability of homes to be effectively zoned from an IAQ perspective is limited by opening of interior doors, operation of HVAC equipment, and movement of occupants between zones.

The smart ventilation control tested in the zonal simulation models that both saved energy and provided consistent equivalent IAQ across most contaminant types (most of the time) was the varQ controller developed in the single-zone simulations. It shifts ventilation rates seasonally based on outdoor temperature. When using an exhaust fan, this control provided median site ventilation savings of 16% in CZ1, 35% in CZ3, and 47% in both CZ10 and 16. The corresponding median TDV ventilation energy savings in each climate zone were 16%, 50%, 81% and 53%. This makes the varQ control nearly as effective as most heat recovery ventilators. However, the varQ control often increased personal particle exposures, because this control increased annual outside airflows, which increased the concentration of outdoor particles indoors. These increases were typically modest (<10%). The zonal controls offered some additional energy savings potential, but they consistently compromised IAQ for at least one contaminant. To illustrate, the zoneExposure controller tended to worsen all non-particle contaminant exposures, but particles were reduced as ventilation rates were lower. The site ventilation energy savings varied from roughly 5-45%. This control appears to make most contaminants worse, but if particles dominate health impacts, then it is possible that this controller provides a net-benefit with similar energy performance to the varQ.

Contaminant control approaches are completely dominated by the difficulty in achieving the OEHHA limit for formaldehyde. The systems in this study ventilated at their maximum flow rates (double the ASHREA 62.2 and Title 24 required minimum) and still did not achieve the 9 $\mu g/m^3$ OEHHA limit and also doubled ventilation energy use.

The simulation of advanced homes led to results that could be somewhat counter-intuitive. A good example of this is the apartment building that had very little heating or cooling load from the envelope. This led to it being dominated by internal loads where the ventilation flows provided ventilation cooling for much of the year, even in CZ 16. In this particular case, reducing ventilation air flows (which was the aim of many of the controls) reduced this ventilation cooling such that heating energy savings were offset by increased cooling energy use. This result is of key importance when developing HVAC systems for high performance homes where strategies that worked well in typical homes do not translate into good systems for high performance housing.

Future work

More work is required in order to allow builders and designers to take credit for smart ventilation control strategies in demonstrating compliance with California's Title 24 Building Energy Code. Also, field demonstrations of the energy and IAQ performance of smart ventilation controls are needed in new California homes, before these technologies can be adopted at scale.

This work focused on chronic/long term exposures to contaminants, because this can be directly addressed by current performance standards such as ASHRAE 62.2 and Title 24. The results of this study showed that including outdoor particles can have a significant impact on IAQ and ventilation system performance. Without a unifying metric that balances the net-health effects of zonal smart controls, we cannot either assess or design controls that provide equivalence to code compliant baseline systems. In the future, short-term/acute exposures could also be evaluated, in particular for California exposure to wildfire contaminants, where the ability to reduce ventilation rates for short periods may be advantageous.

Because the contaminant controls were so dominated by current formaldehyde requirements, future work should consider using other limits based on concentrations measured in homes. Alternatively, formaldehyde control in dwellings should be considered largely a product emissions issue, and the state should avoid any additional building ventilation regulations targeting formaldehyde control, beyond what is already in the 2019 code, which eliminates very low ventilation rate homes (when fans are operated).

Additional work is required in the area of sensors to develop sensors for indoor air contaminants that operate robustly over long periods. Currently, these sensors do not exist, particularly for key contaminants of concerns such as formaldehyde and NO_2.

To broaden the application and increase energy savings, smart ventilation approaches need to be developed for existing homes as a potential retrofit strategy.

Future work will investigate the application of smart ventilation controls to typical existing homes and more detailed approaches including internal air flows between units in multi-family buildings.

GLOSSARY OR LIST OF ACRONYMS

Term	**Definition**
ACCA	Air Conditioning Contractors of America
ACH	Air Changes per Hour
ACH50	Air Changes per Hour at 50 Pa
ACM	Alterative Calculation Manual
ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
CZ	Climate Zone
DALY	Disability Adjusted Life Year
DCV	Demand Controlled Ventilation
ELV	Exposure Limit Value
EPA	Environmental Protection Agency
HENGH	Healthy, Efficient New Gas Homes
HVAC	Heating Ventilating and Air Conditioning
IAGV	Indoor Air Guideline Value
IAQ	Indoor Air Quality
IEA	International Energy Agency
LBNL	Lawrence Berkeley National Laboratory
MLS	Multiple Listing System
OEHHA	Office of Environmental Health Hazard Assessment
PM10	Particles less than 10 microns in diameter
PM2.5	Particles less than 2.5 microns in diameter
Ppm	Parts per million
REL	Reference Exposure Level
RESNET	Residential Energy Services Network
RH	Relative Humidity

Term	Definition
TAC	Technical Advisory Committee
TDV	Tine Dependent Valuation
TRV	Toxicity Reference Value
TVOC	Total Volatile Organic Compounds
US DOE	US Department of Energy
WHO	World Health Organization
ZNE	Zero Net Energy

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APPENDIX A:
Valuing IAQ in the Marketplace: Metrics and Appraisals

Introduction

California is on a path toward zero net energy (ZNE) homes. The air-tightness of new and existing homes with electric heating and cooling is expected to increase as homes become more energy efficient. As homes become more energy efficient through air-sealing (or tightening), the possibility of poor indoor air quality (IAQ) increases (Levin and Phillips 2015). Poor IAQ associated with stringent energy-efficiency requirements is a major barrier to California's energy-savings policy goals. Additionally, improvements in building thermal envelopes imply that the nominal energy needed to provide and condition ventilation air to achieve acceptable indoor air quality will represent a larger fraction of home energy use going forward. New approaches and technologies, including smart ventilation, are needed to keep California on the path toward healthy ZNE homes while saving energy. The purpose of this project is to develop smart ventilation technology approaches that reduce ventilation energy use and cost while maintaining IAQ. To ensure that smart ventilation technology incorporates air cleaning, IAQ metrics will be developed for optimizing ventilation.

This report provides an overview of existing residential programs for assessing IAQ in new and existing homes. The purpose of this report is to establish the framework for developing and evaluating new IAQ metrics for smart ventilation. Specifically, this report includes a summary of current metrics used to evaluate IAQ and considerations for development of new metrics.

New metrics need to be developed that go beyond a simple air flow requirement, or simple DCV systems if we want to better address health, moisture and odor concerns and to enable the use and valuation of new technologies and ventilation approaches among a greater diversity of market actors.

New metrics for evaluating IAQ are needed to focus more on contaminants of concern rather than the generic or surrogate contaminant approaches of current ventilation standards and industry practice. The metrics will include health-based assessments using the contaminants of concern as well as moisture and odor to address occupant perception and acceptability.

The metrics need to focus on being a method of test: a way to obtain a score, rather than setting a standard for performance, or a minimum level of performance as these will be set by building codes and/or performance standards. Without the new metrics, codes and standard bodies will not be able to act on many significant IAQ-related building industry changes. There are a couple of recent and developing changes related to IAQ that require new metrics. The first change is the development of smart ventilation strategies and controls that attempt to meet IAQ targets with varying ventilation rates. These smart ventilation strategies employ energy saving strategies that move ventilation around in time to avoid times of higher energy requirements to condition the air, accounting for operation of all mechanical air flow systems in a home—not just the whole dwelling ventilation system—pollutants in outdoor air (such as high ozone or particle levels), and deliberate pollutant removal (such as particle filtration systems). The second change is the emergence of pollutant sensing technologies that will allow specific contaminants to be targeted.

Current Metrics used in Implementation

Checklists, Guidelines, and Protocols

Several checklists are currently available for addressing features of homes that may contribute to indoor air quality (IAQ). Many of these lists focus on reducing emissions of contaminants into homes, primarily from building materials, that use third-party assessments of emission rates. The following is a non-comprehensive list of such checklists:

- Scientific Certification Systems
- Green Guard
- Green Seal
- Carpet and Rug Institute
- Collaborative for High Performance Schools products database
- Pharos database
- Cradle-to-Cradle
- GreenScreen assessed
- Living Product Challenge

More detailed guidelines and protocols are also available for new and existing homes. For example the American Lung Association provides the Health House Builders Guidelines that contains detailed protocols for building new homes, which include inspecting the site location, foundation, framing, ventilation system, and finishes and furnishings. The EPA's IndoorAirPLUS program, also for new construction, includes specifications for addressing moisture and radon control, pest control, combustion appliance inspections, as well as using low-emitting materials. Like the Health House Builders Guidelines and Indoor AirPLUS, the WELL certification program includes many aspects of healthy buildings beyond air quality. However, WELL primarily focuses on non-residential applications and includes aspects beyond IAQ such as lighting, comfort, and mental health. The LEED for Homes Indoor Air Quality Assessment includes two approaches for establishing better IAQ. The first approach does not have IAQ metrics, instead the building is flushed prior to occupancy. The second approach allows for one-time air sampling and measured levels of contaminants must be below tabulated levels. Listed contaminants include PM2.5, PM10, ozone, CO, TVOC and a targeted VOCs.

For existing homes, EPA's Healthy Indoor Environment Protocols for Home Energy Upgrades provide guidance and references to resources on improving or maintaining indoor air quality and indoor environments during home energy upgrades, retrofits, or remodeling. Healthy Indoor Environment Protocols for Home Energy Upgrades provides assessments and actions for controlling harmful contaminants (e.g. Asbestos, combustion emissions, environmental tobacco smoke, lead, ozone, radon, polychlorinated biphenyls), moisture, pests, building materials, and ventilation.

Although these checklists, guidelines, and protocols provide valuable guidance for assessing IAQ, none provide methods for easily comparing new and existing homes, strategically targeting IAQ issues, or performing more detailed evaluations for mitigating risk while optimizing smart ventilation for energy savings.

Mechanical Control Systems

CO_2 as an IAQ metric: Demand Controlled Ventilation (DCV)

DCV systems have been used for many years in commercial HVAC systems for controlling comfort and air quality associated with occupancy. For these systems, measured CO_2 is used as an indicator of occupancy and, quantitatively, of human bioeffluents. When the measured CO_2 exceeds a set threshold, the system circulates air to control comfort and odor-related issues in the building. Although this method is effective for high-occupancy commercial buildings, the use of CO_2 levels as a metric representing occupancy (and bioeffluent emissions) is less applicable to residential applications for the following reasons:

1. Occupant densities are much lower and the available CO_2 signal is much harder to discern from background concentrations. This makes CO_2 much harder to use as an occupancy indicator and a control parameter for operating the ventilation system.
2. Due to the proportionally lower source strengths, there can also be considerable delays between initiation of occupancy and CO_2 levels reaching the control limit for operation of ventilation system.
3. Lower occupancy densities and a larger range of activities mean that occupants are no longer the primary source of pollutants (and thus CO_2 is a less meaningful indicator) that we want to control. A primary example of this is the emissions from building products and materials.
4. The nature and degree of air mixing can be quite different in residential buildings.

Despite these drawbacks, CO_2 concentrations have been used as a ventilation evaluation metric in some European building energy codes, often in conjunction with relative humidity (RH). The metrics differ in detail from country to country but have the general form that limits the concentration and exposure time of CO_2 and/or RH. For example, French regulations use a limit of hourly average CO_2 concentrations of 2000 ppm. Each hour above this limit is weighted by the CO_2 concentration for that hour. These products are summed for the year and cannot exceed 400,000 ppm-h (see Equation 1). For RH the limit is set at an hourly average of 75%, and the number of allowable hours above this limit is set at 600 hours in kitchens, 1000 hours in bathrooms and 100 hours in other rooms (see Equation 2). Both these requirements must be met. Note that the RH regulation is a multi-zone metric because it sets different levels for different rooms. Further details for European DCV metrics can be found in the literature review performed by Guyot *et al.*[1].

$$E_{2000} = \sum_{t=0}^{T} C_{CO_2>2000}(t) * t < 400\,000\ ppm.h \quad \textbf{(1)}$$

where: C_{CO2} is CO_2 concentration (ppm),

t is time (hours)

E_{2000} is the CO_2 exposure indicator

$$T_{RH>75\%} = \sum_{t=0}^{T} t < 600\ h\ in\ kitchen, 1000\ h\ in\ bathrooms, 100\ h\ in\ other\ rooms \quad \textbf{(2)}$$

where: T_{RH} is the RH exposure indicator

Equivalent Ventilation

Equivalent ventilation is a key metric for evaluating different ventilation approaches. The central idea behind this technique is that there is a baseline ventilation strategy that can be used as a basis for comparison and that any other ventilation approach should result in the same, or lower, exposure to pollutants. Hence, it would be "equivalent". The only current implementation of this approach is in ASHRAE Standard 62.2-2016. The methods therein were developed by LBNL[2] based on some of the assumptions integral to the ASHRAE Standard, i.e., that the pollutants can be represented by a generic contaminant emitted at a constant rate. The continuous ventilation rate from the ASHRAE standard can then be used as a basis of comparison with time-varying ventilation rates. An equivalent ventilation system is one that produces the same (or lower) exposure to this generic contaminant averaged over a year.

This basic approach only applies (as most residential ventilation requirements) to chronic exposures. However, the calculation procedure has been adapted to limit peak contaminant levels and avoid acute exposures. This is particularly useful for ventilation control strategies that are occupancy-based and the equivalency principle can be adapted such that it is evaluated only during times of occupancy. This equivalency approach can also be used with time-varying emission rates, e.g., a reduced emission rate can be stipulated during unoccupied times, and studies are underway to investigate this approach. Although this equivalency metric is for

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[1] Guyot, G., Walker, I.S., Sherman, M.H. and Clark, j. D. 2017. Residential Smart Ventilation: A Review. LBNL Report (in press).

[2] Walker, I., Sherman, M., Dickerhoff, D., 2011. Development of a Residential Integrated Ventilation Controller (No. LBNL-5401E). Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US)

Sherman, M.H., Walker, I.S., Logue, J.M., 2012. Equivalence in Ventilation and Indoor Air Quality. HVACR Res. 18, 760–773. doi:10.1080/10789669.2012.667038 ventilation rather than IAQ directly, the principles and adaptations discussed here will also be useful for direct IAQ metrics.

This equivalency metric has been used by LBNL in the development of the RIVEC controller that allows for time-varying ventilation rates to:

- shift ventilation to times of lower indoor-outdoor temperature difference (or humidity difference)
- account for operation of kitchen, bath and clothes dryer and economizer fans
- pre-calculate required fan sizes and temperature cutoffs for outdoor temperature-controlled ventilation
- ventilate less during unoccupied times
- pre-ventilate for pre-cooling energy conservation and peak demand reduction
- include the use of passive ventilation systems
- avoid exposure to acute pollutant levels

IEA-EBC Annex 68

The International Energy Agency (IEA) established an Implementing Agreement on Energy in Buildings and Communities (EBC) in order to undertake research and provide an international focus for building energy efficiency. The purpose of Annex 68 is to provide a scientific basis for the design and operational strategies of low-energy residential buildings, while maintaining high IAQ standards by controlling sources, sinks and flows of heat, air, moisture, and pollutants when buildings are occupied. Additionally, Annex 68 aims to collect and provide data about properties for transport, retention and emission of chemical substances in new and recycled building materials under the influence of heat and moisture transfer.

Annex 68 will provide data and tools that can be used to guide the operation of buildings that are energy efficient and ensure very good indoor environmental conditions for human occupancy, the project will develop the following:

- Definitions of IAQ performance metrics
- Mechanistic emission source and sink models to estimate pollution loads under realistic environmental conditions
- A database of material storage and transport properties, as well as pollution loads in existing buildings
- A modeling framework and design tool for integrated and coordinated design of low-energy and high-IAQ buildings
- A guidebook on operational strategies for optimal energy performance and good IAQ in residential buildings
- A report presenting and analyzing residential green buildings that achieve optimal energy and IAQ conditions under various climatic situations
- Recommendations for regulatory authorities and guidelines for occupants and building operators

A report for defining IAQ performance metrics for low-energy residential buildings (Subtask 1 of Annex 68) is currently under review. The purpose of this report is to define target pollutants in low-energy residential buildings and identify metrics required to evaluate IAQ and its relation to energy consumption. Specifically, this report compiles published indoor air pollution data in residential buildings from several countries (Australia, Belgium, China, France, Japan and USA). This information was used to compare pollutant concentrations from residential buildings that qualify as low-energy with residential buildings that do not qualify as low-energy. The document also identifies target pollutants that negatively affect indoor air, compiles corresponding pollutant Exposure Limit Values (ELV) associated with the pollutants, identifies IAQ indices developed previously, and defines metrics for achieving very good indoor environmental conditions while maintaining low energy consumption.

Generally, Annex 68 Subtask 1 concludes from published indoor air pollution data that the average pollutant concentrations in qualified low-energy buildings are lower than non-low-energy buildings, with the exception of, ɑ-pinene, hexanal, styrene, trichloroethylene, and dodecane (and note that the ranges largely overlap for the two housing types for these exceptions). The maximum (peak) pollutant concentrations in low-energy buildings are lower than measured in the current building stock, except for styrene, ɑ-pinene dodecane, and hexanal.

Based on the above results, sixteen target pollutants were selected as potential short-term and long-term exposure risks in low-energy residential buildings: acetaldehyde, acrolein, ɑ-pinene, benzene, carbon dioxide, formaldehyde, naphthalene, nitrogen dioxide, PM10, PM2.5, radon, styrene, toluene, trichloroethylene, TVOC, and mold.

Recommended IAQ Metrics

Two methods are recommended for incorporation into an IAQ metric to assess the health risk of these sixteen pollutants. The first method compares measured exposure concentrations to existing exposure standards or Exposure Limit Values (ELVs). ELVs correspond to concentration thresholds above which exposure presents a potential health concern. ELVs are often based on Toxicity Reference Values (TRVs) and Guideline Values for Indoor Air (IAGV). TRVs are based on animal experiments and applying a safety factor of at least 100, while IAGVs are determined from epidemiological studies examining correlation between health symptoms observed in a population of individuals exposed to the compound indoors. Although ELVs can easily be communicated to building contractors, the combined effects of multiple pollutants is currently unknown and averaging or multiplying risks can lead to further uncertainty.

The second recommended method is evaluating the direct health impacts of the pollution through the estimation of Disability-Adjusted Life Years (DALYs) lost. Details for this method are described in Logue *et al.* (2012). The major advantage of using DALYs over ELVs is that individual pollutants can be summed to estimate a combined effect of exposure. However, this approach is easier to communicate to policy and decision makers than building contractors or building occupants.

Although the Subtask 1 report for Annex 68 presents several ideas for developing an IAQ metric, the methods and data analysis specifically focus on low-energy buildings. Because some of the IAQ hazards and metrics identified may not be equally applicable across the current housing stock. For example, air tight low-energy buildings include design elements that can eliminate hazards, such as using conditioned crawlspaces that are air and ground sealed thus reducing the possibilities for moisture and mold problems. For this reason, further evaluation and expansion of the proposed methods is needed for developing a more universal IAQ metric that easily compares residential buildings, regardless of energy efficiency.

Development of new metrics

Due to the limitations described in the previous sections, new metrics are required for comparing IAQ in residential buildings across the range of existing housing stock. These new metrics must be applicable to the entire housing stock, which includes new and old homes of varying energy efficiency, and enable the use and valuation of new technologies and ventilation approaches. The metrics must also be expanded beyond a simple airflow requirement or DCV systems. Additionally, the metrics must focus only on IAQ and exclude cost or energy criteria for the following reasons:

- The cost and energy use of individual measures is highly variable and selecting a fixed cost would be very misleading in most circumstances.
- It is better to allow builders/contractors and other users to determine if their specific costs are worthwhile in terms of IAQ metric improvement.
- Cost (and energy use to a potentially lesser extent if it can be modeled) cannot be determined for emerging technologies that have yet to develop a track record.
- The cost of various measures varies in time – as new technologies are adopted and increase in number their costs can be reduced substantially and these changes would be very difficult to incorporate.
- Cost and energy vary significantly in time and location and it would be impractical to track this and constantly be updating the metric. This also leads to ratings given to the given features changing with time and location, which would result in confusing and inconsistent ratings.
- Building occupants (or others in the marketplace, e.g., property appraisers) may also place value on other potential benefits such as comfort, and this could change rankings compared to those that are determined by considering only by energy costs.

The marketplace needs metrics that assess health, moisture, and odor. If all of these are not addressed a metric is likely to be less acceptable to the building industry. If a health-only metric is used then a home may receive a good rating under that metric but still have moisture or odor problems that would be unacceptable to occupants and the metric will be seen as having little value and/or as being an unreliable indictor for IAQ. Therefore it is likely that even if a single metric were emphasized when evaluating a home, it would be a good idea to have several individual sub-metrics such as for health, moisture and odor. Without the new metrics, code and standard bodies will not be able to act on many significant IAQ-related building industry changes, such as: IAQ valuation of smart ventilation systems, reduced material emissions, improved air filtration, accounting for outdoor pollutants.

Because IAQ is of great value to homeowners, builders, and energy auditors, and code and standard bodies, we will develop new metrics that focus on managing IAQ to reducing the risk of degraded IAQ. The metrics will focus on identifying features and characteristics of the home that both increase and decrease risks of poor IAQ. This "asset rating" approach (discussed in more detail below) is strongly supported by the key constituents of builders (based on feedback from discussions at home performance conferences such as RESNET, EEBA and HPC), DOE's Home Energy Score program, and appraisers (see Annex A). Broader concerns associated with Indoor Environmental Quality (IEQ), such as lighting and comfort may be noted, but will not be addressed by these new metrics.

To appropriately manage real and perceived IAQ, the metrics will include health-based assessments using the contaminants of concern as well as moisture and odor to address occupant perception and acceptability. The outcome from these metrics will be a score, rather than a standard for performance or a minimum level of performance. This will allow flexibility for building codes and performance standards to set minimum performance targets.

In the following sections, we provide potential methods for developing new IAQ metrics that address health, moisture, and odor. The methods are designed for IAQ risk reduction and expand beyond current checklists, guidelines, and protocols. These metrics will also allow the user to compare health, moisture, and odor concerns across the residential building stock (including new and existing homes).

Key Aspects of IAQ

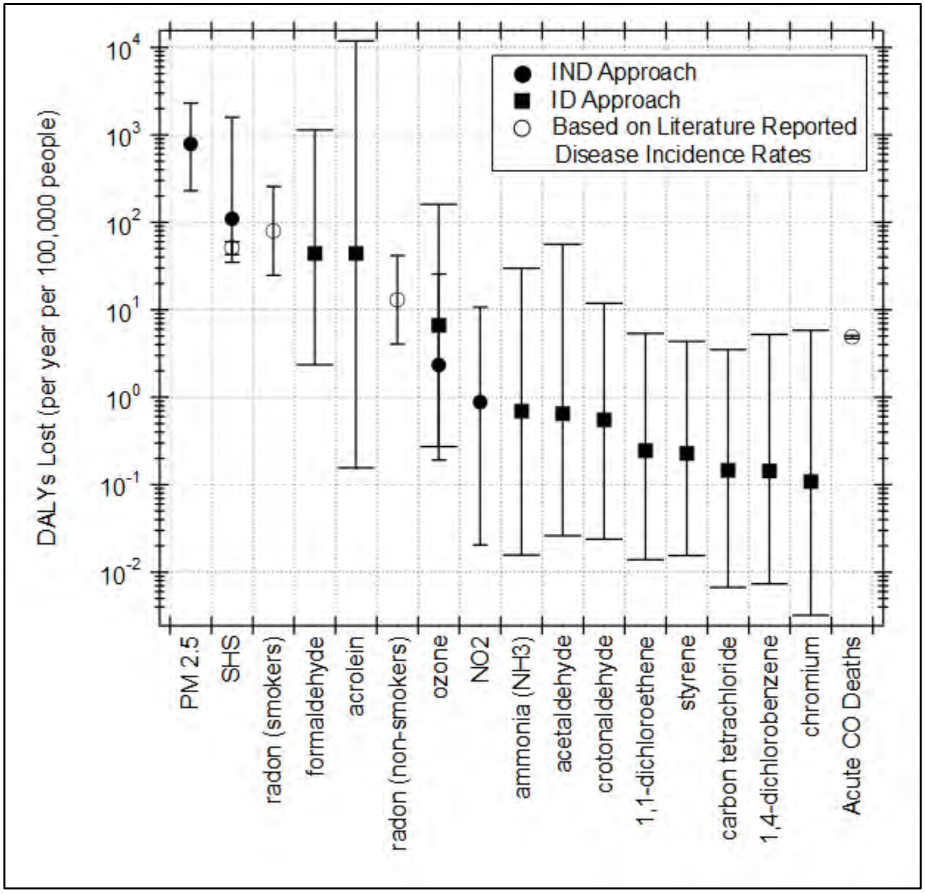
Health

The IAQ Health Metric should focus on identifying home features and characteristics that cause contamination or may help to manage IAQ, and on evaluating the chronic hazards associated with contaminants. Standard metrics such as ELVs and DALYs could be used as quantitative tools for quantifying the potential harm of pollutant intake.

For example, previous studies (Logue et al. 2012) investigated health impacts to prioritize pollutants. Logue et al. (2012) used DALYs to identify the most important pollutants in homes. The results, shown in Figure A-1, indicate that PM2.5, NO_2, Formaldehyde, acrolein, ozone, radon, and secondhand smoke are the highest-risk pollutants. Based on these results, the metrics could suggest the use of low-formaldehyde building products or a good range hood to remove particles from cooking. Pollutants associated with the behavior of occupants, such as smoking, will not be considered by the metric. However, tobacco contaminated materials will be considered, as they are now a part of the asset.

Acute health issues (such as CO poisoning) are beyond the scope of this metric, as they are rare, difficult to predict, and sometimes the result of occupant behavior as opposed to inherent characteristics of the building. However, chronic conditions caused by acute exposure such as allergies or asthma will be included. Also, there may be some ways to include acute issues in metrics. For example, a home ventilation system with a high flow "boost" mode might be able to respond to extreme heat, moisture, and bioeffluents in a tight energy efficient home during times of high occupancy (e.g., birthday parties). The inclusion of some aspect of this flexibility to deal with extreme events would be very useful in an IAQ metric.

Figure A-1: DALYs Lost from exposure to different pollutants taken from Logue et al. 2012.



Moisture

Health hazards associated with moisture (specifically excessive moisture as a substrate with a food source for microorganisms and mold potential) are well established. However, it is difficult to predict how much (quantitatively) home features increase or decrease the risk of mold growth. Additionally, the risk of moisture and mold through certain asset deficiencies or conditions is not clearly quantified. For example, having high relative humidity may lead to moisture and mold issues, but the threshold may vary greatly between homes. Therefore, the IAQ Moisture Metric will focus on addressing features that are known to increase moisture, such as the following:

- **Water leaks** – either from interior plumbing or exterior foundation or rainwater. These are basic construction integrity issues and are the source of many indoor humidity problems. Their solution is more likely in the remedy of the building envelope of plumbing issue rather than through systems that dehumidify indoor air.
- **Air humidity** – including outdoor air and operation of humidifiers and dehumidifiers. The latter includes latent moisture removal by cooling equipment.
- **Interior sources** – there are usually three main indoor sources of moisture: cooking, bathing, and human respiration.

Often a home will have exhaust fans to remove cooking and bathing moisture, but human respiration (and perspiration) moisture is removed by general household ventilation or the operation of dehumidification systems. For comfort and perceived IAQ, the metric will include humidification during the winter in cold dry climates. Although the IAQ metrics will not address all aspects of comfort (such as radiant thermal issues or drafts), comfort associated with IAQ will be included.

Odor

Odor, as well as moisture, is commonly associated with perceived IAQ. Presently, data and quantitative methods for evaluating odor in residential buildings are not readily available because individual human odor response is highly variable. Some guidance for addressing odor are available for commercial buildings, specifically related to ventilation and airflow requirements based on human and environmental bioeffluents, and could be extrapolated to develop an IAQ Odor Metric for residential buildings.

Historically, odor was often the basis for setting ventilation air-flow requirements – based on human and environmental bioeffluents. Additionally, because odor is classically dealt with by dilution using uncontaminated (or less contaminated) air or source reduction, there may be opportunities to use technologies such as carbon filtration (that can also be used for VOC control) to control odor rather then only using dilution. Other considerations for developing an IAQ odor metric are addressing activities such as cooking or other fragrant hobbies, and pets. Because odor is linked to perceived IAQ by many homeowners, addressing these concerns and quantifying the results is of utmost importance. One approach for synthesizing the risk, benefits, and occurrences of odor and odor related activities are through expert elicitation.

Desirable Characteristics of New Metrics

Asset rating

The focus of these new metrics is on an asset rating rather than an in-use rating because we want to evaluate the dwelling and not its occupants. This allows consistent use between new and existing construction and is a better measure for future occupants to assess the IAQ they would experience. It also makes the metrics more robust in that the same house will receive the same rating independent of its occupants and that the rating is not dependent on day-to-day activities of the occupants that could lead to inconsistent ratings (i.e., the same house on different days would get different ratings).

Outdoor Air Valuation

New metrics may consider the impact of outdoor air conditions. Some pollutants, such as particles, NO_2 and ozone, have outdoor air as a primary source. In which case moving more air from outside to inside without paying attention to filtering may lead to worsened IAQ. These pollutants tend to be location- and climate-specific (as does another key pollutant: radon) In some cases they are also seasonal, e.g., in areas of the US with chronic summertime wildfire seasons and the associated degradation of outdoor air quality. Any new metric should attempt to account for outdoor air quality.

Identifying target audiences

The metrics will be designed so that they can be created and used by building industry professionals, including energy raters and home inspectors. Because they will be broadly useable by the building industry and likely encountered by home occupants or prospective buyers and intermediaries involved in the sale and purchase of homes, the final result must be easy to understand for non-professionals – a single numerical score would be preferable. Discussions with builders have indicated that they like the ideas of a numerical score. This allows users to compare different homes in marketing strategies, get credit for a home with better IAQ, and to assess how best to invest in home upgrades (this is analogous to the $/point exercise they currently use for home energy ratings).

A key audience for IAQ metrics for existing homes will be home appraisers. Once the value of good IAQ is included in a home appraisal it will be easier for the IAQ industry to get homeowners to act and move away from only addressing acute issues, thereby drawing attention to chronic health and other IAQ issues. Appraisers report specific interest in IAQ related issues such as: tobacco odors, pet odors, and signs of moisture damage, etc. Therefore it will be important to include these in IAQ metrics for evaluating existing homes. Appraisers also report that it would be easier to discuss and value IAQ in homes if there were a rating system.

Annex A discusses more of the issues surrounding IAQ assessment by home appraisers. This includes appropriate language to use when engaging with the appraisal industry that should be borne in mind when discussing the choice of metrics, and that any metric must be very robust so that it is credible and reliable.

Multizone Approaches

As new homes become tighter and high-efficiency heating and cooling systems move away from central forced air, homes are becoming more zonal in terms of their airflow and thermal loads. It is becoming increasingly popular to use zoned systems to condition energy efficient homes – in particular mini-split heat pumps. New homes are also getting tighter with a resulting reduction in natural infiltration airflows. This results in less air mixing inside homes and presents an opportunity to remove pollutants from the rooms where they are generated that can use less airflow compared to whole-house dilution approaches. One example would be bedroom ventilation at night – where an isolated bedroom with a closed door can be ventilated to control for odors, moisture and bioeffluents, enabling lower rates of ventilation in the rest of the home. Current metrics tend to view the house a single well-mixed zone and new metrics are required to address these zonal issues. For example, one could imagine a metric for IAQ that is applied to individual zones of a home and combined to produce a single metric for the home. This would help guide requirements for zonal approaches to ventilation. Another approach (as discussed above in the example of French regulation) is to produce metrics for multiple rooms, all of which must be considered individually. Lastly, the approaches summarized in the Annex 68 work attempt to combine sub-metrics in different ways that account for dominant metrics.

Some ventilation standards in Europe and Canada have an implied zonal approach in which they require specific airflows to individual rooms (often accomplished with a ducted balanced/HRV system). A metric that allowed the assessment of this approach compared to the single zone approach could be valuable if US (and California) ventilation standards were to use a zonal approach.

A zonal metric would also enable technology development where pollutants known to be common to specific home locations (particles in kitchens, moisture in bathrooms, etc.) could be managed in those locations, or providing pollutant control in occupied rooms. An example of this might be a particle filtration system in a kitchen or a dehumidifier in a bathroom or bedroom.

The multi-zone simulations for this project could be used to inform the potential development of zonal metrics.

Ease of use

A consistent message we have heard from builders, designers, trainers, code officials, standards writers, code bodies, equipment manufacturers, appraisers, and home raters is that any metrics that are developed need to be easy to use. Approaches that require expensive expert and a time consuming research level testing and evaluation of a home will not be successful. At the same time, metrics must have sufficient quality, predictive power, reproducibility, and robustness that they can be relied upon by the buildings industry and potential users to provide good guidance. This is clearly a balancing act, and the primary issue is one of the ease with which a metric can be used rather than its inherent calculation complexity. The underlying calculations can be hidden inside automated software, but any user-facing checklists, field measurements or design considerations need to rely on easy to obtain information (for a building professional). Therefore, the development of metrics will not consider, for example, requirements to monitor individual pollutants for extended periods of time, as we would do for a research project. Instead the focus will be on checklists, observations about a home and some simple field diagnostics, most of which are already conducted in high-performance homes. Examples of field testing include envelope and duct leakage, ventilation system airflows, combustion appliance flue venting assessments, etc. The typical target audience for those who will use the metrics will be some one like a home energy rater, IAQ consultant or HVAC contractor.

IAQ Score – An Example Metric

One metric that we will investigate in this study is the idea of a home IAQ Score that is also being developed by LBNL for the US DOE Building America Program. Home energy scores have provided an important tool in the market place for assessing a buildings energy performance. Energy scores have allowed the market to place a value on energy efficiency and have allowed home buyers to identify homes that will have lower utility bills and less of an environmental impact. A similar tool for IAQ would allow homeowners to identify homes that have a lower health/irritant impact. An IAQ score would also provide a driver for homebuilders to design healthier homes since an IAQ score would likely have a market value and application in real estate transactions.

The overarching goal of the IAQ score is to create an asset-rating tool for a home with respect to its indoor air quality. As an *asset* rating it will necessarily assume certain baseline conditions, such as occupant behavior, and thus does not predict the actual IAQ of the actual home. The development of the IAQ score for homes is being supported by the US DOE Building America program.

The Score has a scale similar to that for a HERS Score, where a score of zero is a very healthy home with an extremely low potential for IAQ issues and a core of 100 would be a typical current home with little or no addressing of IAQ issues. It will be possible to have a score greater than 100 for a home with many serious IAQ hazards and insufficient mitigation.

How to create a numerical score

To create a numerical score, the individual IAQ hazards and mitigation strategies for a home are identified. The various hazards add to the score and the mitigation strategies subtract from the score.

Different hazards have different IAQ impacts and are given numerical values reflecting these differences. These can be summed to give a total hazard score for the home if there are no mitigation strategies in place.

Mitigation strategies impact the score in several ways. Firstly they are evaluated for their potential effectiveness for on each hazard – i.e., what is the risk reduction if the mitigation strategy is implemented as intended. Few mitigation strategies will affect all hazards in a home. For example, a kitchen range hood has a strong impact on cooking-related contaminants, but much less impact on formaldehyde from building contents. They are then assessed for their effectiveness. For example, a exhaust fan whose air flow is verified will be more effective than one that is not, or an automated range hood that does not require the occupant to operate it would be more effective than a manually operated hood. There will be negative and positive adjustments to the score for other aspects of mitigation strategies:

- Usability: How easy and intuitive is it to use or implement the measure?
- Durability: Is the measure likely to retain its utility and performance over time?
- Robustness: How commonly does the system work when implemented as intended?
- Maintenance: How much effort is required to maintain the measure?

This way, no measurements or diagnostics are require to obtain a score for a home, but homes that do have confirmed performance will get a better score.

There will be limits on mitigation for some hazards. Once mitigation strategies have completely addressed a hazard, additional mitigation will not further reduce the score. For example, if the subject home has an excellent range hood that removes all cooking-related contaminants, then other mitigation strategies that would affect these contaminants (such as an air filtration systems) will not influence the score.

Next Steps

This guidance and summary of IAQ valuation approaches will be used to develop metrics for the analysis of IAQ simulations that will investigate ventilation and IAQ approaches for high-performance California homes. This information will also be used in the development of an IAQ Score in collaboration with the US DOE Building America program.

Annex A. Perspectives from the Home Appraisal Industry

This appendix begins with some context about appraisers, their methodologies, and the history of efforts to bring green and high-performance considerations into the residential valuation process. Key barriers and challenges are noted, along with recommendations for how they might be addressed in the context of efforts to promote LBNL's IAQ Score. Feedback from real-world appraisers on the IAQ score concept is provided. Appraisers from California, Colorado, Florida, and Kentucky were interviewed to gain perspective on how the industry views IAQ and how they might receive an IAQ score.

History and disposition of the industry

While efforts to quantify incremental property values conferred by high-performance features go back at least to the early 1980s, the vast majority of activity has taken place within the past five years. There have been scores of studies and an array of disjointed policy efforts to engage and compel the appraisal industry to consider building performance in their valuations. A detailed history of activities is given in Mills (2016). Federal agencies and others in the "high-performance homes" community have had little to show for all these years of work, largely due to lack of understanding of the appraisal practice as well as market and business conventions and constraints.

Many players have engaged in efforts to promote improved property valuation practices regarding green and high-performance features. These include the Appraisal Foundation, The Appraisal Institute, Colorado Energy Office, Earth Advantage, EcoBroker, Elevate Energy, Fannie Mae, Federal Housing Administration, Home Innovation Research Labs, The Institute for Market Transformation, Northwest Energy Efficiency Alliance, National Association of Homebuilders, National Association of State Energy Officials, National Association of Appraisers, RESNET, USEPA, USDOE and some of its National Laboratories, the U.S. Green Buildings Council, and the Vermont Green Homes Alliance. Many activities have resulted, ranging from trainings, to data-gathering instruments, and the emergence of a literature attempting (largely through Hedonic Pricing techniques) to statistically isolate the effects of green/high-performance characteristics on home values. In some cases, the results of studies have been analytically flawed, overgeneralized, and oversold.

Leading efforts to date have focused largely on energy, and to a lesser degree water and other "green" factors such as building materials. Little to no effort has been spent on indoor air quality, primarily due to lack of interest on the part of homebuyers (as perceived by appraisers), and, to a lesser degree, due to difficulty in quantification. The proposed IAQ Score will help with the latter and, perhaps, over time, with the former.

Worthy of consideration, the U.S. appraisal industry is in the doldrums. In part a reflection of the evolving economic and regulatory environment faced by appraisers, the demographics of the trade (residential and non-residential) show a shrinking and aging workforce with fewer new appraisers entering the field. Nearly two-thirds of appraisers are over 50 years old, with 80% having a bachelor's degree or less education. Median salaries are under $53,000 per year. As of mid-2015, there were 78,500 active real estate appraisers across the U.S., about three-quarters of which were men. The actual number has fallen by about 8,000 from the year 2011, or at the rate of 3% per year. The advent of Appraisal Management Corporation (AMC) clearinghouses has cut the fees received by appraisers by up to 50%, leading to a less skilled and motivated workforce. Approximately 80% of appraisers report dropping fees in 2015. Two thirds of these are sole proprietors. Only 4% of appraisers exclusively practice commercial appraising, 80% exclusively residential, and 15% both. Only 22% of appraisers are optimistic about the future of their profession. Two-thirds of appraisers do not belong to any trade association. Trade association membership is very fragmented, the top three being the Appraisal Institute, with membership representing about 43% of the those being members of any association, followed by State Coalitions (~25%), NAR (~20%), and NAIFA (~15%). These industry dynamics complicate outreach efforts.

How Appraisers See their Role

Traditional appraisers see their job as one of gathering property information on factors that are important to buyers (e.g., granite countertops and swimming pools) and translate that into an estimate of market value. Other use cases apply, e.g., for insurance appraisers who are focused strictly on the replacement cost of structures.

Most do not see their role as driving buyers to assign more value to specific factors or to consider new factors not currently on their radar. However, there is a strata of appraisers in the industry eager to educate their customers and who see their role more clearly reflect social responsibility and environmental values.

In the real world, there are of course influential drivers that are not property-specific (e.g. panic buying in hot markets, proximity to good schools, etc.). These tend to swamp considerations of building performance.

Appraisal Methodologies

Appraisers (both residential and non-residential) utilize three well-established methods of valuation, often used in tandem or in combination.

> The Cashflow method entails defining value as a multiple of income and expenses. While typically used only for non-residential "income" properties, it has been applied to assessing the incremental value of energy features in homes.   This does not appear to be relevant for IAQ issues.
>
> The Comparable Sales method requires finding "like" homes that have been recently sold and analyzing those outcomes, with adjustments up or down for differences in the subject property. Lacking IAQ data or scores that can be correlated with large numbers of home sales, makes this approach largely a

non-starter in the near to medium term. Perhaps once there are large numbers of homes receiving IAQ scores and, if those data are publicly disclosed, sales data can be correlated with scores. Isolating the IAQ signal from all the other noise in the marketplace will be a major challenge. There is no sign of this happening any time soon, even with energy use, although efforts like the "Green MLS" are trying to do so. That said, the IAQ ratings and associated documentation can be valuable to appraisers via the "Cost Basis" method long before it is affecting the broader market in measureable ways.

The Cost Basis method sets value equal to cost, with adjustments. It can be applied to incremental improvements to a property, although potentially de-rating investments in particular new features if the appraiser deems that the market will not fully value the feature (e.g., maybe a $5k granite countertop project is only worth $3k to prospective buyers). Cost-basis appraisals must also consider changes in codes since the structure was built. This method is perhaps the most promising angle for IAQ if the costs of remediation can be identified and incorporated into the sales transaction/negotiation process. Appraisers interviewed for this study said that remediation costs for an "as-is" property can readily be subtracted from the preliminary valuation. Alternatively, the value can be given "as-repaired", with the idea that sellers and buyers negotiate a credit in the case where a seller will correct the deficiency prior to sale. Where "comps" values are available, they can be adjusted based on information regarding deficiencies. By analogy, existing pest and structural reports generate familiar "cost-to-cure" lists that appraisers (and buyers) readily use in tuning their valuations. In some markets, the need for radon mitigation is a familiar instance of such costs. While initial scoring methods would not provide information on costs to correct deficiencies, other entities could do so. One appraiser suggested that training home inspectors (who are already in the building) to estimate these costs may be one way to achieve this.

The appraisal industry is not at all amenable to adding new high-level valuation "Methods" to their practices. Proposals from the buildings performance community need to fit into the existing three approaches in order to get any sort of traction. In practice this should not be an issue—the current methods are readily extensible for application IAQ considerations—but it is important to know that appraisers are sensitive to external proposals for changes in their tried-and-true methodologies.

Aside from the actual valuation methods, appraisals also serve an important role in assembling qualitative and quantitative documentation. This is where IAQ information could most readily make its mark.

Early examples of IAQ being recognized by appraisers

Over the course of a 5-year Memorandum of Understanding, the U.S. Department of Energy has collaborated with The Appraisal Foundation (TAF) to produce several reports. The first defines "competency" as it pertains to appraisers' ability to incorporate green and high-performance building considerations into their valuation assignments (Black *et al.,* 2015). This document references IAQ a number of times and points to various resources. A subsequent document in the series (Curry *et al.,* 2016) focuses on specific applications in residential settings. This document goes into slightly more detail on IAQ--including examples of issues to be on the lookout for and types of tests and reports to look for—and refers to the Information Atlas for appraisers (created by LBNL) for more information.[3]

In 2013, the Appraisal Institute (a 'competitor' of TAF) created a 5-page "Residential Green and Energy-Efficient Addendum," intended to be a template for assembling key information for attachment to a standard appraisal. The focus is primarily on energy. The addendum includes a single scant row for information in IAQ, with a set of three eclectic checkboxes for whether Indoor Air PLUS was applied, ERV or whole-building ventilation system, and/or Non-toxic Pest Control. There are no official statistics on how many appraisals are including this addendum, but indications are that the number is small and that appraisers have great difficulty finding the information asked for as well as justifying the effort/cost to do so. There is no specific crosswalk for using this information in the valuation process, with the implication that it is intended primarily as background contextual information. It could prove far more effective for the Addendum to simply reference the results of the score described here.

The 308-page tome entitled "Value Beyond Cost Savings: How to Underwrite Sustainable Properties" (Muldavin 2010) is often cited as a definitive report for appraisers, but has only passing references to IAQ (mostly pertaining to non-residential settings), and offers no practical techniques for appraisers. The report cites LBNL's IAQ Scientific Findings Resource Bank as "the best, and most scientifically sound summary of the potential health benefits of sustainable properties".[4]

A series of hands-on appraisals of Colorado homes with a range of green and energy-efficient features provides useful examples of how IAQ can be approached in practice (Desmarais *et al.,* 2015).

Challenges and Recommendations

In recent work for DOE (Mills 2015), we identified a high-level set of barriers to the incorporation of IAQ and other home performance considerations into residential valuations, along with recommendations. The following discussion includes observations on how these considerations might apply in the case of the proposed IAQ score.

Highly limited awareness and interest; sometimes aversion

Issue: The IAQ issue is hardly on the radar of appraisers, and they do not generally perceive homebuyers as caring about it. One very seasoned appraiser

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[3] https://sites.google.com/site/appraisinghpbuildings/key-topics/indoor-environmental-quality

[4] http://eetd.lbl.gov/ied/sfrb

stated that “I have actually never had a Realtor, a builder, a developer, a buyer, or a seller express any concern to me about valuing the indoor air quality of a property.” In the case of refinance appraisals, owners can be defensive about appraisal notations on mold, odor, etc. The situation will of course vary significantly by geography and local market conditions. For example, a Kentucky-based appraiser interviewed said there is nearly zero awareness of or interest in “green” in the local market, while those interviewed in Colorado noted high interest.

Recommendations: While “IAQ” may not be a familiar concept to appraisers, many, in practice, actually do observe relevant factors in a home (tobacco odors, pet odors, and signs of moisture damage, etc.). One interviewee mentioned a recently listed home in a very hot market that was well priced but had serious cat odors – 30 prospective buyers passed on the offering because of this. Some appraisers of course operate in areas where radon testing and mitigation are required. In these cases, they are more keenly aware of the need for assessment. One interviewee mentioned homes in proximity to chicken farms and pig feed lots (aka “external obsolescence” in industry parlance). In these cases, comparable sales can be sought for similarly disadvantaged homes or for otherwise similar homes without the problem as a means of identifying the effective impact on value. “Curable” obsolescence can be addressed, e.g., with air filtration systems.

All interviewees said that a scoring system would help back them up in terms of logging these otherwise nebulous and subjective issues. To ensure that appraisers are cognizant of the state of buyer sentiment, information should also be assembled to help characterize public views on IAQ, particularly at the time of home purchasing or refinancing. Per the American Housing Survey there are only a few questions of interest. AHS asked about mold, musty smell, thermal comfort (too hot / too cold), asthma, and general satisfaction. The results are what one might suspect. People who live in newer homes give their homes a higher rating. Older homes have more mold problems and more occupants reporting musty smell. Occupants report more problems with thermal comfort in older homes. Data show quite clearly a higher incidence of asthmatic children in homes that have mold. To be usable by appraisers, such information must have a high level of geographic specificity. Realtors are important ‘trade allies’ in this regard, as they are a key source of information to appraisers.

Competency

Issue: Few appraisers are literate on matters of IAQ research, risk weightings, or mitigation technologies and have correspondingly few, if any, techniques for including IAQ in the valuation process.

Recommendations: It will be important to create appraiser-specific trainings to introduce an IAQ score or score and establish related literacy in IAQ concepts and third-party reports. Appraisers will need to understand this information and be comfortable adopting the findings. As the methods become more widely used, appraisers will need to know how to access the data needed to identify comparable scoreed or scored homes in their region.

Information deficiency

Issue: Appraisers have great difficulty obtaining information about the performance of a subject property. They have precious little time for research beyond the bread-and-butter aspects of their assignments. A numerical score, in and of itself, will not likely be usable in the valuation process although appraisers may still incorporate it in their reports for background.

Recommendations: It will be essential that the IAQ indicators are readily available and understandable to appraisers. Owners are a natural party to convey the information to the appraiser, but it can also come through other channels (realtors, inspectors, lenders, etc). For homes seeking FHA financing, FHA requires that appraisals be disclosed to buyers no later than three days before the purchase contract is signed. This provides an opportunity to expose buyers to IAQ information and recommendations before purchase negotiations are concluded. Until very large numbers of homes have been evaluated, appraisers will not have particular use of the score itself for comparables analyses, but the associated documentation stands to be more useful, particularly if specific deficiencies are identified and, ideally, costed.

Time/budget pressures and process commoditization

Issue: Financial regulations implemented in the wake of the 2008 housing market meltdown resulted in the entry of new “middle-men” into the appraisal process, along with efforts to automate and commoditize the appraisal process. Appraisers’ fees have been cut in about half in the process (appraisers take home maybe $100-$150 per typical appraisal and spend less than an hour at the property), and appraisers’ discretion has also been reduced as the process has become more commoditized.

Recommendations: Transaction costs associated with IAQ score documents must be reduced to an absolute minimum. Entities creating appraisal templates and protocols should be engaged and compelled to recognize the relevance of this information. Financial incentives to help appraisers justify the added time to consider IAQ would no doubt increase their use of the information.

Professional differences between appraisers and building performance professionals

Issue: Few appraisers understand building science, or the associated terminology. Building performance experts, in turn, have limited grasp of the appraisal process or ability to put their points into a language that appraisers will understand and respond to. An example includes the near nil value of properties that are highly obsolete or not appropriate to the location and thus likely to be replaced by future buyers. Conversely, properties that are over-built ("super-adequate" in appraisal jargon) cannot garner additional value through performance enhancements.

Recommendations: The IAQ scores or indices need to utilize plain language. IAQ "experts" brought in to educate appraisers must be sensitized and not leave them in the dust with jargon and science-heavy presentation. These considerations will of course also apply to other target audiences. It would be wise to create a brief "primer" on the methodologies and reports written expressly for appraisers, using their language. Conversely, it behooves the building-performance community to better understand real-world property-valuation considerations and language. For example, the appraisal jargon for IAQ problems is "functional obsolescence" and the corrections would be known as "cures", and this language should be used to help acclimatize appraisers to the otherwise foreign information.

Risk aversion

Issue: Appraisers are cautious about extending the scope of their practices, partly due to aforementioned time/budget pressures, but also due to professional liability considerations and reputational risks such as those that "bit" appraisers when they were taken to task for being part of the housing bubble. As a result, attributing additional value to a property is something they are more cautious about than previously.

Recommendations: The credibility of the score, those applying it, and associated documentation will be key to appraisers' comfort level.

Public policy vacuum

Issue: DOE, EPA, HUD, Fannie Mae, state energy offices, and others thus far had little impact on appraisal practices (Mills 2016). This is largely because efforts have been limited largely to disjointed trainings, workshops, reports, etc., with no long-term strategy or staying power. One key strategy that has not been well explored is efforts to create demand for improved appraisals.

Recommendations: More two-way interaction with the appraisal community is needed, with increased emphasis on listening and adapting existing offerings to meet the needs of these stakeholders. Meanwhile, educating buyers to be asking the right questions is of central importance. Educating lenders, Realtors, home inspectors, and others will also result in better information received by appraisers.

Additional appraiser comments and suggestions regarding implementation

Following are an assortment of ancillary comments made by the appraisers interviewed:

There are already many ratings out there. Yet another 1-10 or 1-100 scale could easily add to confusion. One interviewee suggested denoting rating as “IAQ-1, IAQ-78,” etc. to help reinforce the distinction.

Incorporating outdoor air quality data and consideration would be welcome. It is a known issue but appraisers don't currently have information at their fingertips about it.

Plain-language checklists (e.g., of curable deficiencies) are valuable, even if not quantitatively part of the score computation. Such checklists would, of course, serve multiple constituencies.

Getting scores into the MLS (there is already an extensive “Green MLS” movement) would be a good way to ensure that appraisers can readily find the scores through an information channel with which they are familiar.

Home occupants can sometimes seek to conceal IAQ problems (e.g., by using incense or diffusion sticks). IAQ assessors need to keep an eye out for such diversions.

Appraisers like the idea of considering particularly sensitive populations (allergies, asthma, children). However, they cautioned that having “modified scores or indices” for different groups could easily make the report difficult to absorb. A more elegant solution would be if certain thresholds (e.g. scores 80 and above) can be flagged as thresholds of acceptability for certain sensitive populations.

Stating the date of the assessment is important, along with guidance as to how rapidly circumstances can change in the home. The score should perhaps have an associated “expiration” date.

Appraisers agree on the importance of looking at “asset” vs the “occupancy” characteristics, and are familiar with this notion from energy ratings.

The Appraisal Institute’s Addendum will be revised and there is interest in improving treatment of IAQ. A place for noting the IAQ Score could presumably be added to the report.

Severe hoarding is an important “red-flag” for IAQ problems. One appraiser noted that this often correlates with mold issues, pests, and hidden property damage, etc.

Photographs are a very important part of deficiency documentation. The IAQ score protocols should encourage photo documentation.

Insurance appraisers are also tasked with identifying and communicating observed risks back to the insurers. For IAQ these can involve readily observable issues such as moisture entry/damage, suspicious odors, unvented appliances, etc. Insurers then stand to become engaged in driving the remediation process. Insurers are already engaged in other aspects of green and high-performance buildings (Mills 2012). An IAQ score or score can thus be relayed to insurers via the appraiser.

Potential partnerships and collaborators

No one trade association has a large "market share", and many residential appraisers are not members of any association. Despite a 5-year collaboration with DOE, the Appraisal Foundation has been highly ineffectual and has shown little interest in disseminating the results or otherwise putting the results into practice. The other key professional organization working in the space is the Appraisal Institute. AI has a series of trainings and publications, and produces the Green Addendum.

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APPENDIX B:
Smart Ventilation for Advanced California Homes – Single Zone Technology

Abstract

This study is intended to demonstrate the potential for energy savings while providing acceptable Indoor Air Quality (IAQ) for ZNE homes. It uses the concept of Smart Ventilation where ventilation systems are designed and controlled to produce the same, or better, IAQ compared to simple, continuously operated ventilation systems. The key energy saving principle for smart ventilation is that ventilation is shifted in time to when the energy required to condition the air is lower. A variety of smart ventilation controls based on outdoor temperature, occupancy and auxiliary fan sensing were developed and assessed across homes built to the 2016 Title 24 Prescriptive standards in California climate regions. Simulations used a co-simulation strategy that combines EnergyPlus with CONTAM. The IAQ calculations were based on the equivalent ventilation principle outlined in the ASHRAE 62.2-2016 ventilation standard, Appendix C. Two prototype homes were simulated (1-story 2,100 ft^2 and 2-story 2,700 ft^2). Their envelope airtightness was varied between 1, 3 and 5 ACH$_{50}$. Climate zones were chosen to reflect the variety of heating and cooling demand throughout California. A weighted average analysis was used to generalize the energy predictions across the projected new housing stock in the state. Temperature-based controls were found to be effective, with the most successful smart controls reducing weighted average site ventilation energy use by about 50%, while TDV weighted average ventilation energy reductions were higher, up to roughly 60%. Results were also normalized to ensure identical IAQ in all cases, and the weighted average site and TDV ventilation savings increased, up to 64% and 68% ventilation savings, respectively, for the top-performing temperature-based controls. Peak demand during the 2-6pm period on the hottest days of the year was reduced by up to 300 watts. More than 90% of site energy savings were for heating end-uses, while TDV energy savings were split more evenly between heating and cooling. On average, the smart controls reduced occupant pollutant exposure by 0-15%, and they increased ventilation rates by roughly 40%. Occupancy-based controls that accounted for contaminants released by building materials and furnishings during unoccupied times were generally ineffective, with very low energy savings. Performance was improved somewhat through use of a 1-hour pre-occupancy flush out period, though savings were still marginal compared to temperature-based controls. All temperature and occupancy controls were also tested with auxiliary fan sensing capability (i.e., accounting for the use of other exhaust devices in the home, like bathroom or kitchen fans). Auxiliary fan sensing increased energy savings in all cases, from roughly 5 to 15%.

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Introduction

Ventilation is the intentional exchange of outside air with the air inside a conditioned space. Its purpose is to displace pollutants of indoor origin such as human bioeffluents, emissions from consumer products and building materials, products of combustion, by-products from cooking and other sources. Ventilation also contributes to a building's energy balance, and thus can be either a driver of energy consumption, or a means of reducing energy use when outdoor conditions are favorable.

Research on how best to ventilate buildings is motivated by several factors. First, increased recognition and awareness of the substantial public health burden that results from exposure to contaminants of concern in indoor environments. Logue et al. (2011) estimated the number of disability-adjusted life years lost per 100,000 people in U.S. residences as a result of exposure to indoor pollutants on the order of 1,000 from fine particulate matter alone, and on the order of 10-100 for both formaldehyde and acrolein.

Second, these exposures are becoming even more important in the context of energy efficiency requirements in building codes and voluntary standards that require substantial air leakage reductions, compared with homes of the past. For example, in many U.S. climates, the International Energy Conservation Code (IECC) requires an envelope leakage rate of 3 ACH_{50} (ICC, 2012), and select voluntary programs, such as Passive House, require extreme airtightness at <0.6 ACH_{50}. New California homes are typically in the range of 4-6 ACH_{50} (Chan, Kim, Less, Singer, & Walker, 2018). Typical values for new homes even a decade ago were in the range of 6-10 ACH_{50}, while older, existing homes range from 10-30 ACH_{50} (Chan, Joh, & Sherman, 2013).

In this context, codes and standards have begun to require mechanical ventilation in residences. Airflow requirements vary, but most standards in the U.S. are based on current or previous versions of the ASHRAE 62.2 ventilation standard. For example, all new homes in California have been required to provide whole house dilution ventilation since 2008 (California Energy Commission, 2008). Similar requirements exist in the IECC and in select state energy codes and voluntary programs (e.g., State of Washington Energy Code). Without dedicated ventilation systems, concentrations of indoor pollutants in advanced California homes would be significantly higher than their older, leakier counterparts.

Third, increasing ventilation at times when outdoor conditions are favorable is increasingly being understood as a viable means of providing energy-efficient thermal control. Strategies include passive cooling via natural ventilation, the use of economizers, and (as this study explores) modulation of dedicated ventilation in response to outdoor temperatures.

Finally, stress on the electric power grid is a major concern as mechanical cooling and renewable energy saturation increases in California homes and businesses. Ventilation loads are greatest at times of day, and times of the year, when the grid is already stressed the most, or when rapid ramping of supply is needed (late afternoon and evening). Shifting ventilation to times of lower grid demand may provide substantial benefit.

Given these motivations, this study explores possible approaches to providing ventilation that both ensures acceptable indoor air quality, and minimizes the energy penalty associated with conditioning ventilation air. As implemented in this work, smart strategies do not require direct sensing of individual pollutants of concern[1]; instead, all IAQ considerations use the concept of *relative exposure* to a continuously emitted, indoor generic pollutant. Smart controls must maintain annual average exposure to this contaminant that is that same as would be achieved by a continuous fan sized to the ASHRAE 62.2 ventilation standard.

Specifically, we look at "smart" ventilation strategies that involve modulating ventilation rates throughout the course of a day or year. These strategies may respond to outdoor air temperature, occupancy detection, predicted exposures, and the operation of auxiliary ventilation devices such as bathroom fans. The recent explosion in Internet of Things research and development has paved the way for such a means of controlling buildings to be possible. A thorough review of available smart ventilation strategies that have been previously studied can be found in I. Walker, Sherman, Clark, & Guyot (2017).

Past work has used related approaches to develop and assess smart ventilation controls in homes in a variety of climates. A controller named RIVEC (short for **R**esidential **I**ntegrated **Ven**tilation **C**ontroller) was developed and briefly field-tested in California that used occupancy, auxiliary fan sensing, grid signals and timer-based temperature controls (Iain S. Walker, Sherman, & Dickerhoff, 2012). Less, Walker, & Tang (2014) studied the effects of several temperature-based control strategies that used cut-off temperatures below which IAQ fans were turned off (fan airflow were increased during all other hours). Smart controls for humidity control in hot and warm-humid climates were developed for similar homes in Less, Walker, & Ticci (2016). Less & Walker (2017) examined the performance of occupancy and auxiliary fan smart controls in Zero Energy Ready homes across U.S. DOE climate regions. Finally, work at the Florida Solar Energy Center (Martin, Fenaughty, & Parker, 2018) has developed a multi-parameter smart ventilation controller using outdoor temperature and moisture levels, paired with pre-calculated seasonal ventilation targets. They also reported on

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[1] The next phase of our work will look at strategies that involve sensing of individual pollutants.

limited field-testing of an occupancy-based smart controller deployed in a Deep Energy Retrofit home in the Pacific Northwest.

Concurrently, more and more consumer building products are emerging on the market that provide some form of ventilation control based on measured temperature and humidity, but which do not track relative exposure to preserve IAQ, and are not compliant with codes and standards. An incomplete descriptive list of these products is provided in Table 38 in 0, including summaries of cost, sensor options and control schemas. Products are diverse, costing between $50 and $300. They include a variety of either indoor or outdoor (or both) temperature and/or humidity sensors, and many are limited to use with certain fan types, or are embedded within certain fan technologies. Some controllers have hot-humid climate control features, but lack cold climate features. This brief review suggests that products are available and can be economically integrated with systems, sensors and varied control features; what they lack are optimized controls that maintain compliance with ventilation codes and standards.

While past work has explored smart controls broadly in U.S. climates, this study considers only advanced homes in the State of California, defined as homes that conform to the 2016 Title 24 energy efficiency standard. This study looks only at homes with dedicated mechanical ventilation, and does not explore natural ventilation strategies. All of the analyses use detailed annual simulations of reference buildings with thermal and airflow characteristics of homes built to the 2016 Title 24 standard, under a variety of different ventilation control strategies, described in the next chapter. All homes are considered well-mixed zones for the current work. Multi-zone approaches will be studied in detail in a subsequent phase.

With this in mind, we pursued three objectives:

1. Provide guidance to the building community, and the State of California, on the most effective means of sizing and controlling ventilation fans in high-performing California homes.
2. Estimate the energy savings available with different Smart Ventilation controls.
3. Assess the effects of Smart Ventilation controls on occupant exposure to pollutants of indoor origin.

Sections 0 through 0 describe the smart ventilation control strategies we analyzed in this work. Section 0 outlines the modeling and analysis methods, and Section 0 present the primary energy results. The final Sections 0 and 0 discuss these results, present conclusions, and provide guidance.

Smart Ventilation, Relative Exposure and Airflow

In this work, we investigate smart ventilation control (SVC) strategies in advanced California homes. The goal of SVC is to improve home performance in comparison to a baseline continuous fan, in terms of both IAQ and energy use.

The IAQ analysis presented in this work uses the concept of *relative exposure*. This is an approach for assessing the IAQ performance of variable ventilation strategies (Max H. Sherman, Mortensen, & Walker, 2011; Max H. Sherman, Walker, & Logue, 2012). Relative exposure assesses the relative concentration of a generic pollutant emitted at a constant rate indoors, with no outdoor sources and no non-ventilation removal processes (e.g., deposition, filtration, etc.). The metric compares the concentration of that pollutant under time-varying versus continuous ventilation schemes. Over short time periods (i.e., about the time needed to replace all the air in the building), a relative exposure of 1 means the two ventilation rates are equal. Averaged over longer periods (e.g., annually), a value of 1 means the two ventilation strategies provide equivalent pollutant exposure—even though the instantaneous ventilation rates may vary dramatically. Values less than one reflect over-ventilation relative to the reference airflow rate (lower pollutant exposure), while values above one reflect under-ventilation (higher pollutant exposure).

Relative exposure is the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard. The standard requires that exposure be estimated at each time step of the assessed period, which in this work was once every 5-minutes. Annually, the arithmetic mean 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 value of one implies that the annual mean occupied exposure to the generic contaminant is the same as would have occurred if the house were ventilated continuously at the whole house target airflow (Qtot) calculated in 62.2-2016. These cases are said to be "equivalent". Note: use of this new approach is limited, as most homes comply using either a continuous or timer-controlled fan that is sized using simple equations or lookup tables.

Under steady-state conditions, the indoor concentration due to an indoor source, and with no removal other than by ventilation, is inversely proportional to the ventilation rate. As a result, the airflow increase required to reduce the concentration by some marginal amount Δc is much greater than the reduction in airflow needed to increase the concentration by Δc. For example, a home ventilated at 0.5 air changes per hour (ACH, hr^{-1}) and a formaldehyde concentration of 30 ppb would need to double its airflow, to 1 ACH, in order to halve the concentration to 15 ppb. But the same house would reach 45 ppb (30

+ 15) after only a 33% reduction in the ventilation rate, from 0.5 to 0.23 ACH. Thus it can cost more to reduce a pollutant concentration than is saved by allowing the concentration to increase in the first place. This effectively biases time-varying ventilation patterns towards overall higher airflow rates (when maintaining equivalence, i.e., the same long-term mean concentration), which must be compensated for by increasing airflow when the energy penalty for doing so is small. Controllers that fail to do this may have limited value.

All of the control strategies are designed to comply with the calculation methods and requirements in ASHRAE Standard 62.2-2016 Appendix C. The relative exposure (R_i) for a given time step is calculated from the whole house target ventilation rate (Q_{tot}), the current house ventilation rate (Q_i), and the relative exposure from the prior step (R_{i-1}). The current house ventilation rate (Q_i) is either a controller estimated value ("controller") or the result of the CONTAM mass balance ("real").

In this work, the target ventilation rate used in IAQ calculations for all cases is the Total Required Ventilation Rate (Q_{tot}) from ASHRAE Standard 62.2:

$$Q_{tot} = 0.15A_{floor} + 3.5(N_{bed} + 1) \tag{1}$$

where A_{floor} is the floor area of the house (m^2), N_{bed} is the number of bedrooms, and Q_{tot} is in liters per second (L/s).

Using the estimated whole house airflow (calculation described below), the relative exposure is calculated at each time step using Equation 2.

$$\boldsymbol{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t/V_{space}}} \tag{2}$$

R_i = relative exposure for time-step, i
R_{i-1} = relative exposure for previous time-step, i-1
Q_{tot} = Target ventilation rate from ASHRAE 62.2-2016, L/s
Q_i = Ventilation rate from the current time-step, L/s
Δt = Simulation time-step, 300 (seconds)
V_{space} = Volume of the space, L

In time steps where there is no ventilation airflow, Relative exposure is calculated using Equation 3.

$$\boldsymbol{R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \tag{3}$$

The relative exposure provides a snapshot of the ventilation rates at an instant in time. Some of our control strategies (e.g., Occupancy SVC and Lockout TSVC) attempt to maintain the daily average exposure equal to one. To do so, we define the *relative dose* as the 24-hour integrated relative exposure. Relative dose is calculated using Equation 4.

$$\boldsymbol{d_i = r_i * \left(1 - e^{\frac{\Delta t_c}{24}}\right) + d_{i-1} * e^{\frac{\Delta t_c}{24}}} \tag{4}$$

d_i = relative dose at time-step i

d_{i-1} = relative dose at the previous time-step i

r_i = relative exposure at time-step i

Δt_C = controller time-step, 5 / 60 (hr)

We report two different relative exposure values in this study, and they differ only in terms of which house airflow estimate they use. First, is the *controller relative exposure*, calculated using the airflow estimate available to the house's ventilation control system. This is the best information that a real controller could use to estimate exposure and control a ventilation fan. Second is the *real relative exposure*, calculated using the total airflow for the home that includes natural infiltration through envelop leaks. For this simulation study, we predict the actual house airflows using the CONTAM mass balance model described in Section 0.

At each time-step, *i*, the smart controller estimates the whole house combined mechanical and natural airflow to use in relative exposure calculations detailed above. Sizing of mechanical IAQ fans is detailed in 0, where we also describe the biases in ASHRAE 62.2-2016 fan sizing and airflow estimates that lead the baseline cases to be marginally under-ventilated. This estimate always includes mechanical and natural infiltration airflows, and it may also include auxiliary fan airflows (e.g., bath and kitchen exhaust) depending on the control type. The airflow is estimated as outlined in the ASHRAE 62.2-2016 smaller time-step method of compliance. Infiltration ($Q_{inf,i}$) and mechanical fan airflows ($Q_{fan,i}$) are combined using:

$$\boldsymbol{Q_i = Q_{fan,i} + \emptyset\, Q_{inf,i}} \tag{5}$$

The sub-additivity coefficient, Φ, is calculated as follows:

$$\emptyset = \frac{\boldsymbol{Q_{inf,i}}}{\boldsymbol{Q_{inf,i} + Q_{fan,i}}} \text{ For unbalanced fans, and 1 for balanced fans} \tag{6}$$

When auxiliary fans are included in the whole house controller airflow estimate, they are added directly to the main IAQ fan airflow and included in the $Q_{fan,i}$ term. When the main IAQ fan is a balanced fan (and the auxiliary fans are unbalanced), the sub-additivity coefficient is calculated using only the auxiliary mechanical airflows included in the $Q_{fan,i}$ term when calculating Φ, and all the mechanical flows are used in $Q_{fan,i}$ when calculating Q_i.

The natural infiltration rate (Q_{inf}) used in estimating whole house airflow is determined using two separate methods allowed in the ASHRAE 62.2-2016 standard. First, is use of a fixed value for all hours of the year that reflects the annual effective infiltration for a given climate zone and home. For annual effective infiltration, we converted the envelope leakage from Air Changes per Hour at 50Pa (ACH_{50}, the metric most commonly used to specify air leakage in energy standards) to Normalized Leakage (NL) and calculated the annual effective infiltration airflow using:

$$\boldsymbol{Q_{inf}} = \frac{\boldsymbol{NL(wsf)A_{floor}}}{\mathbf{1.44}} \tag{7}$$

where:

Q_{inf} = annual mean effective infiltration airflow, L/s

NL = normalized leakage, derived from blower door testing;

wsf = weather and shielding factor from Normative Appendix B 62.2-2016, varies by climate zone;

A_{floor} = floor area of residence, m^2;

Time-varying infiltration estimates are also allowed by the ASHRAE Standard, using a simplified version of the enhanced infiltration model in the ASHRAE Handbook of Fundamentals, also known as the AIM-2 model (I. S. Walker & Wilson, 1998). The AIM-2 calculation procedure is described in detail in 0 and is aligned exactly with the procedures in ASHRAE 62.2-2016.

These relative dose and exposure calculations are used to determine when the fan being controlled is turned on or off in such a way as to achieve equivalent exposure over a year of operation. The fan on/off decision is made once every 5-minutes, which aligns with the overall simulation time step of 5-minutes. The SVC strategies analyzed in this work also turn the ventilation fan on or off in response to one or more of three different signals: outdoor temperature, occupancy, and auxiliary fan operation. In response to these signals, a ventilation fan is modulated to provide more ventilation when advantageous and less when not. The relative dose and exposure are tracked at all times – whether the ventilation fan is running or not.

To determine the energy savings from different smart ventilation strategies, we first determined the energy used to condition the ventilation air that was added by installing a continuous fan sized to the ASHRAE 62.2-2016 standard (see sizing method in 0). This was done by simulating homes with no mechanical ventilation, and then simulating the same house with constant mechanical ventilation. Simulations were performed using EnergyPlus version 8.3.0, as described in Section 0. The difference in energy use is the baseline energy use for code-compliant mechanical ventilation in the homes. We then compare the energy used in different smart ventilation scenarios to determine their energy savings. These energy estimates include fan energy, as well as space conditioning energy required to treat the incoming air due to mechanical ventilation and natural infiltration. As such, there is some dependence in these estimates on the type and efficiency of the equipment specified for heating and cooling (see specs in Section 0).

Smart Control Descriptions

Temperature Controls

The energy impact of mechanical ventilation is primarily due to the changes in space conditioning loads, and to a much lesser degree, direct fan energy use. The load introduced or removed by ventilation airflow is proportional to the indoor – outdoor temperature difference, adjusted for air density and specific heat capacities. Therefore, we examined control strategies based on outdoor temperature signals.

While an infinite number of strategies based on this signal could be devised, we focused on five outdoor temperature-based smart ventilation control strategies (TSVC) that require only on/off fan control. For convenience we named these Lockout, Cutoff, MedRE, Seasonal and VarRE, which are arranged in order of increasing complexity. We also looked at one strategy that would require a continuously variable fan drive (VarQ). We describe each strategy briefly in the following sections, and we provide more detail, as needed, in 0 through 0.

Most of the TSVC described in the following sections function seasonally, which means they require of estimate of when they are in Heating or Cooling modes. For example, the lockout controller described in Section 0 needs to determine whether it should turn the ventilation fan off during the hottest or the coldest hours of the day. It makes this determination using the Season indicator. Our season indicator follows the same definition that the CEC uses in its energy analysis to determine heating and cooling seasons. A 7-day running average outdoor dry-bulb temperature is calculated, and it is "Heating" if the running average is <60°F and is otherwise "Cooling".

Finally, in order to time-shift ventilation while maintaining equivalence with the target airflow from ASHRAE 62.2, the IAQ fan airflow must be increased above that used for the continuous fan baseline simulation. All smart control cases use over-sized fans, with most doubling the fan airflow from the matching baseline case. These Fan Size Multipliers (FSM) are described in greater detail in 0.

Lock-Out (Lockout)

A lockout TSVC strategy is a timer-based strategy that controls ventilation based on the relatively predictable diurnal variation in outside dry bulb temperature.

Using pre-calculated estimates of best timer strategies and required fan size, a smart controller turns the ventilation fan off during the hottest or coldest hours of the day (depending on season). The ventilation airflow is increased during all other hours of the day to ensure equivalence with a continuous fan. This strategy is simple and requires no sensors or internet communication: only a timer. The specification of this control type is described in greater detail in 0.

For our analysis, the lockout period (coldest vs. hottest hours) was selected each day based on the CEC definition of heating and cooling seasons. To calculate the best hours to turn the ventilation fan off, we used all 16 CBECC-Res weather files for the representative California locations. For each month of the year (1:12), an average outside temperature was calculated for each hour of the day (0:23), resulting in 288 values (12*24). This was done for each of 16 climate zones. We then sorted the hourly average temperatures for each month from lowest and highest, and we categorized the lowest and highest hours for every month and climate zone. The hours that occurred most frequently in the low and high categories were selected for the lockouts in Table 1.

Time Period	***Coldest Hours***	***Hottest Hours***
4-Hour	03:00 – 07:00	13:00 – 17:00
6-Hour	02:00 – 08:00	12:00 – 18:00
8-Hour	00:00 – 08:00	11:00 – 19:00

Table 1 Coldest and hottest 4-, 6- and 8-hour periods in each day. Used in TSVC lockout strategy.

As an example of control operation, Figure 1 shows the relative exposure, relative dose and outside temperature for a temperature lockout strategy. The lockout period is highlighted in pink. As expected, the relative exposure climbs quickly during the lockout period, up to peak around 1.8 (1.8 times the average of a constant-ventilation scenario). Then the over-sized ventilation fan operates continuously during all other hours, bringing the relative exposure down to roughly 0.7 and the relative dose (integrated exposure normalized to constant-ventilation strategy) to roughly 0.97, which reflects the integrated exposure over the prior 24-hours.

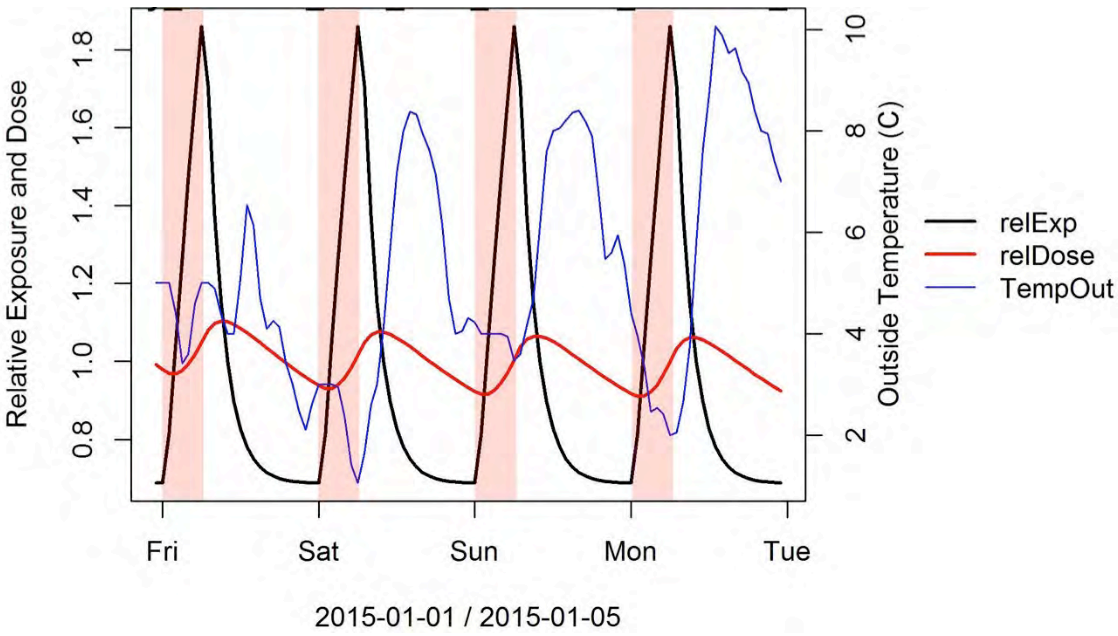

Figure 1 Illustration of the lockout control in 2-story, 1 ACH_{50} home in CZ1. Six-hour lockout period highlighted in pink.

Running Median (MedRe)

This smart control targets custom high and low relative exposure values based on comparing the current outside temperature (T_i) to its running median value ($T_{rollmedian}$). When in heating season, if T_i is currently colder than the running median, the ventilation is reduced (target RE_{high}), otherwise it is increased (target RE_{low}). Vice versa in the cooling season. 0 describes the process for selecting these exposure targets.

An illustrative example of this controller is shown in the time series plot in Figure 2, with the relative exposure, dose and outside temperature shown for a week in January. The high exposure target of 1.4 is maintained when the outdoor temperature is below the running median temperature, and when the temperature warms above the running median, the ventilation rate is increased and the exposure is driven down towards the low exposure target of 0.6.

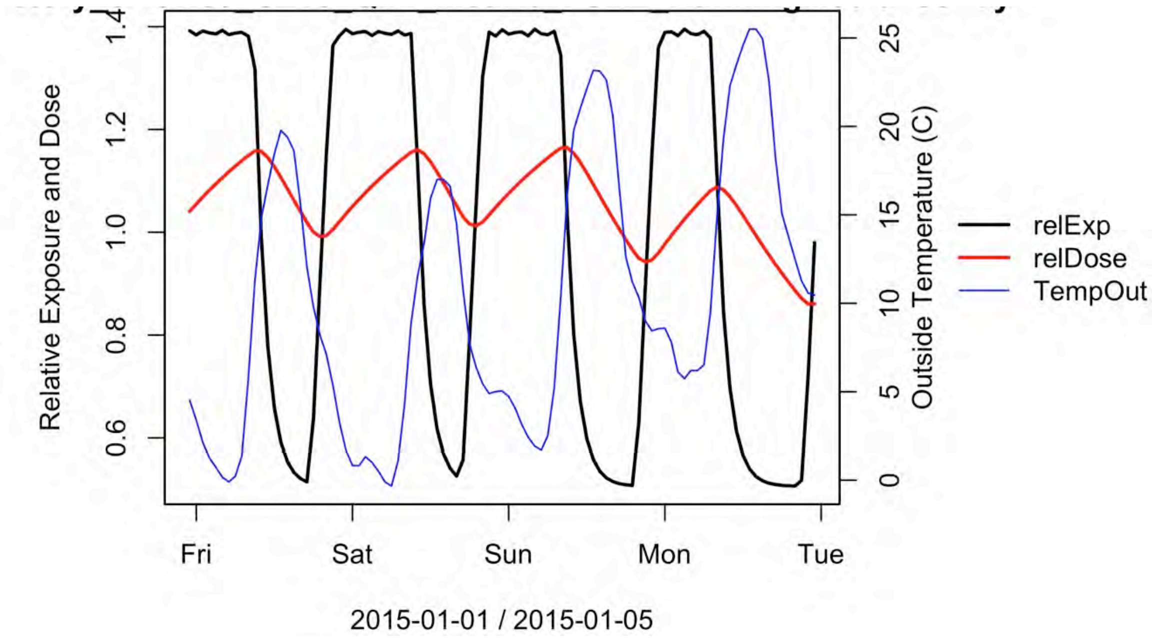

Figure 2 Example of the Running Median TSVC controller. 1-story medium, 3 ACH_{50} home in CZ10 with an FSM of 2. High RE target of 1.4 and low target of 0.5.

Seasonal Control (Season)

The Seasonal ventilation controller targets higher average exposure during heating season (reduced ventilation rate) and lower exposure during cooling season (higher ventilation rates), while maintaining annual relative exposure below one

High and low exposure targets can be calculated for any climate zone using a weighted average approach that provides an annual average very close to one. Again, the process for selection of these control points is not straightforward and we explain it in detail in 0.

We illustrate the simple and consistent operation of this TSVC using daily minimum, mean and maximum controller exposure values in Figure 3. This example case is a 1-story medium 5 ACH_{50} prototype in CZ10, with a heating season exposure target of 1.5 and cooling season target of 0.61. When in heating season, the 1.5 target is consistently maintained, with very little variability over the course of a day; same for the cooling season at the low exposure target. This predictable behavior ensures relatively straightforward estimation of the annual average exposure during design phase.

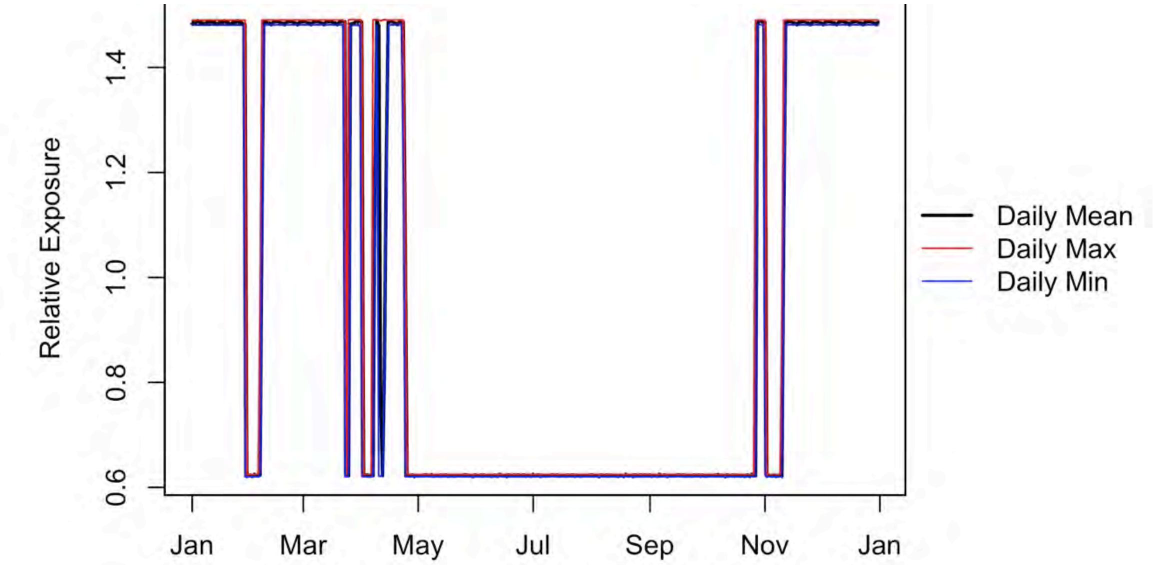

Figure 3 Seasonal TSVC illustration of daily minimum, mean and maximum values for controller relative exposure. 1-story medium 5 ACH50 homes in CZ10 with heating season RE target of 1.5 and cooling season target 0.61.

Cut-Off Temperature Control (CutOff)

It may be possible to achieve greater energy savings if an additional level of complexity is added onto the Seasonal control. Past work on temperature-controlled smart ventilation suggested that a simple cut-off temperature was an effective approach to reducing ventilation load through smart control (Less et al., 2014). In this work, we developed a cut-off approach that ensures annual relative exposure less than one using a weighted average approach. This approach uses two cut-off temperatures: one for each season (heating and cooling). We found that it was not practical to simply turn a ventilation fan on or off when outdoor temperature crossed these temperature thresholds. Instead, we elected to change the target value of relative exposure when the outdoor temperature crosses the temperature threshold.

For example, in the winter, when outdoor temperatures are relatively warm (above the cut-off temperature), the lowest relative exposure would be targeted (increasing ventilation rates). When outdoor temperature is low (below the cut-off temperature), a higher exposure would be targeted (reducing ventilation rates). The high and low exposure targets are selected for each season, so that the seasonal exposure averages equal those used in the Seasonal controller. Figure 4 illustrates such a control strategy with the cut-off temperature shown as a dashed green line. When the outdoor temperature rises above the cut-off, the ventilation rate is increased and a low exposure is targeted; otherwise the high target of roughly 1.8 is maintained. The process for choosing temperature cutoff thresholds and RE targets is explained in depth in 0.

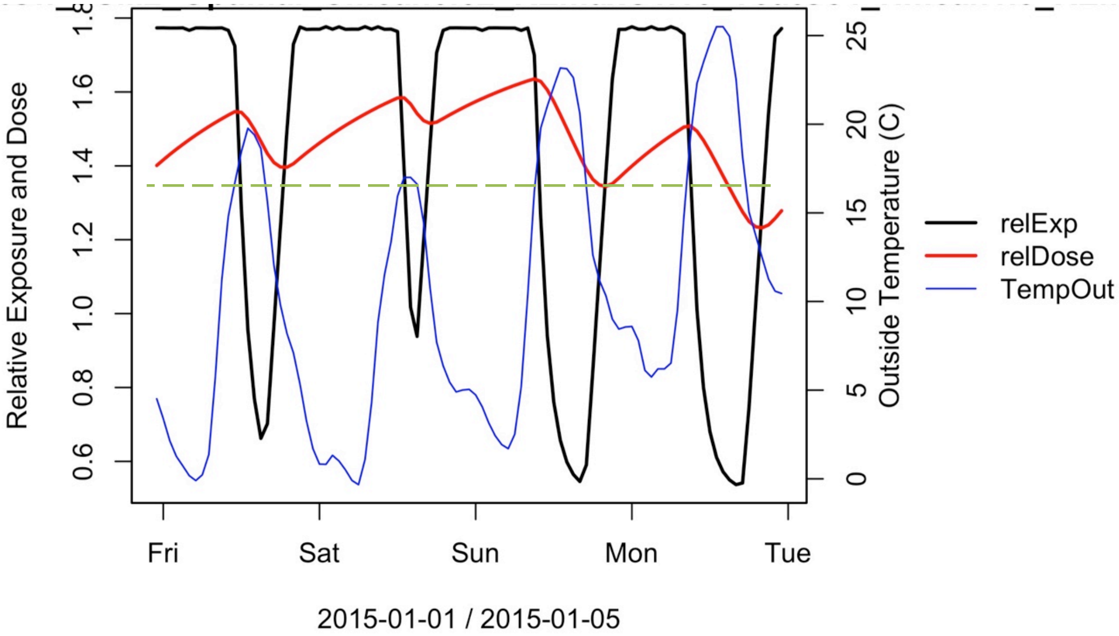

Figure 4 Time-series illustration of Cutoff TSVC controller exposure, dose and outside temperature in a 1-story 1 ACH_{50} home in CZ10. Low exposure target (high ventilation rate) is targeted when outside temperature (blue line) exceeds 16.7°C (dashed green line).

Optimized Variable Relative Exposure (VarRe)

Another level of complexity can be added to try and extract more energy savings by targeting not just high and low exposure values, but instead to make the exposure target a continuous function of outdoor temperature. We propose a method for continuously calculating this optimized relationship target throughout the course of a year while maintaining equivalence with the ASHRAE ventilation standard in 0.

An example VarRe control is plotted across a range of outside temperatures in Figure 5, showing the relative exposure target at each outside temperature. Recall that higher exposure values mean reduced ventilation rates. The RE_{max} values are different in heating (4.0) and cooling seasons (2.0), the RE targets scale linearly between the thermostat setting and the annual minimum temperature in heating (or maximum temperature in cooling season). When outside air is above the thermostat setting in the heating season, ventilation is increased to its maximum to get free heating (RE target of 0.5), vice versa in cooling season.

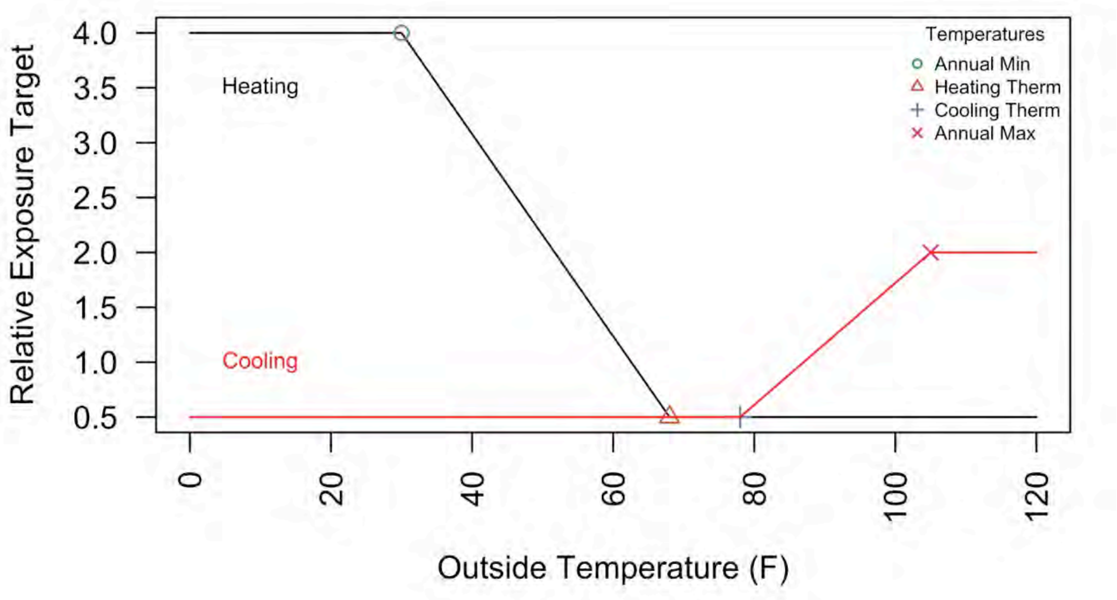

Figure 5 Relative exposure targets that vary continuously with outside temperature, using an RE_{max} values optimized independently for heating and cooling seasons.

The VarRe TSVC strategy is illustrated by the time-series plot in Figure 6 showing a 1-story 1 ACH_{50} home in CZ10 with a peak heating season exposure target of 4.1 (unusually high). We see that the exposure values (real and controller) are inversely proportional to the outside temperature, with peak exposure occurring at the lowest temperature (around 0°C). The controller functions as intended, to shift almost all house ventilation to warmer periods of the day and year (in heating season).

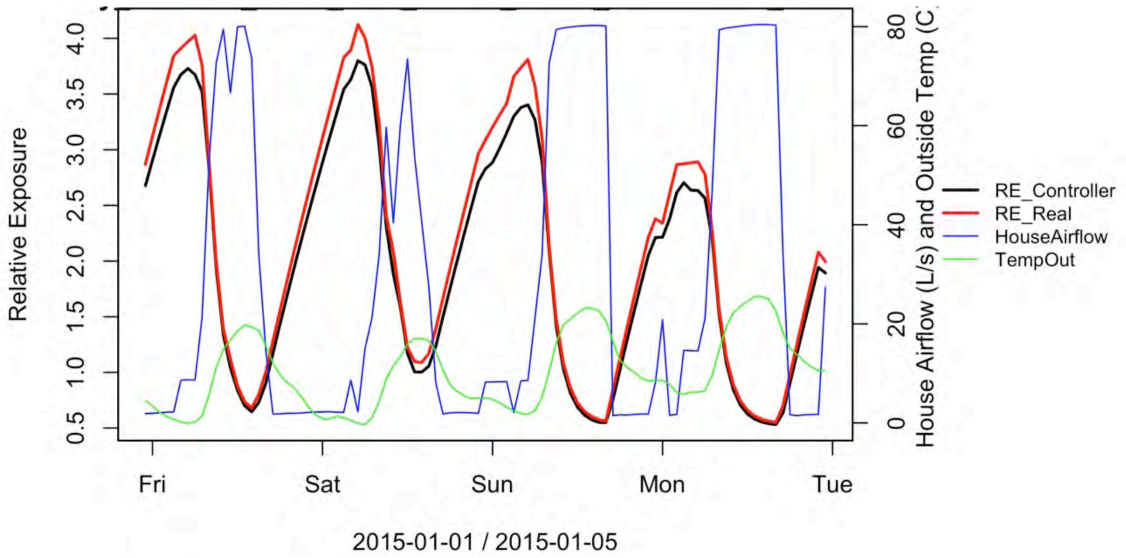

Figure 6 Time-series illustration of the VarRe TSVC controller in a 1-story 1 ACH$_{50}$ home CZ10 (Riverside), with a fan size multiplier of 2 and a peak heating exposure target of 4.1. Includes real and controller exposure, along with whole house airflow and outside temperature.

Optimized Variable Airflow (VarQ)

In homes equipped with variable speed fan drives, continuous modulation of fan speed and thus ventilation rate in response to outdoor temperature signals will be possible. We called this type of strategy VarQ. This scales the target fan airflow between 0 (off) and maximum in response to outdoor temperature signals, exactly as the VarRe controller scales the exposure target with temperature. We illustrate an example strategy across a range of outside temperatures in Figure 7. The heating season airflow (black line) is set to 0 when outside temperature is below the T_{max} value (roughly 45°F here), it scales fan airflow linearly up to the maximum airflow when outside air is the same as the thermostat setting (65°F), and the fan airflow remains at maximum at all temperatures warmer than the thermostat setting (free heating). The opposite happens in cooling season (see the red line). The choice of maximum and minimum temperature control points is based on parametric optimization and is explained in 0.

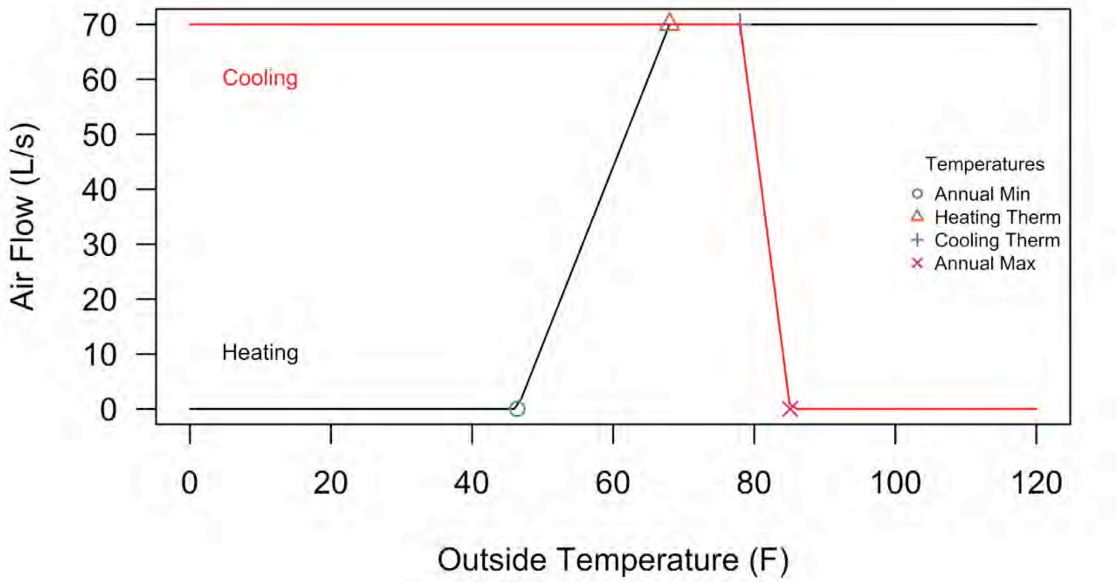

Figure 7 Example airflows for a 70 L/s smart ventilation fan in heating (black) and cooling (red) seasons, generated using F-scale factor across range of outside temperatures.

A time-series illustration of this VarQ controller is plotted in Figure 8 for a 1-story 5 ACH_{50} home CZ10 (Riverside) with a fan size multiplier of 2. This plot shows the real and controller estimates of relative exposure, along with the house airflow and outside temperature. The real exposure is higher than controller exposure due to having lower air exchange. This is due to differences in calculating the natural infiltration between the real and controller approaches. We see that for most hours of the day, the VarQ controller keeps the house airflow at a low number, essentially equal to the natural infiltration rate. When the outside temperature increases, the IAQ fan airflow ramps up proportionally until it is at full airflow around 80 L/s at any temperature exceeding the thermostat set point.

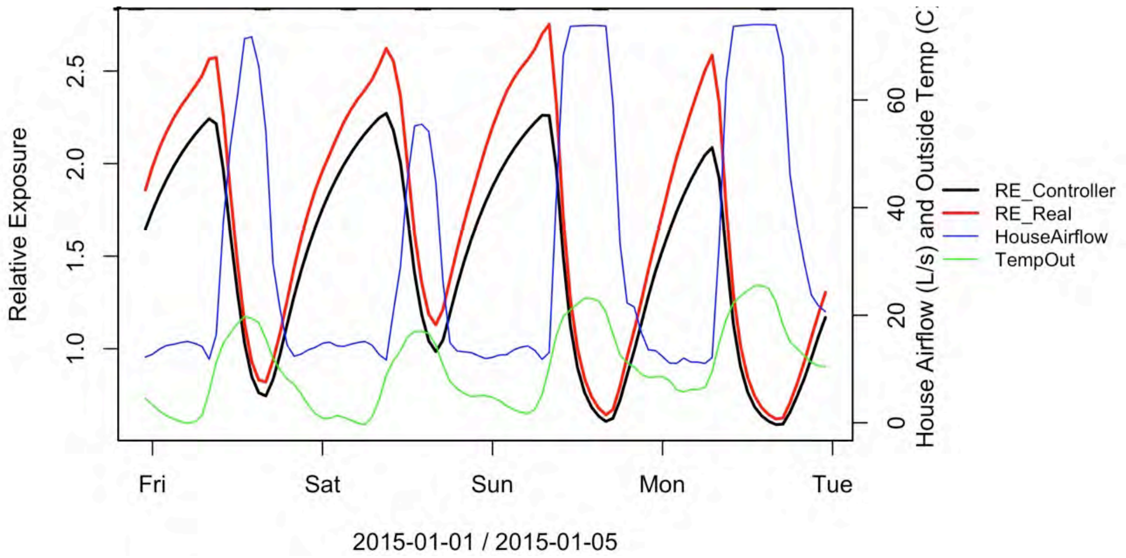

Figure 8 Time-series illustration of the VarQ controller in a 1-story 5 ACH$_{50}$ home in CZ10 (Riverside), including controller and real exposure, along with house airflow and outside temperature.

Occupancy Controls

In addition to or instead of temperature, SVC strategies may also respond to occupancy signals and reduce ventilation during unoccupied periods. Occupancy-based smart ventilation control (OSVC) is distinguished from many other demand-controlled devices, which have historically used either relative humidity or CO_2 as indicators (Emmerich & Persily, 2001; Fisk & De Almeida, 1998; Raatschen, 1990). This approach assumes that occupancy is directly detected by any variety of methods, which could include IR motion sensors, smart phone network detection, smart meter analytics, simple timer-based scheduling, etc. Unlike the temperature-based controls described in the prior section, the occupancy controller is intended to save energy by reducing the average ventilation rate of the home, while maintaining exposure less than one during occupied times.

In this work, we assess the performance of three versions of OSVC: (1) ventilation off during unoccupied periods ("Unocc"), (2) fan on low speed during unoccupied periods (Reduc), and (3) a version that flushes the house at a high ventilation rate one hour before occupancy (Flush). These are described in more detail presently. See 0 for more details on Occupancy SVC.

Off while unoccupied (Unocc)

During the unoccupied period, the ventilation fan is turned off, while the relative exposure is continually calculated. If at any point during the unoccupied period a maximum exposure of 5 is exceeded, the ventilation is turned on to maintain this maximum value. This is a requirement of ASHRAE 62.2-2016. This maximum relative exposure is based on the acute to chronic concentration ratios for pollutants of concern. More details are available in M. H. Sherman, Logue, &

Singer (2011) and Max H. Sherman et al. (2012). In most homes, this means the IAQ fan is turned off during the entire unoccupied time period, because the occupants are not exposed to the contaminants in the space and exposure never reaches 5. This is acceptable, as long as the controller accounts for the increased exposure the occupants receive when returning home after the ventilation system had been off. To account for this, our Unocc control increases the ventilation rate immediately after occupants return home, and it operates at this higher level until the daily-integrated pollutant exposure is equivalent to a continuous fan.

An illustration of the Unocc SVC is provided in Figure 9. The day begins with the IAQ fan maintaining relative exposure (*relExp*, red line) near 1. Light grey highlighted periods show IAQ fan "on" periods, and the aqua region shows the unoccupied mid-day period. The relative dose (*relDose*, blue line) tracks the running average of the relative exposure and is fixed at almost exactly one. The unoccupied period is marked by relative exposure increasing to a peak around 2.7 when the occupants return home. The relative dose increases slightly when occupants return home reflecting their exposure to this high concentration, and it is reduced back below one during the recovery period when the ventilation rate is increased. The IAQ fan is off during the entire unoccupied period, and then it is on continuously until the recovery period ends when both relative exposure and relative dose are less than one (approximately 23:00). This same pattern is repeated each day of the week with an occupant absence.

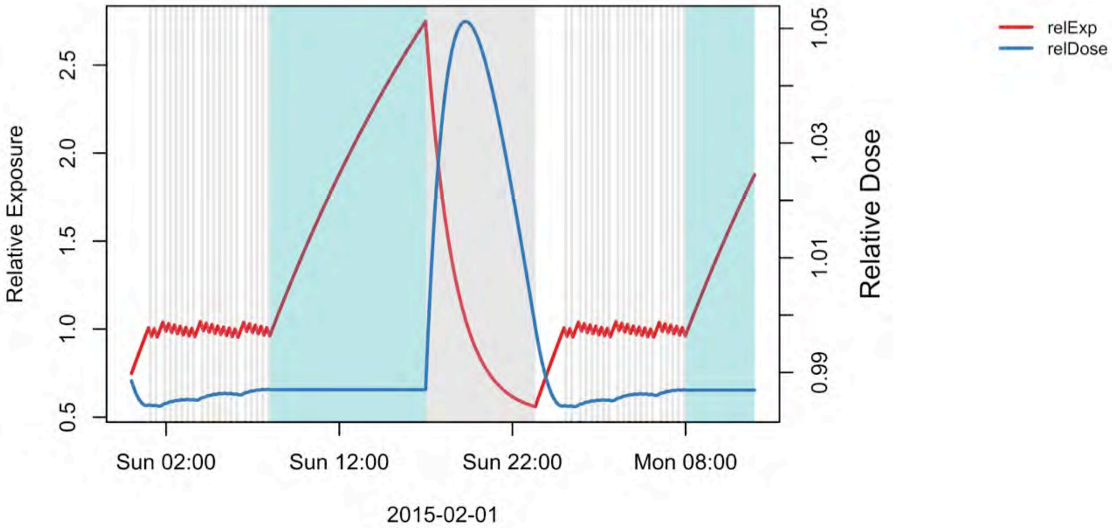

Figure 9 Illustration of Occupancy control operation with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey, unoccupied period in aqua.

Ventilation reduced while unoccupied (Reduc)

Rather than turning the fan off during unoccupied periods, it may prove advantageous to operate it at a low airflow instead. Mortensen, Walker, & Sherman (2011) showed that for a variety of unoccupied periods, emission assumptions and constant fan airflows, the peak effectiveness of an-occupancy controlled system occurred when the ventilation rate during unoccupied times was between 0.13 and 0.4 of the constant system. Their results suggest that a value of roughly 0.35 will be appropriate for the cases we are simulating. So, we analyzed a strategy that operated the continuous fan airflow at 0.35 times the baseline rate during unoccupied time periods. It was expected that this approach would reduce the peak exposure experienced everyday by the occupants, and hopefully reduce the average ventilation rate required to maintain exposure below one, thus saving energy.

Pre-occupancy flush out (Flush)

We also tested a version of the occupancy SVC where the controller can predict when occupants will return home. In these example cases, the controller begins the over-ventilation recovery period before occupants return home. We have reproduced a figure from Less & Walker (2017) demonstrating typical relative exposure patterns in an occupancy controller with no pre-venting, 1- and 2-hour pre-occupancy flush outs in Figure 10.

This shows how the flush outs drastically reduce peak exposure to the occupants and lessen the over-ventilation period. For example, in the 9-hour absence pattern detailed in Figure 10 the occupants return home at 17:00, and this controller would turn the fan on continuously starting at 15:00 for a 2-hour flush out or 16:00 for the 1-hour flush out. This approach should reduce occupant peak exposure, lessen the recovery period and save energy. Less & Walker found that 1- and 2-hour flush outs had very similar energy performance, so we only test a 1-hour flush out in this work.

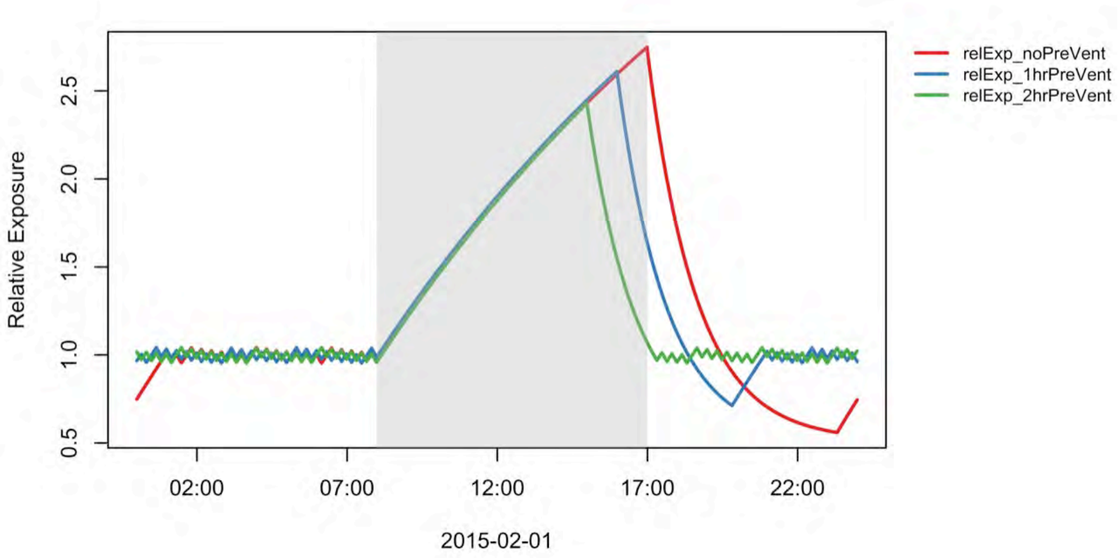

Figure 10 Relative exposure with no, one- and two-hour pre-occupancy flush out periods. Unoccupied period highlighted in light grey. Reproduced from Less & Walker (2017).

The risk with the pre-occupancy flush out strategy is that it may be more difficult for a controller to predict when occupants will return home than it is to sense that they have returned home. The prediction requires a predictable pattern, whereas the simple approach with no flushing period requires only an accurate sensor (the low airflow during unoccupied times might also be more flexible in response to variable occupancy patterns). In addition, this only works for typical workweek schedules, with predictable home and away periods. Luckily, Less & Walker (2017) showed that a one-hour flush out was roughly equivalent in energy performance as the two-hour flush out, which gives the controller flexibility.

A simple approach to predicting when occupants will return would be a running average of the prior five work day return times. The system could also work on a schedule that is manually entered by the occupants that reflects their typical home and away patterns. Alternatively, a system could be used that is integrated with an occupant's cell phone that informs the controller when the occupants are within a certain radius of their home or some such approach.

Auxiliary Fan Controls

A smart control strategy may be augmented by detection of other exhaust devices in the home, including bathroom, kitchen and laundry fans, vented clothes dryers and economizers. These additional airflows can be added by the controller to the ventilation rate used in calculating relative exposure and dose. The central fan's operation can be traded off on a one-to-one basis with auxiliary fans, reducing the overall ventilation rate. This is distinct from controls that time-shift ventilation (i.e., temperature-based controls), because they have to increase the average ventilation rate in order to maintain exposure less than one, whereas this control reduces the average ventilation rate. The benefits of this type of control scale directly with the amount of auxiliary fan use and airflow. More details are provided about auxiliary fan sensing in 0.

Combined Controls

Less & Walker (2017) have already demonstrated that combining an occupancy controller with auxiliary fan sensing greatly improved the overall performance. We extended this further to include occupancy controls with pre-occupancy flush out and a low airflow fan operation during unoccupied periods. We also add auxiliary fan sensing to each of the previously described temperature-based smart controls. A combination of all three control inputs may be possible, but was not explored in this work.

Smart Controls Overview

For the reader’s convenience, all smart controls described above and in the Appendices are listed and briefly summarized in Table 2.

Control Name	***Description***
Lockout	Turns IAQ fan off during the hottest hours of the day in the cooling season and during the coldest hours of the day in the heating season. Lockout hours (4-, 6- and 8-hours) are pre-calculated using weather files. Fans are oversized to run continuously outside of lockout hours to ensure daily exposure ≤0.97. See 0.
Running Median (MedRe)	Compares current outside temperature against the running median outside temperature, and selects either a high exposure target (reduced airflow) or a low exposure target (increased airflow). During heating season, ventilation is reduced when below the median and increased when above the median. Opposite in cooling season. See 0.
Seasonal (Season)	Reduces ventilation rates in the heating season and increases them in the cooling season. Exposure targets for each season are pre-calculated using a weighted average to ensure that annual exposure will be ≤0.97. See 0.
Cutoff	Uses the exposure targets from the Seasonal controller, and adds cut-off temperatures for each season selected by parametric optimization, with a low and high exposure target. Reduces ventilation during the heating season, with a focus on the coldest hours, while still ventilating at high rates during mild weather. Vice versa in cooling season. See 0.
Variable Airflow (VarQ)	Ventilation fan airflow is continuously varied proportional to outdoor temperature. Airflow is scaled using the ratio of the current indoor-outdoor temperature difference, compared with the seasonal maximum temperature difference. The seasonal maximum values are selected using parametric optimization to ensure maximum energy savings, with annual exposure ≤0.97. See 0.
Variable Exposure (VarRe)	Target exposure is continuously varied proportional to outside temperature. Exposure varies between the minimum value (highest airflow) and a maximum value (lowest airflow) for each season. High exposure target is selected using parametric optimization to ensure maximum energy savings, with annual exposure ≤0.97. See 0.
Occupancy (Occ)	IAQ fan is turned off when the home is unoccupied, and ventilation rate is increased when occupants return home to account for background contaminant emissions. Daily-integrated exposure is maintained ≤0.97. See 0. Three versions are assessed: • Fan off when unoccupied • Fan at 35% flow when unoccupied • Pre-ventilate the home 1-hour before occupancy
Auxiliary Fans (AuxFans)	This option senses the operation of other exhaust devices in the home, and it includes these flows in the controller airflow estimate, which reduces IAQ fan runtime and overall ventilation rates. This controller was added onto each of the other control types to assess combined control performance. See 0.

Table 2 Description of each smart control strategy.

Modeling and Analysis 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, in several different California climates. We then analyzed the performance of these homes with respect to both energy and IAQ under a variety of different smart ventilation control strategies.

The following sections describe the models used in the simulation program and the specifics of the simulation protocol. In general, we followed the following procedure in this study:

1. Develop CONTAM models to assess the IAQ portion of the problem for each of 6 representative homes: three different air-tightness levels for each of the two prototype homes.
2. Develop EnergyPlus models to assess the thermal and systems portion of the problem for each of two homes
3. Co-simulate EnergyPlus and CONTAM models across the homes, climates and control strategies of interest via an automated parametric modeling approach.
4. Process the outputs.

Each of these portions of the simulation work is described below.

All energy assessments included both site energy and time dependent valuation (TDV) energy, which is a metric used in demonstrating Title 24 compliance that accounts for time-varying impacts of energy consumption. Our TDV methods are described in 0 TDV energy weights peak demand periods heavily for electricity consumption, so it partly reflects peak demand reductions. We also performed a specific peak period analysis that is described in 0 to analyze the potential grid services provided by the controllers. We present detailed results across climate zones and house types where possible, but we also use a weighted average calculation method to generalize our results across new homes constructed in the state (see a complete description in 0).

Homes simulated

We simulated homes matching the specifications of the two CEC single-family prototype units (Nittler & Wilcox, 2006), whose properties are made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 energy code. We created detailed models of two prototype homes: a 1-story 2,100 ft^2 prototype home and a 2-story 2,700 ft^2 prototype home, with forced air space conditioning systems. The HVAC equipment was auto-sized using the sizing feature in EnergyPlus. Gas furnace efficiency was specified as an AFUE of 0.92, and the cooling system COP was 3.95 (EER of 12.7 or SEER 16).

Thermostat schedules were set to meet those specified in the 2016 ACM. The systems are compliant with ASHRAE 62.2-2016 that includes with infiltration credits and sub-additivity adjustment (see sizing calculations in 0)[2].

Several deliberate deviations were made from the Title 24 prescriptive path prototypes: we did not include whole house economizer fans that are present in the prototype homes, we improved the HVAC equipment efficiencies, and we did not automatically open windows for ventilation cooling. We did not model any duct leakage because we modeled advanced homes with ducting assumed to be within conditioned space, consistent with Title-24 2016 prescriptive path option C. Equipment efficiency was increased beyond prescriptive minimums to SEER 16 A/C and 92 AFUE gas furnaces in order to align with standard new construction practice encountered in HENGH field study and based on TAC feedback. Figure 2 shows the front view of the two prototype homes. The specific model input values for the two prototypes are summarized in Table 3.

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[2] This fan sizing is not the same as that adopted in the 2019 Title 24 building energy code cycle. The newly adopted Title 24 fan sizing method uses the same calculation procedures as the ASHRAE 62.2-2016, but for all homes with envelope leakage 2 ACH_{50} and greater, a default of 2 ACH_{50} is used in fan sizing calculations. For homes that are below 2 ACH_{50}, the newly adopted fan sizing method requires use of the small leakage value in calculating the fan airflow. So, for homes ≤2 ACH_{50}, the methods are identical, and in leakier homes, the adopted sizing procedure leads to larger fan airflows than are required by ASHRAE 62.2-2016.

Figure 11 CEC one- and two-story homes (front view)

Element	*Prototype 1*	*Prototype 2*
Ceiling height (ft)	9	9
Conditioned Floor Area (ft^2)	2,100	2,700
Conditioned Volume (ft^3)	18,900	25,750
Gross Areas		
Slab (ft^2)	2,100	1,250
Slab perimeter, outside (ft^2)	162	128
Slab perimeter, garage (ft^2)	30	30
Ceiling (ft^2)	2,100, unvented attic	1,450, unvented attic
Roof slope (%)	20	20
Roof Deck R-value	R13 (airspace) below deck insulation, in CZ4 and 8-16	R13 (airspace) below deck insulation, in CZ4 and 8-16
Ceiling Insulation	R38 (R30 in CZ3, 5, 6 and 7)	R38 (R30 in CZ3, 5, 6 and 7)
Radiant Barrier	No	No
Wall U-value	0.051 (0.065 in CZ6&7)	0.051 (0.065 in CZ6&7)
Slab Perimeter R-value	0 (7 in CZ16)	0 (7 in CZ16)
Window U-value	0.32	0.32
Window SHGC	0.25	0.25
Window Area	20% floor area	20% floor area
Gas Furnace AFUE	92%	92%
AC SEER	16	16

Table 3. Model input values for prototype homes

Climates

Locations were first selected that represented a broad range of climatic conditions in California. It was important to capture the variety of heating, cooling and moisture regimes throughout the state, in order to allow statewide estimates that interpolate between the results in these limited locations. Table 4 gives the climatic design data for 4 representative cities, from the harshest Blue Canyon (CZ16) to the very temperate Oakland (CZ3), and Riverside (CZ10) in the central valley that represents a location with greatest growth in new construction.

CEC Climate Zone	$HDD_{18.3}$	$CDD_{18.3}$	Design Temperature (Heating – Cooling, °C)
1 – Arcata	2,658	1	0.6 / 20.6
3 – Oakland	1,436	85	2.2 / 26.7
10 – Riverside	1,011	888	1.7 / 37.2
16 – Blue Canyon	3,174	151	-4.4 / 27.2

Table 4 Climate zone design information, including heating and cooling degree days calculated at 18.3°C reference temperatures, and heating/cooling design temperatures.

Weather files (.epw) are available for each of these locations; however, these differ substantially from the CEC weather files (.csw) used to demonstrate Title 24 residential compliance. The team used data (dry-bulb temperature, dew-point temperature, wet-bulb temperature, wind direction, wind speed, global horizontal irradiance, direct normal irradiance, diffuse horizontal irradiance and total sky cover) from the CEC weather files, to generate corresponding .epw files. Where required, these values were converted from the IP system in the CEC .epw files to SI units for use in EnergyPlus. Relative humidity was derived using dry-bulb and wet-bulb temperatures from the CEC file with the paired atmospheric pressure in the original epw files.

Energy Model

For each home and climate, we modeled the thermal interaction of the building with its environment and internal loads with EnergyPlus (U.S. DOE, n.d.). EnergyPlus is a comprehensive building operation simulation tool supported by the Department of Energy (DOE), which has sophisticated models for building heat balance, HVAC operation, lighting, etc. The simulations were executed on a 5-minute time-step, with hourly time-series reporting.

EnergyPlus models for the two prototype homes were developed with BEopt, using detailed construction and HVAC system parameters described in Section 0. This determines the system capacities and their associated airflows. BEopt implements residential-specific models in EnergyPlus using a simple graphical user interface, including user-friendly specification of building geometry and performance features, along with residential defaults for internal heat gains, appliance and lighting usage, etc. After the baseline models were developed, we performed a series of verification exercises to ensure that the models adequately represented house airflows, indoor temperatures, HVAC system behavior, etc. In doing so we identified a number of issues and addressed them, described further in 0 Detailed HVAC system and indoor temperature operation.

Once we were satisfied with the dynamics reflected in the EnergyPlus models from BEopt, these were then modified to include the objects that handle the interactions with CONTAM via the FMI, and our EMS control code. The EMS code is used to calculate the:

- Total infiltration and inter-zonal mass exchange.
- Operating behavior of the HVAC system.
- Operation of the various smart ventilation control strategies.
- Fan power use.
- The whole house flow rates used by the smart controller, including infiltration, the IAQ fan, and when required by the control strategy, the auxiliary mechanical flows.
- Control and "real", exposure and dose.

These EMS programs influence the behavior of the model principally by setting values of commonly used EnergyPlus objects (schedules, infiltration flows etc.) using an EnergyPlus object called an *Actuator*. See the EnergyPlus references to learn more about that. 0 lists the main EMS programs and the actuators they control in more detail.

EnergyPlus fixes indoor temperatures at the thermostat set-points, with the HVAC system energy consumption modulated to meet that exact temperature. This does not account for the dynamics of indoor temperature that cycle up and down with HVAC system cycling, or float during temperatures of low load. This was very important in our simulations because we are controlling ventilation on sub-hourly time steps and calculating the resulting changes in energy use. Getting house temperatures to adequately reflect real homes is critical when using temperature-based smart ventilation controls.

In order to get the models to reflect indoor temperature and HVAC system behavior in real homes, we imposed a thermostat dead-band of plus and minus one degree C. In the context of this HVAC system this means that the system will generally operate at full capacity before turning off. This addresses the issue of variable HVAC capacity that is the default behavior in EnergyPlus. This results in the house temperature cycling above and below the thermostat setting.

Airflow Model

EnergyPlus also has the capability to model multi-zone air flow and contaminant balances. However, its functionality for multi-zone airflow modeling is limited. EnergyPlus does not account for contaminant removal within the HVAC system loop, and is otherwise limited to CO_2 and a single generic contaminant. It is also limited in a few other ways: its ability to model the impact that HVAC system operation has on envelope infiltration is limited; implementing an EnergyPlus Air Flow Network model with HVAC distribution, is limited to a subset of air distribution systems and most importantly it cannot handle variable speed fans, which is critical for our smart control strategies.

CONTAM, in contrast, developed by National Institute of Standard and Technology (NIST) (Dols & Polidoro, 2015), cannot model building energy use, but has more sophisticated and flexible models for contaminant transport and loss. Using CONTAM, we are able to model contaminant loss mechanisms both in the zone and in the HVAC pathway itself. It also allows us to model multiple-contaminants or species of the same type of contaminant. These two features are essential requirements for the SVACH project, particularly for phase two of the study, where combinations of multiple pollutants are considered.

Thus, in order to understand the combined effect of wind- and buoyancy- driven infiltration, mechanical ventilation fan operation and envelope leakage, we built airflow models of each of the two prototype homes in CONTAM. The geometry, aspect ratio floor area and zone heights were also specified to match the EnergyPlus model. In total, we developed six different CONTAM files: three levels of air tightness for each of the two prototype home sizes; there is no variability in CONTAM models by climate zone. Each model effectively had two well-mixed thermal zones to match the corresponding EnergyPlus model:

1. The main conditioned living area which we were analyzing, and
2. The attic, which was used to appropriately treat the ceiling airflows and any HVAC system interactions with the attic (such as duct leakage).

The major advantage of the CONTAM simulation platform is that it has a detailed accounting of infiltration at each time step (5-minutes, in this work) via solution of pressure-flow relationships. This is described detail in 0 along with the assumptions we used for wind-driven ventilation and leakage area distribution.

Implementation of the EnergyPlus and CONTAM Co-simulation

To model the energy and IAQ implications of our various control strategies we used a co-simulation based approach, using CONTAM to perform mass and contaminant balances, and EnergyPlus to model energy consumption and implement smart ventilation controls and calculations.

Performing a co-simulation involves running the two simulation engines in parallel, with critical data connections passed back and forth at each time step, as shown in Figure **12**. This allows us to take advantage of the relative strengths of each tool, and to meet all of the simulation objectives of the work, that no single tool could meet. Our method was based on an approach developed and validated by Dols et al. (Dols, Emmerich, & Polidoro, 2016), with a number of significant differences discussed later in this report. Dols et al. used a Functional Mockup Unit- (FMI, http://fmi-standard.org/) based implementation of CONTAM, which is then coupled to EnergyPlus via its FMI implementation (Thierry Nouidui, 2014) .

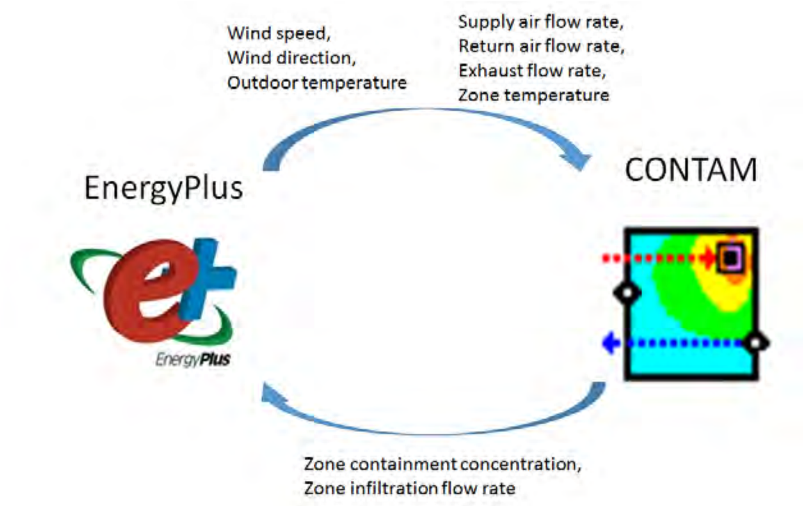

Figure 12 Co-simulation variable exchange diagram.

We used EnergyPlus to model the building envelope; HVAC system and controls; occupants and building energy use. CONTAM was used to model the air flow mass balance including inter-zonal air flow, mechanical air flow and infiltration, and contaminant transport. At each timestep, environmental data (wind speed, direction and outdoor temperature), and system operation data (mechanical system flows), are sent from EnergyPlus to CONTAM. Figure **12** illustrates this flow of information between CONTAM and EnergyPlus. The EnergyPlus Energy Management System (EMS) is used to manage this interchange and to implement required calculations and control strategies.

The IAQ fan and auxiliary fans flow rates are calculated in EnergyPlus using system operation schedules, defined in the EnergyPlus model file. Once transferred to CONTAM via the FMI, they are represented in CONTAM as "flow paths". CONTAM then calculates the resultant infiltration and inter-zonal mass flows, considering these mechanical flows, along with wind driven and stack effects to determine the resultant mass flow rate. This infiltration is then returned to EnergyPlus to align the two models' air change rates.

Once both the EnergyPlus and CONTAM models were defined the team used an approach based on prior work by NIST (Dols & Polidoro, 2015) to establish the co-simulation. NIST provides a publicly available tool (CONTAM 3D Export tool) that can be used to generate much of the necessary elements that are needed to perform co-simulation. These elements can be broadly categorized into 3 types. Firstly, additional EnergyPlus objects are required to handle the interchange of data via the FMI. Secondly, interface definition files are required so that EnergyPlus and CONTAM know what data they are exchanging. Finally the CONTAM project file, the interface definition files and the ContamFMU.dll file are packaged together to create an FMU file. The Contam 3D Export tool is used to generate the required EnergyPlus objects and data exchange files, and to generate the FMU object, using the CONTAM project as its input. The data exchange files generated by the tool are the variable verification dictionary, "contam.vef" and the model description file "modelDescription.xml". The tool assumes all of the "split or pass" inputs or outputs are intended to be used for data exchange. If this is not the case the user can manually edit the interface files to remove unrequired data exchange items. The methods and regulation for variable matching are described in (Dols & Polidoro, 2015). After creating our co-simulation models, we verified that the air change rates predicted by CONTAM were correctly transferred to EnergyPlus.

Parametric simulation of scenarios method

We performed the simulations using:

- Two prototype homes (1-story, 2,100 ft^2, 2-story, 2,700 ft^2)
- Envelope leakages of 1, 3 and 5 ACH$_{50}$
- Balanced IAQ ventilation systems in 1 ACH$_{50}$ homes, and simple exhaust IAQ fans in the others (3 & 5 ACH$_{50}$)
- Four CEC climate zones (1 (Arcata), 3 (Oakland), 10 (Riverside), 16 (Blue Canyon)).

Ventilation control scenarios included baseline cases with and without IAQ fans, six temperature based controls, three occupancy based controls. Each smart control type was assessed with and without accounting for auxiliary fans. Finally, each control was assessed using two different infiltration models for the controller logic (annual effective and time-varying), as allowed by ASHRAE 62.2 – 2016 (see descriptions in Section 0 and in 0). In total 1,056 cases were simulated.

In order to speed up the simulation, testing, and correction of the model scenarios outlined above, the team developed a simulation parameterization and results processing tool. This tool first generates a unique .idf file for each scenario to be simulated, runs that simulation, and then processes the results. The tool generates this idf by combining multiple snippets of EnergyPlus objects (.imf files) that individually describe the models geometry, constructions, climate specific objects, control strategies, as well as the co-simulation set-up, with parameters set to values specific to that scenario. We used a .csv file to describe each scenario and any input parameters the control strategy needs, one scenario per line. Figure 13 shows this process flow.

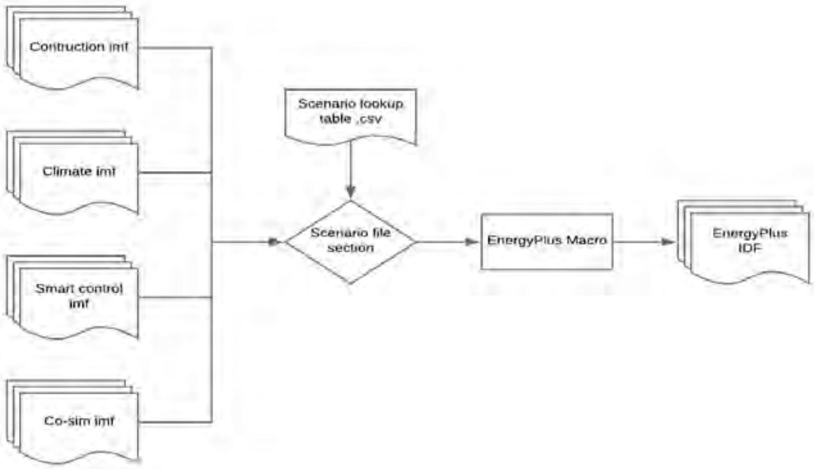

Figure 13 Generation of idf model process flow

These model variations are defined in a csv scenario definition file that describes each scenario, and gives a value for each of the scenario input parameters. 0 Detailed Scenario File Description, lists and describes each of the parameters representing a single row of the scenario file.

After generating a complete set of imf files, the tool then runs this batch of EnergyPlus simulations and stores the simulation results to the designated directory. Figure X gives a flow diagram describing the complete process, starting with the generation of the input idfs, then running the EnergyPlus and CONTAM co-simulation and finally processing the results and generating figures. The R-script based post processing generates both tabulated summary data and summary plots.

Results

The following sections describe the energy savings results generated in the simulation program. Not all cases resulted in controller relative exposure of 1, which means the IAQ is not the same in all cases.

Figure 14 illustrates the variability in energy savings and relative exposure for all the controllers. Relative exposure varied typically between 0.95 and 1.05, with some outliers in both low and high directions. Because energy savings are sensitive to exposure, we need to normalize the results by exposure if we want to identify controllers that consistently save energy, while providing the same IAQ. We will present energy savings estimates un-normalized where the relative exposures differ, and normalized by relative exposure to ensure equivalent IAQ. The non-normalized cases are what we would expect to happen if a controller were used in an individual home. The normalized results are more useful for policy decisions, for example, where we want a more apples-to-apples comparison when comparing potential energy saving strategies.

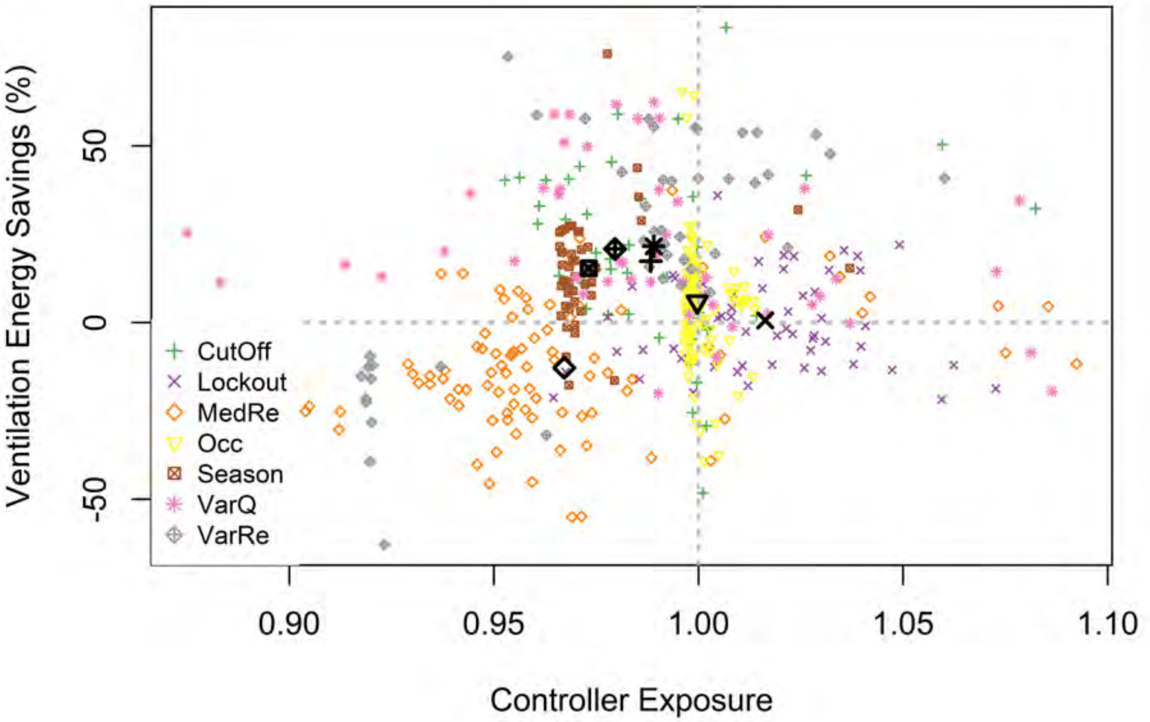

Figure 14 Controller relative exposure vs. ventilation energy savings (%).

In the un-normalized results we excluded simulations where annual controller exposure was greater than 1.0, unless otherwise noted. We first present an overview of un-normalized energy savings (Section 0), including weighted average results for each control type (Section 0), HVAC end-use savings (Section 0), maximum ventilation energy savings for each combination of prototype, airtightness and climate zone (Section 0), and finally peak cooling power reductions during periods of grid stress (Section 0). Next, we summarize the results when real relative exposure is normalized to 1.0 in all cases, ensuring perfectly matched IAQ (Section 0). Finally, we look at the performance of each controller individually (Section 0), using both un-normalized and normalized data in parallel.

Un-Normalized Energy Saving Summary

The distributions of site and TDV ventilation energy savings for all simulated cases are shown for each smart ventilation control type in Figure 15 (TDV savings in Figure 16). These values include all cases, irrespective of whether or not they complied with the ASHRAE 62.2-2016 requirement that annual relative exposure average less than 1.0. Overall, the best performing controllers are the CutOff, VarQ and VarRe cases, with median ventilation savings of 20-30%, and savings in individual cases as high as 50-80%.

Notably, many cases actually increase ventilation energy consumption, including the majority of Lockout and MedRe cases, which were the worst performers, overall. The Occupancy control was also amongst the control types with the lowest HVAC energy savings. Some strategies are simply not effective at reducing ventilation energy use, largely because they increase ventilation rates, but do not sufficiently shift airflow to periods of smaller temperature differences. As discussed in Section 0, the Occupancy controller in fact does the opposite. It concentrates airflow in colder hours of the day and reduces ventilation during the mild mid-day periods. Even the best performing control types had cases where energy use increased, but these were all for cases located in Climate Zone 1 in Arcata, along California’s north coast. This location has no cooling season, is very cold and humid, with next to no diurnal temperature variation. These climate features limited the efficacy of both our seasonal and daily controllers.

TDV ventilation energy savings are higher on average than site energy savings, despite the fact that control parameters were optimized using site energy values, which artificially focused the controls on reducing heating (lower ventilation rates in winter) as opposed to cooling energy. The same control types could be optimized using source energy or TDV energy directly, which would likely drive further cooling energy savings, and even higher TDV ventilation savings. As currently designed, the best control types had TDV ventilation savings commonly in the 20-80% range, with median values around 25% savings.

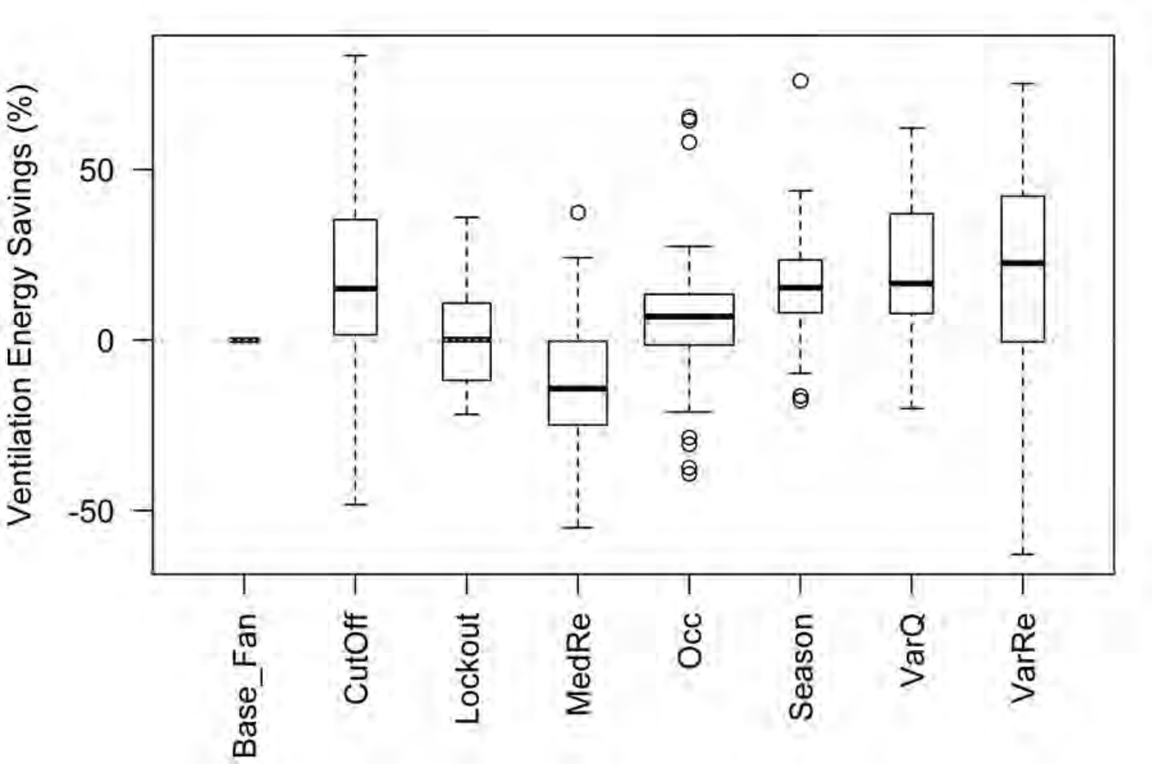

Figure 15 Ventilation energy savings (%) distribution for each smart control type, ALL cases including non-compliant.

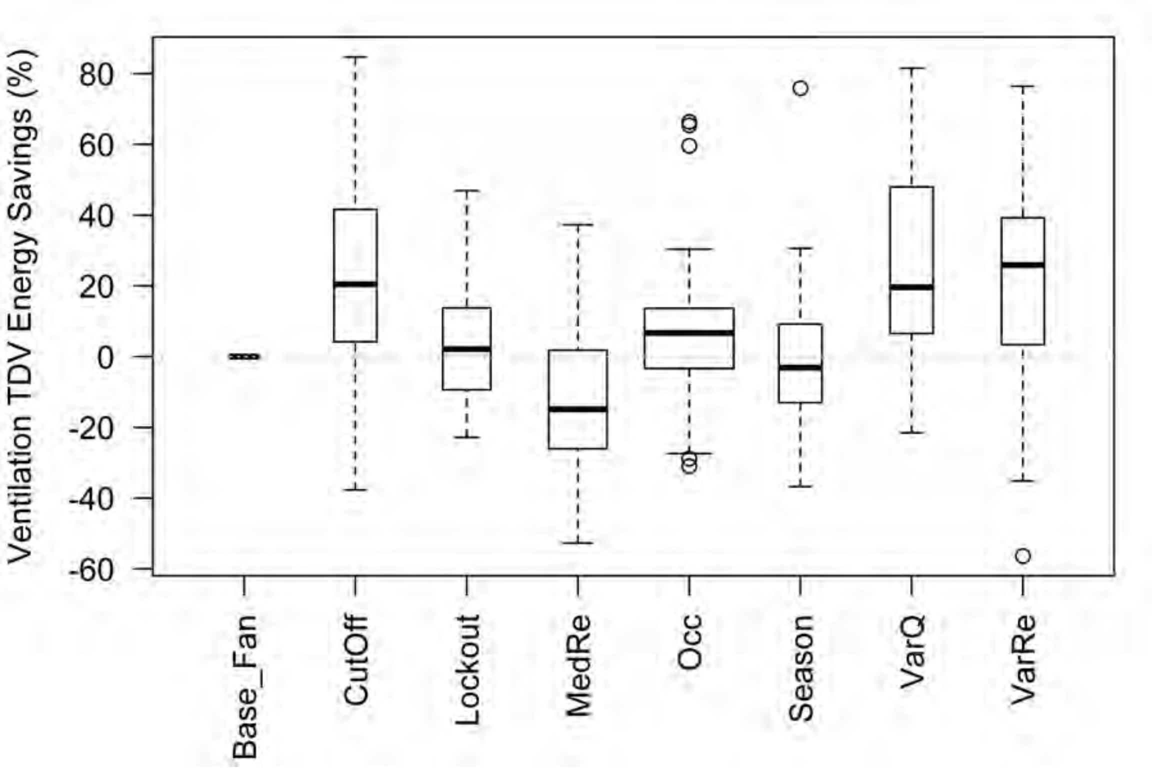

Figure 16 TDV ventilation energy savings (%) distribution for each smart control type, ALL cases including non-compliant.

Weighted Average Results

To generate an overall best estimate of the efficacy of the SVC strategies tested in our simulations across new homes in California, we calculated weighted average results for exposure, air exchange and ventilation site and TDV energy savings (see 0 for our weighted average method). These weighted average values are presented without auxiliary fan sensing in Table 5 and with auxiliary fan sensing in Table 6.

Overall, the top performing strategies for site energy savings are CutOff, VarRe and VarQ, with ventilation site energy savings ranging from 41-51%, while increasing the whole house ventilation substantially from 0.285 hr^{-1} in the baseline to 0.37 or 0.39 hr^{-1} (by roughly by one-third). While potentially unintuitive, in order to be equivalent with the exposure at a fixed airflow, the average of time-varying flows must be increased (Nazaroff, 2009). The smart controls compensate for this greater overall airflow requirement and still save energy by shifting ventilation away from extreme weather and towards mild periods. The worst performing controls increased energy use, because they failed to sufficiently shift these increased airflows to periods of mild outdoor temperature. Most of the control types achieve ASHRAE 62.2-2016 compliance in 70-90% of the cases, with the most complex, seasonal-shifting controls having the lowest compliance fractions.

In all control types, the weighted average real exposure is less than the estimated control exposure, because of inclusion of auxiliary fan airflows in the real air flow estimate. The real exposure calculation is also impacted by time varying natural infiltration that could either increase or decrease the real effective ventilation rates.

Site energy and TDV energy often show substantially different results. The VarQ controller shows strongly elevated TDV ventilation energy savings (61%), much higher than the other top-performing CutOff and VarRe controls (46 and 36%, respectively). This is because the VarQ controller saves more cooling energy than the other top performers (see Section 0) by fully turning the IAQ fan off during peak cooling hours, rather than just reducing the ventilation rate, as is done by the VarRe and CutOff controls. This gets greater credit in TDV assessments, due to higher multipliers for electricity vs. natural gas, especially during peak cooling periods. Similarly, the Seasonal and Occupancy controls both have positive ventilation site energy savings, while TDV savings are either effectively 0% (e.g., Occupancy) or negative (e.g., Seasonal). Again, this is due to the emphasis of TDV assessments on electrical cooling consumption during peak hours. Particularly for the Seasonal controller, weighted average site savings are 20%, while TDV ventilation energy use increases by 15%. Unfortunately, this is predictable based on the structure of the controller, which reduces ventilation rates in the heating season and increases ventilation during the cooling season, when strong TDV penalties exist during peak hours. The Occupancy controller turns ventilation off during the daytime hours, but then doubles ventilation airflows during the late afternoon when occupants return home, once again with predictable impacts during peak cooling hours.

While less robust than our ventilation energy savings, the EnergyPlus simulations estimate whole house HVAC savings of 12-15% for the top performing controls and slightly lower TDV whole house savings of 6-10%.

Control Type	*Compliance Fraction (%)*	*Controller Exposure*	*Real Exposure*	*AER* (hr^{-1})	*Site Energy*			*TDV Energy*		
					Ventilation (%)	*Total (kWh /year)*	*Total (%)*	*Ventilation (%)*	*Total (kWh /year)*	*Total (%)*
Baseline Fan	NA	1.038	1.003	0.285	0.0	0	0.0	0.0	0	0.0
Baseline No Fan	NA	3.085	2.404	0.135	100.0	1112	30.0	100.0	4382	17.8
CutOff	75	0.975	0.868	0.386	41.2	413	12.2	46.4	2094	7.9
Lockout	22	0.984	0.959	0.314	4.3	36	1.6	2.6	152	0.4
MedRe	84	0.962	0.894	0.342	-2.5	-60	-0.6	10.6	596	1.6
Occ	79	0.998	0.945	0.284	5.5	79	1.2	0.2	2	0.0
Season	96	0.973	0.875	0.363	19.8	210	6.2	-15.2	-698	-2.6
VarQ	67	0.972	0.883	0.369	48.3	480	14.8	60.7	2743	10.4
VarRe	77	0.982	0.871	0.376	51.0	505	15.0	36.2	1615	6.1

Table 5 Weighted average summary results for SVC without auxiliary fan sensing, including relative exposure, air exchange rates, site and TDV energy savings.

Including auxiliary fan sensing boosts ventilation site energy savings by 5 to 15% (see Table 6), due to reductions in air exchange rates. The top-performing controls had the smallest benefit from auxilliary fan sensing. Though still compliant with ventilation standards, this increases the real contaminant exposure. VarRe weighted average TDV savings increase a lot more than the VarQ TDV savings when including auxiliary fan sensing. Yet, VarQ still outperforms the VarRe, with 67 vs. 48% weighted average TDV savings.

Control Type	*Compliance Fraction (%)*	*Controller Exposure*	*Real Exposure*	*AER (hr^{-1})*	*Site Energy*			*TDV Energy*		
					Ventilation (%)	*Total (kWh /year)*	*Total (%)*	*Ventilation (%)*	*Total (kWh /year)*	*Total (%)*
Baseline Fan	NA	0.948	1.003	0.285	0.0	0	0.0	0.0	0	0.0
Baseline No Fan	NA	2.271	2.404	0.135	100.0	1112	30.0	100.0	4382	17.8
CutOff	94	0.936	0.908	0.371	49.7	515	15.0	52.6	2350	9.3
Lockout	53	0.983	1.011	0.305	19.5	177	6.0	16.3	702	2.9
MedRe	94	0.952	0.977	0.309	16.2	155	4.9	25.8	1237	4.3
Occ	94	0.991	1.018	0.265	18.2	217	4.9	15.1	619	2.7
Season	98	0.961	0.946	0.337	35.1	379	11.2	2.2	108	0.7
VarQ	90	0.925	0.925	0.349	55.4	571	17.1	66.8	3009	11.7
VarRe	98	0.945	0.923	0.357	57.8	606	17.4	48.1	2094	8.5

Table 6 Weighted average summary results for SVC with auxiliary fan sensing, including relative exposure, air exchange rates, site and TDV energy savings.

Savings by End-Use

Energy end-use savings are aggregated by control type and plotted in Figure 17 for both site and TDV energy. Site energy (right-hand panel) is strongly dominated by heating energy savings in all controls, with over 90% of total savings falling into the heating category (except for Occupancy, due to its IAQ fan savings). TDV energy end-use savings shift more towards an even divide between heating and cooling category savings. In the best performing controls (VarQ, VarRe and CutOff), cooling end-use TDV savings make up slightly less than 50% of total TDV savings. TDV energy use focuses more on electrical cooling energy use during peak times, which helps to explain these higher fractions of cooling TDV energy savings. Air handler savings (and IAQ fan increases) also grew as a fraction of the total TDV energy.

The VarQ controller had the greatest TDV savings, largely because of its improved cooling performance. The VarQ control fully turned the smart IAQ fan off during particularly hot periods, which aligned almost perfectly with peak TDV hours in the summer. The CutOff and VarRe controls, in contrast, only reduced ventilation rates during these hours, rather than fully curtailing them. The Seasonal controller predictably increased cooling energy consumption, both site and TDV, because it increased ventilation rates during the cooling season and decreased them in heating, with predictable cooling energy penalties. The emphasis of TDV energy performance on electricity consumption during peak cooling hours leads to this net-negative effect.

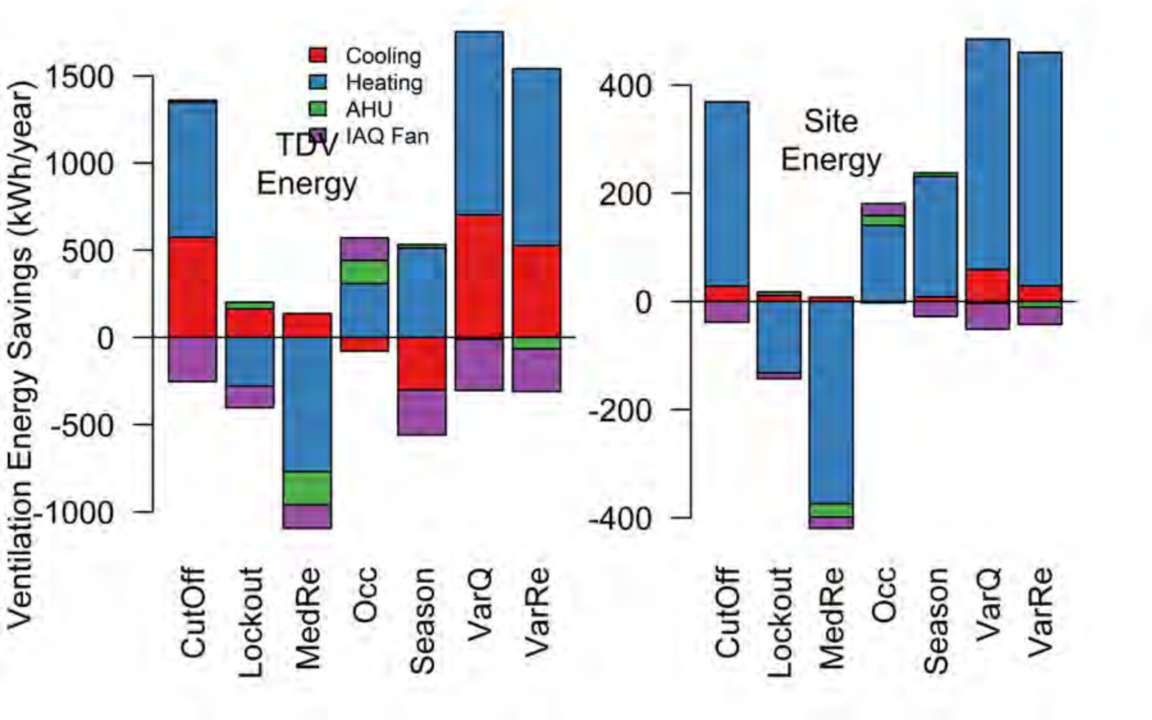

Figure 17 Median ventilation energy savings by end-use category, site and TDV energy. Aggregated by control type.

Maximum Savings for Each Case

In each of the 24 cases (i.e., combinations of climate, house prototype and airtightness), we identified the smart control strategy with the maximum ventilation energy savings. Ventilation energy savings for these best-performing controls are plotted below for site energy % savings (Figure 18), site energy kWh savings (Figure 19), TDV energy % savings (Figure 20) and TDV energy kWh savings (Figure 21). Along with ventilation energy savings, each plot also includes the change in real relative exposure, with negative values indicating improvement in IAQ relative to the baseline constant fan case. As illustrated below, ventilation site energy can be reduced by 20-70%, saving 200-1,500 kWh/year, and ventilation TDV energy varies over a similar range of percent savings, saving 500-4,000 kWh/year of TDV energy. This is achieved while complying with the ASHRAE ventilation standard requirement that annual occupied relative exposure be below 1.0. In fact, most of the best performing cases reduced real exposure and improved IAQ relative to the baseline constant fan cases.

Across these four energy savings metrics, we see that the VarRe and VarQ controls consistently save the most energy (pink and grey bars), with select cases having greatest savings with Season, CutOff or Occupancy. Specifically, the temperature controls were generally ineffective in CZ1 (Arcata), so in those cases, occupancy-based smart controls (yellow bars) often had the greatest savings, albeit at low levels and sometimes with increased energy use.

Percent ventilation savings and absolute kWh savings have related but distinct patterns. For example, percent site savings appear greatest in CZ10, varying between roughly 35-60%. Yet, absolute kWh site savings are similar in CZ3 and CZ10, and are in fact substantially larger in CZ16. This highlights an important distinction, which is that the baseline IAQ fan ventilation energy use varies across climates, and savings are referenced against that baseline usage. Baseline ventilation energy use is sensitive to climate region (energy use is greatest in cold locations) and to baseline IAQ fan airflows, which are affected by envelope leakage and house prototype.

So, similar absolute savings, or even greater absolute savings can appear as less successful in terms of percent savings. This is evident for differing levels of envelope leakage, as well, because the baseline IAQ fan flows are smaller in leakier homes. For example, percent site savings appear consistent across the 1, 3 and 5 ACH_{50} 1-story homes in CZ10 (if anything savings increase with leakage), yet when assessing absolute kWh savings, we see that the leakier cases in fact save less energy than their tight counterparts. The absolute energy savings (both site and TDV) show this reasonably consistently: that the most airtight homes save the most absolute energy, but often have marginally lower percent savings. House prototypes have mixed effects. In some climate zones, the 1-story cases appear to have the greatest savings, while in other climates the 2-story are the best performing. This inconsistency exists for both percent and absolute energy savings.

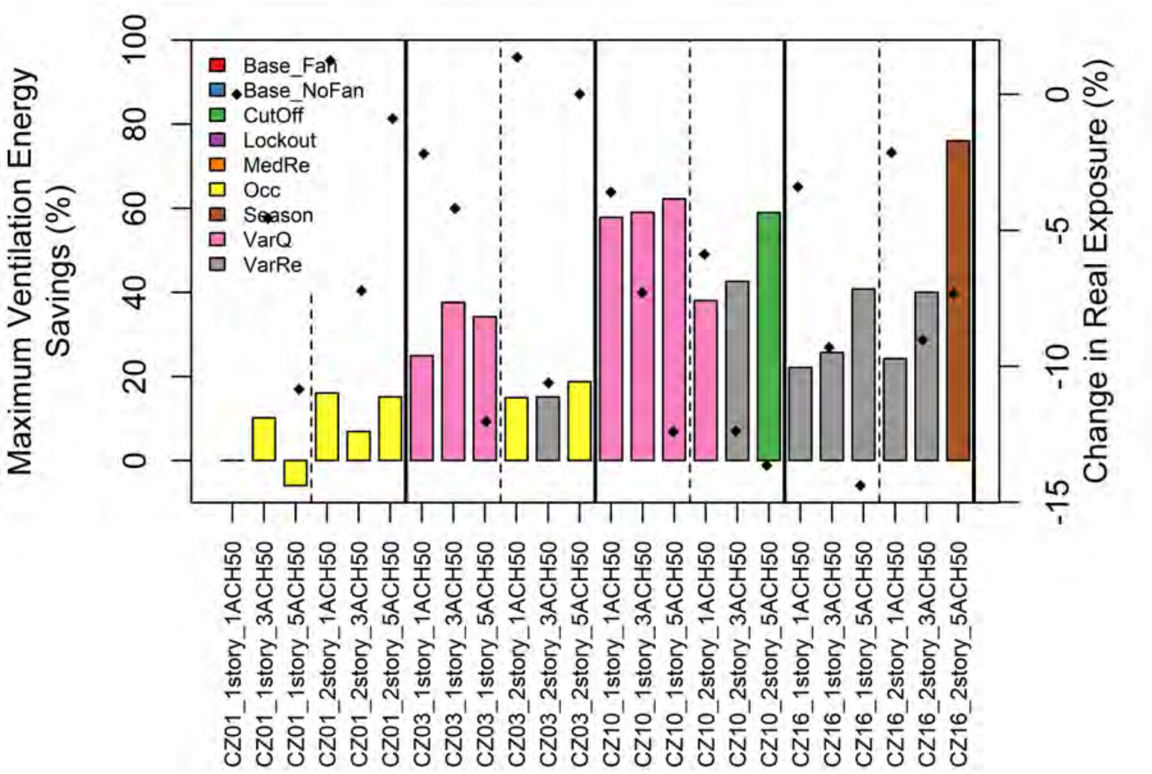

Figure 18 Maximum ventilation energy savings (%) for each compliant case. Colored by control type. Diamond symbols show the change in real relative exposure for the maximum savings case. Negative changes in real exposure represent improved IAQ.

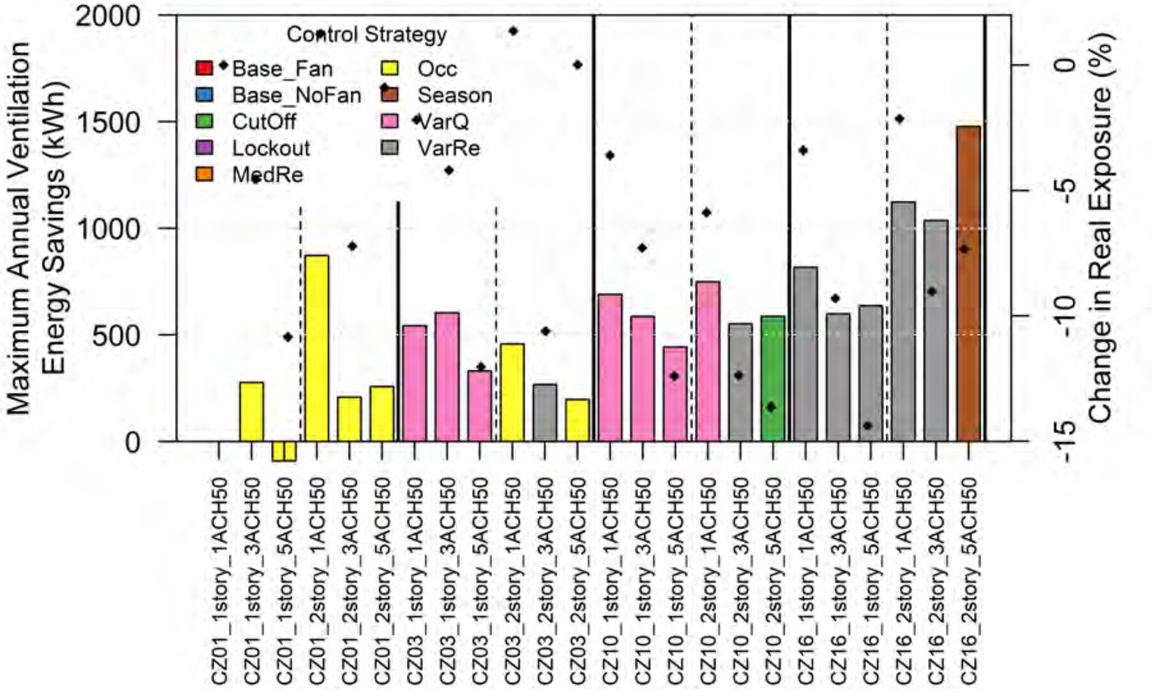

Figure 19 Maximum ventilation energy savings (kWh) for each compliant case. Colored by control type. Diamond symbols show the change in real relative exposure for the maximum savings case.

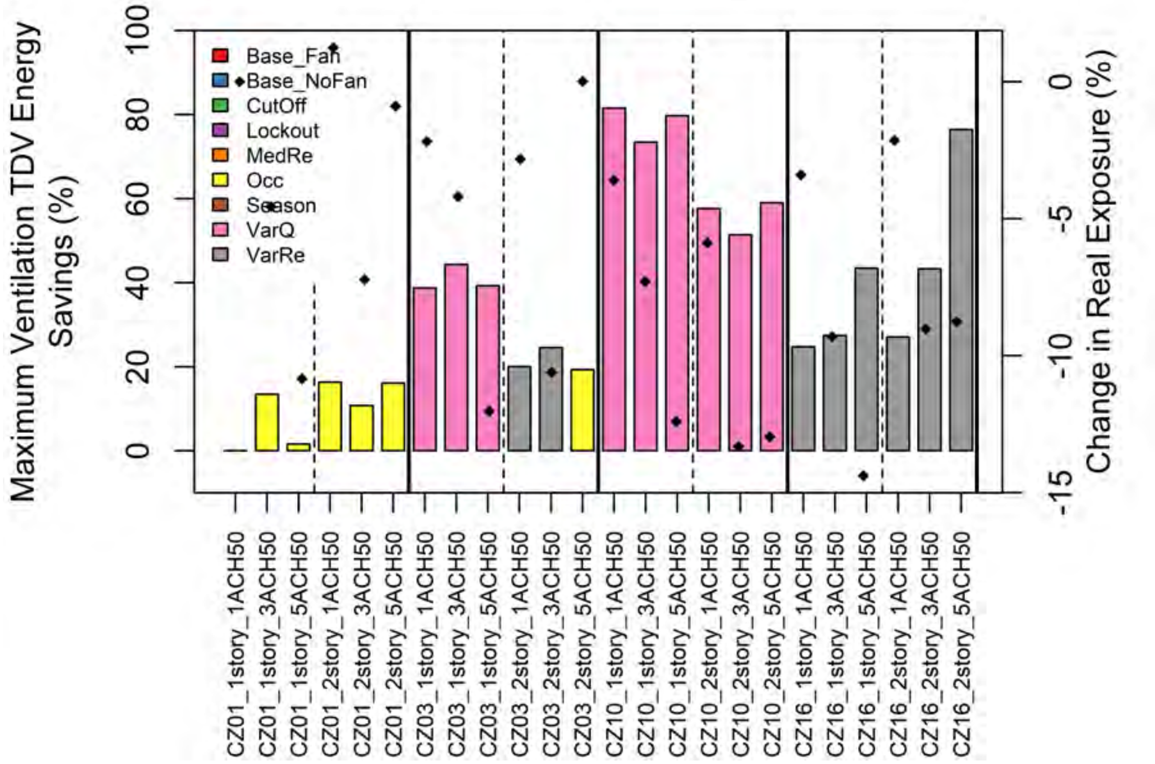

Figure 20 Maximum TDV ventilation energy savings (%) for each compliant case. Colored by control type. Diamond symbols show reduction in real relative exposure for the maximum savings case.

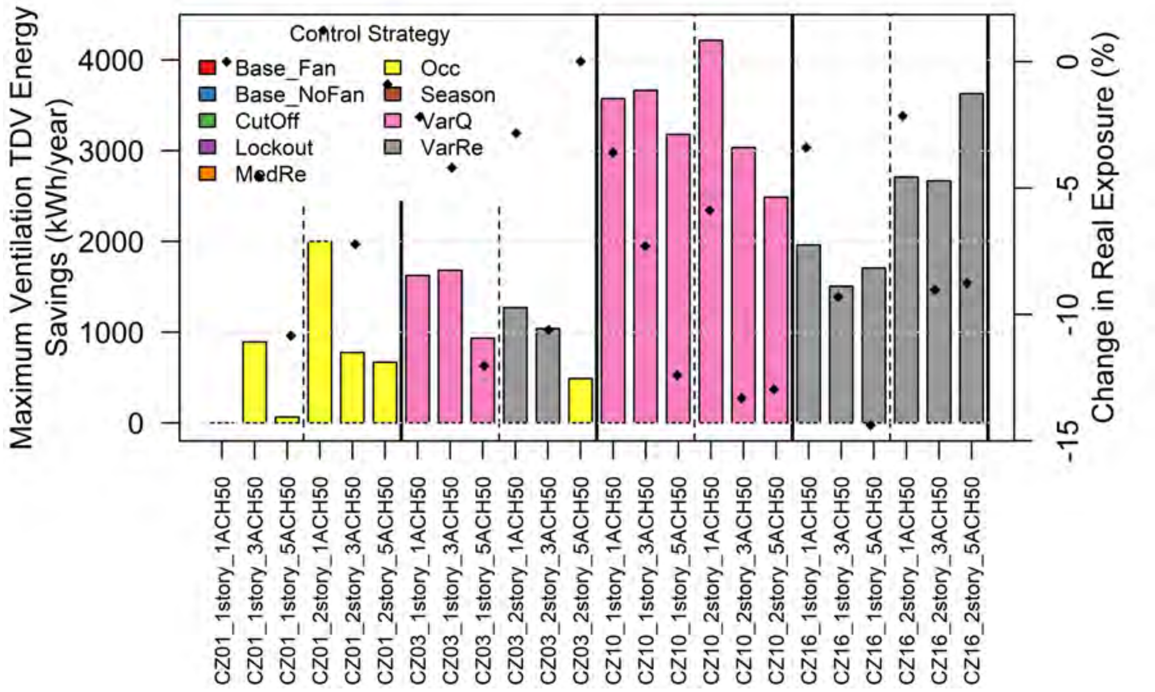

Figure 21 Maximum TDV ventilation energy savings (kWh) for each compliant case. Colored by control type. Diamond symbols show reduction in real relative exposure for the maximum savings case.

Peak Demand Savings

None of these controllers were specifically optimized around shedding peak load. Nevertheless, we assessed peak demand by looking at average watt draw and total site and TDV energy consumption during the peak 2-6pm period on the hottest 10-days of the year, according to the weather files for each climate zone. We show the demand reduction in watts and in percent of total site HVAC energy use aggregated by control type in Figure 22 and Figure 23, respectively. Using only cases from one of the most effective peak saving controls (VarRe), we then show peak demand reduction (watts) by climate zone in Figure 24.

Changes in peak demand varied from roughly a 200-watt increase to savings of 300 watts during peak periods. For the most successful control types (VarRe, VarQ, Lockout and Cutoff), this translated into 0-25% of total HVAC site energy consumption during the peak periods. As we show in Figure 24 for the VarQ control, for the well-performing controls, the energy use increases occur only in CZ1 in Arcata, where slightly more cooling load is introduced. This happens because the controllers think that there is no cooling season in Arcata, so they over-ventilate substantially during the warmest periods, increasing the cooling load very marginally (i.e., total cooling consumption for all CZ cases was 3 or 0 kWh/year).

We also see in Figure 24 that for the VarQ controller (and others) savings are greatest in CZ10 (averaging roughly 250 watts), which has the highest cooling demand of any location we assessed. Notably, the VarRe controller had quite low (<100 watts) savings in CZ10, because the optimized control parameters did not sufficiently reduce ventilation rates during hot weather, rather they emphasized ventilation rate reductions in the heating season. This issue could be avoided by using TDV energy directly in the optimization schemes, or by not independently optimizing heating and cooling season peak RE values, which should lead to larger reductions in ventilation during hot periods (see Section 0 and 0).

It is worth noting that HVAC sizing has substantial impacts on the potential for peak load reductions in homes. We ran some additional simulations in CZ10 such that the cooling runtime was 100% during the peak 2-6pm periods of the hottest days of the year, in both baseline and control cases. This might be considered "ideal" sizing. The additional simulations found that there were no savings, even though the smart control case will have slightly lower loads and cooler indoor temperatures. This demonstrated an important point, which is that "right" sized HVAC systems, which are designed to run continuously during design conditions, will have essentially no ability to reduce peak demand on the grid. This is also the case for any systems that run continuously during peak periods, whether "right" sized or not.

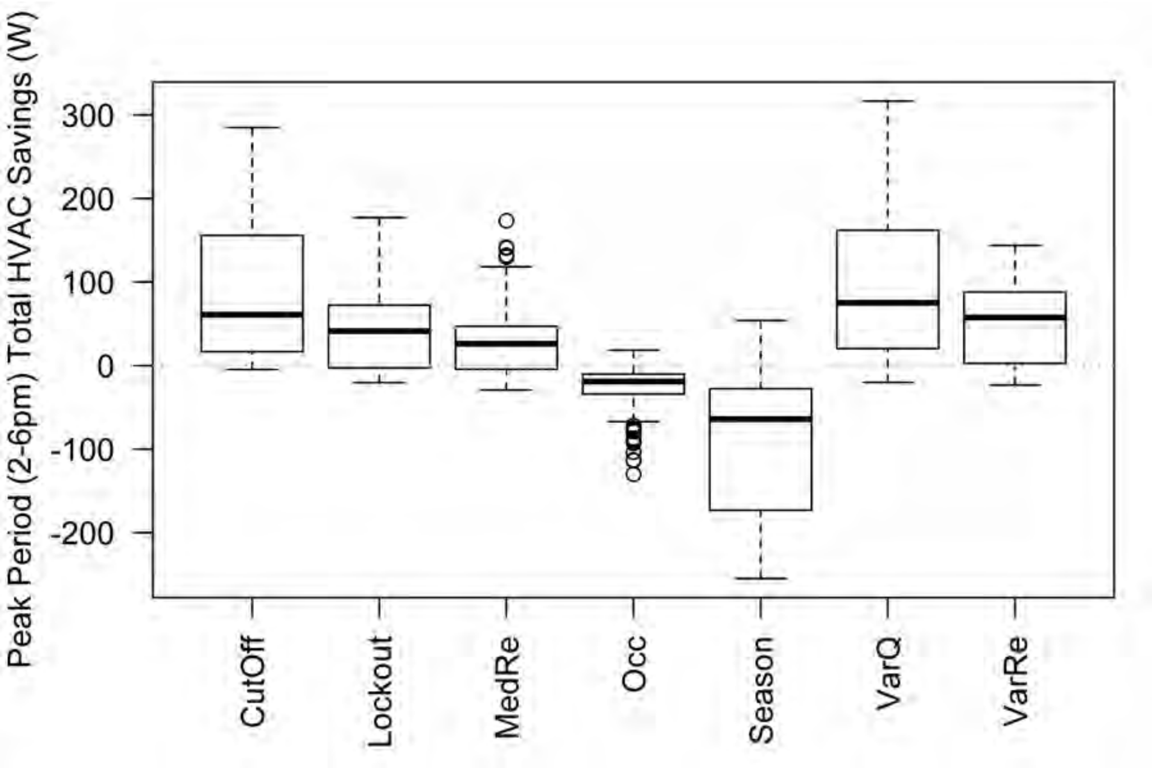

Figure 22 Peak demand (Watts) reduction on the 10 hottest days of the year, 2-6pm, by control type.

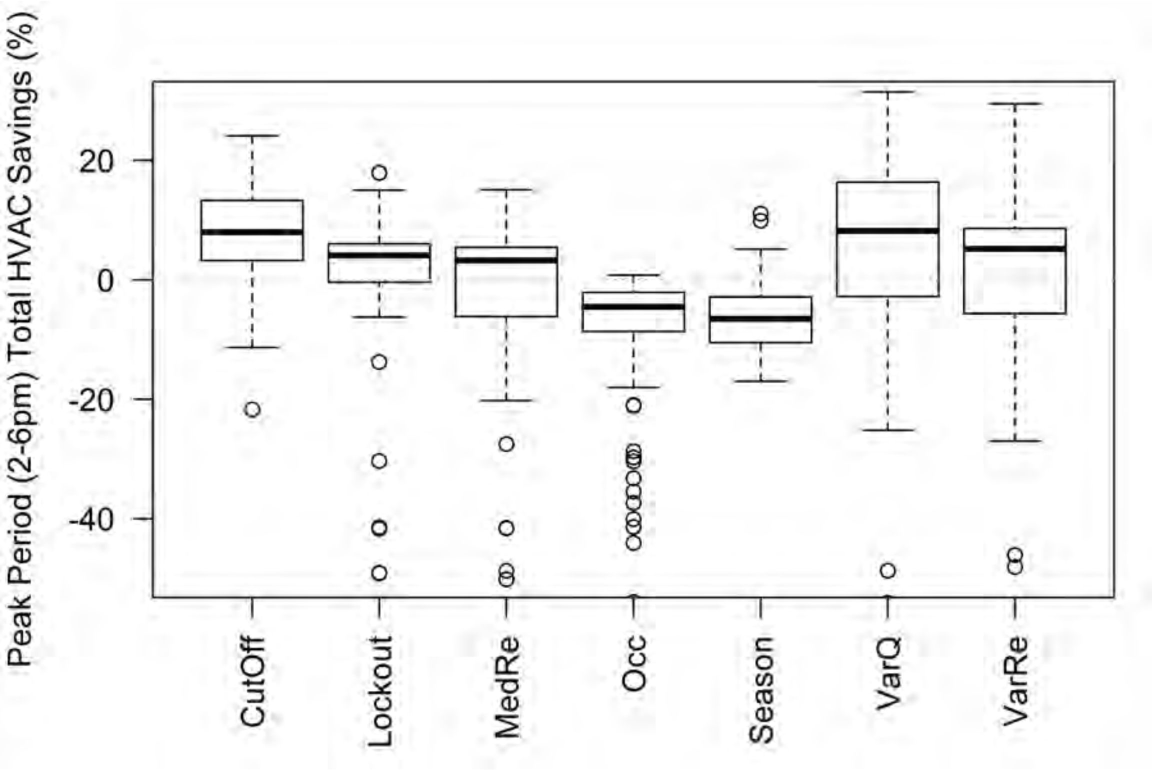

Figure 23 Total HVAC site energy savings on the 10 hottest days of the year, 2-6pm, by control type.

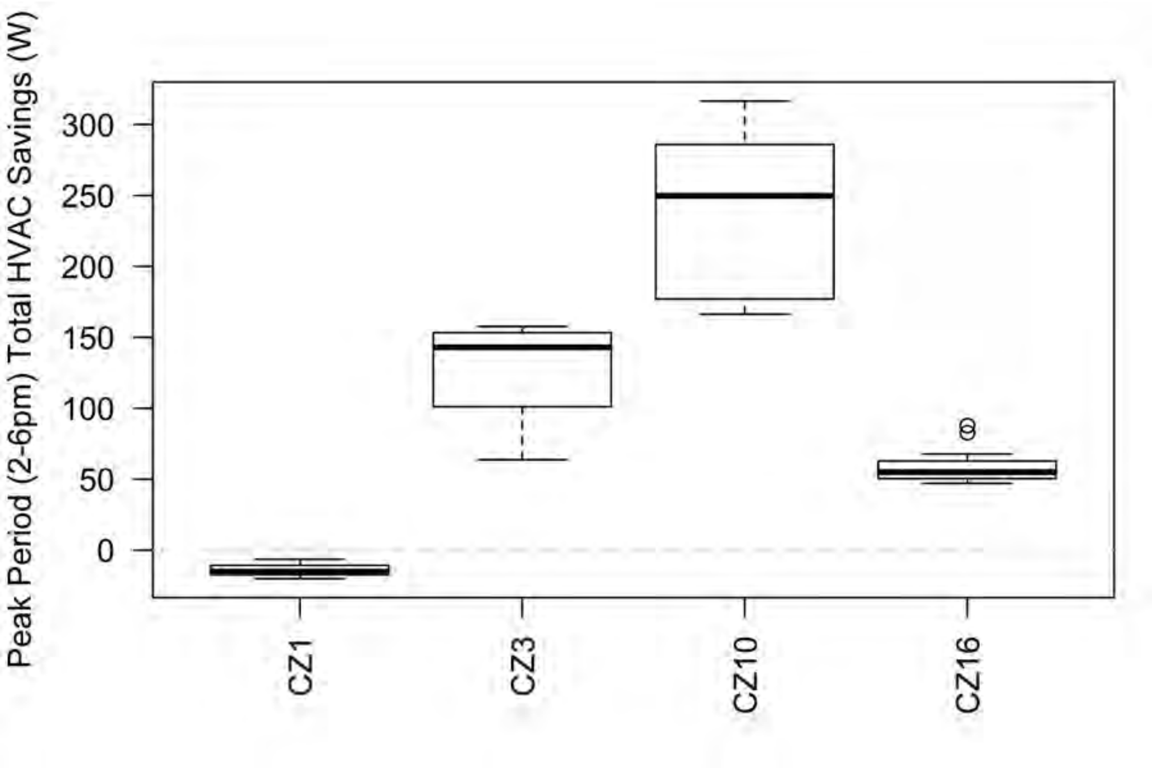

Figure 24 Peak demand (Watts) reduction for the VarQ controller on the 10 hottest days of the year, 2-6pm, by climate zone.

Normalized Energy Savings Summary

In the raw simulation outputs presented in the prior sections, the relative exposure is not always equal to one, either in the baseline continuous fan or smart control cases. So, the energy savings are estimated for cases where the predicted indoor air quality is not the same. To provide energy savings estimates for cases with identical IAQ, we also normalized the site and TDV energy results by the annual mean real exposure for each case. These normalized results represent the performance of perfectly designed/operated smart ventilation controls, compared with perfectly sized baseline continuous IAQ fans. The normalization method is explained in 0.

We compare the normalized savings values with the previously presented raw savings results on a case-by-case basis below. Scatterplots of the percent ventilation energy savings are shown for site energy in Figure 25 and for TDV energy in Figure 26, with all baseline cases removed from analysis. Each scatterplot includes the unity line with a slope of 1 (blue) and a linear regression line (red). For both site and TDV energy, we see that normalization tended to increase predicted ventilation energy savings in most cases (most values are above the blue unity line and so is the red regression line). Select cases had reduced savings when normalized. These are smart control cases that had relative exposures greater than one, so normalization actually increased their predicted energy consumption and reduced their savings relative to the baseline continuous fan cases.

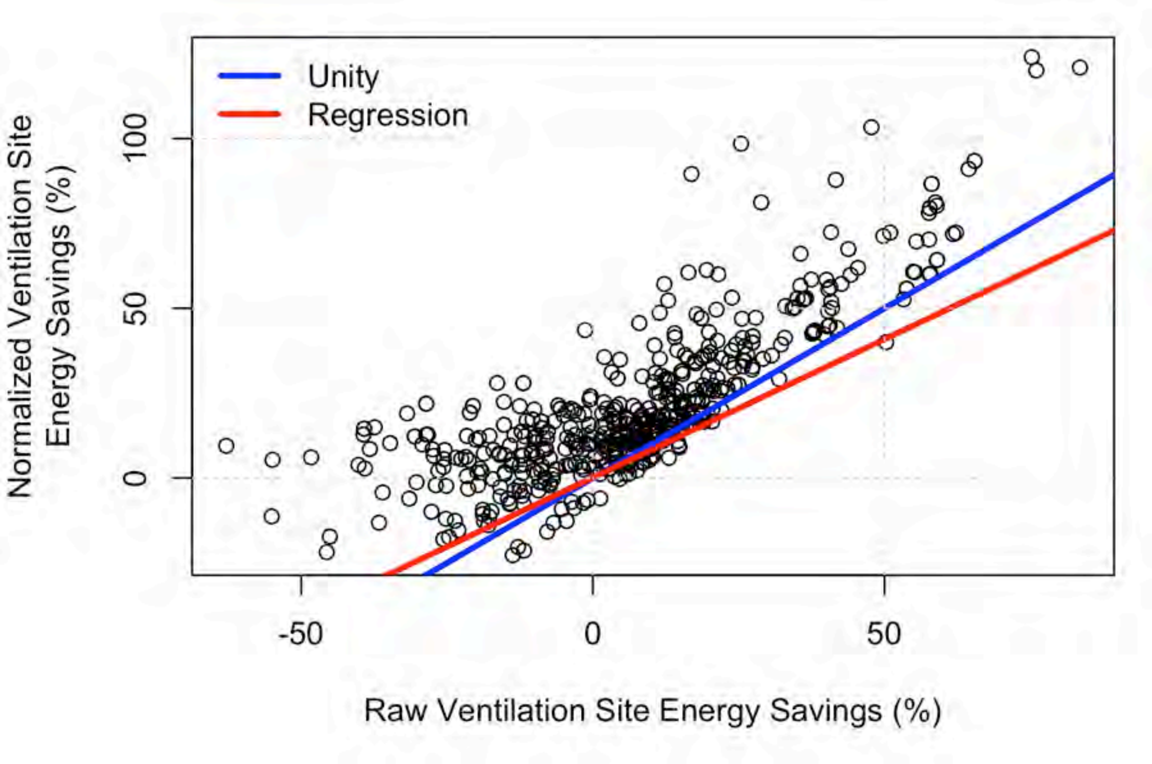

Figure 25 Scatterplot comparing raw vs. normalized site HVAC energy savings. Baseline cases removed.

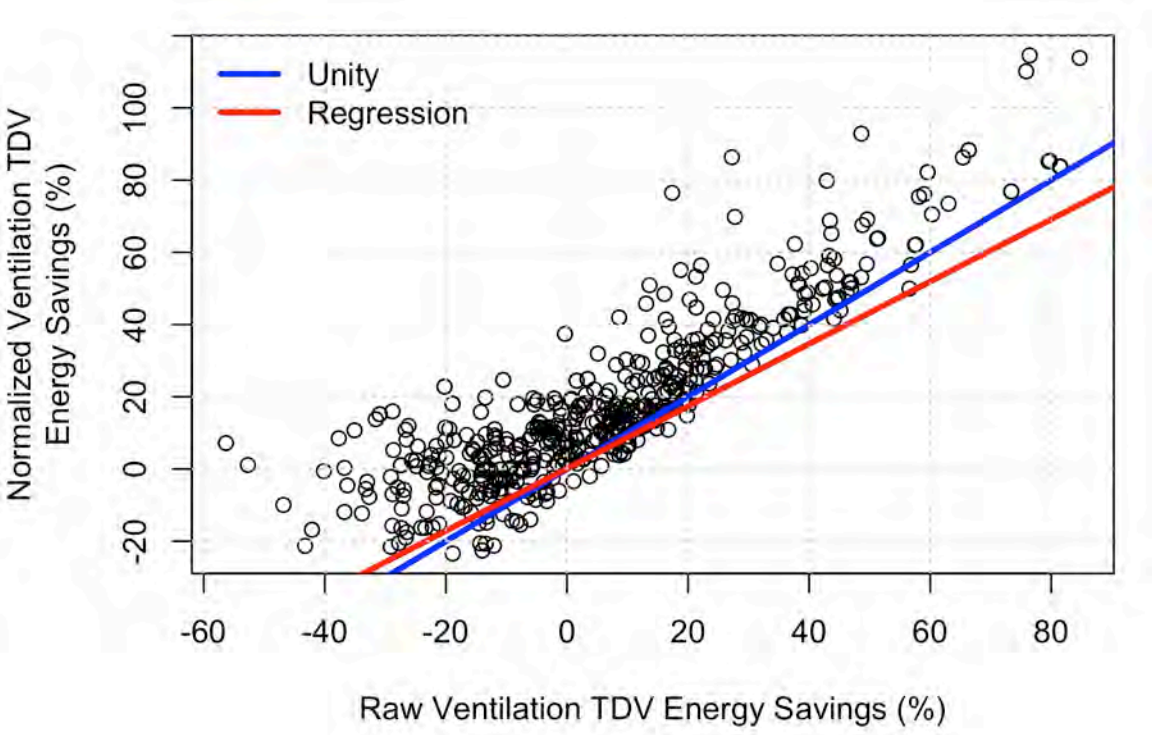

Figure 26 Scatterplot comparing raw vs. normalized TDV HVAC energy savings. Baseline cases removed.

Weighted Average Results

The weighted average normalized performance for each control type is summarized in Table 7 with no auxiliary fan accounting. Compliance fractions are 100% and all controller exposure values were 1.0. The real exposure and air exchange rates were not normalized and are not reported.

The weighted average site energy performance for the VarQ and VarRe controllers are very similar, with average ventilation energy savings of 61% and 64% (site savings of 635 and 676 kWh/year), respectively. These represent total HVAC site savings of roughly 18-19%. For comparison, these same two controllers had 48 and 51% ventilation site savings for un-normalized, compliant cases (see Table 5 in Section 0). The Cutoff SVC was the next best performing controller (weighted mean savings of 56%), while all others lagged substantially behind these top performers, with savings between 15 and 36% of site ventilation energy.

TDV ventilation savings were clearly the greatest for the VarQ controller, with weighted average savings of 68%, compared with 51 and 58% in the VarRe and CutOff controllers. TDV energy savings averaged 3,004 kWh/year in the VarQ cases, representing 12% of total HVAC TDV consumption.

The trends in these results are similar to those based on the raw results (see Section 0), but the savings are roughly 10% higher on average when normalized.

The other notable difference is that no control types increased ventilation energy use on a weighted average basis, whereas the raw results had some controllers with negative savings.

The three best controls (VarQ, VarRe and CutOff) all shifted ventilation airflows seasonally, with increased flows during summer and reduced flows during winter. In addition, within each season, the best controls also modulated airflows in response to mild or severe conditions. Without this modulation within each season, savings were reduced, as reflected in the weighted average savings for the Season controller (36%). These results suggest that modulation of flows within the season gains another 20-25% ventilation energy savings on top of season-based control. Conversely, the controls that shifted ventilation only within a day (Lockout) or within a month (MedRe) suffered from low savings estimates of 15-16% ventilation energy. Like all dynamic smart ventilation controls, annual airflows were increased in these low-performing controls, but they failed to sufficiently shift these larger flows to milder weather periods, so savings were limited.

Control Type	*Compliance Fraction (%)*	*Controller Exposure*	*Site Energy*			*TDV Energy*		
			Ventilation (%)	*Total (kWh/year)*	*Total (%)*	*Ventilation (%)*	*Total (kWh/year)*	*Total (%)*
Baseline Fan	NA	1	0.0	0	0.0	0.0	0	0.0
Baseline No Fan	NA	1	100.0	1119	30.2	100.0	4380	17.9
CutOff	1	1	56.3	591	16.2	58.0	2544	9.8
Lockout	1	1	16.2	141	5.2	22.3	958	4.1
MedRe	1	1	14.7	148	4.3	21.3	1008	3.5
Occ	1	1	16.1	193	4.3	8.6	338	1.5
Season	1	1	35.9	386	10.9	4.0	181	0.7
VarQ	1	1	60.5	635	18.0	68.0	3004	11.7
VarRe	1	1	63.8	676	18.6	50.8	2180	8.7

Table 7 Weighted average savings estimates for normalized energy consumption. NA values were not subject to the normalization, so are excluded.

Maximum Savings for Each Case

For each simulated home (i.e., combination of climate zone, prototype and airtightness), we selected the control type with the highest energy savings. These are shown for site energy savings (relative in Figure 27 and absolute in Figure 28) and TDV energy savings (relative in Figure 29 and absolute in Figure 30). As expected from the weighted average results in Table 7, the VarQ (pink) and VarRe (grey) controllers are most commonly the best performing for any given home, with some individual cases maximizing savings with the MedRe, CutOff or Occupancy controllers. With the exception of CZ1, most cases were able to achieve site ventilation energy savings between 20 and 80% (500 to 1,500 kWh/year). TDV ventilation energy savings ranged between 20 and 80% (1,000 to 4,000 kWh/year TDV).

When normalized, the maximum percent site energy savings consistently increase with envelope leakage. This is true for all homes and climates. This effect was greatest in CZ16 and least in CZ1 and CZ10. This is because of the interactions between natural infiltration (that vary with airtightness) and mechanical ventilation. The absolute site energy savings do not show the same trend. Instead the site kWh savings vary slightly and unpredictably across envelope leakage levels for any given home, except in CZ16 where the trend still favors greater kWh savings in leakier homes. Notably, while the percent ventilation energy savings in CZ1 were much lower than in other climate regions, the absolute savings are similar to those in CZ3, they just represent smaller fractions of the total ventilation energy consumption because the thermal loads are so much greater in CZ1.

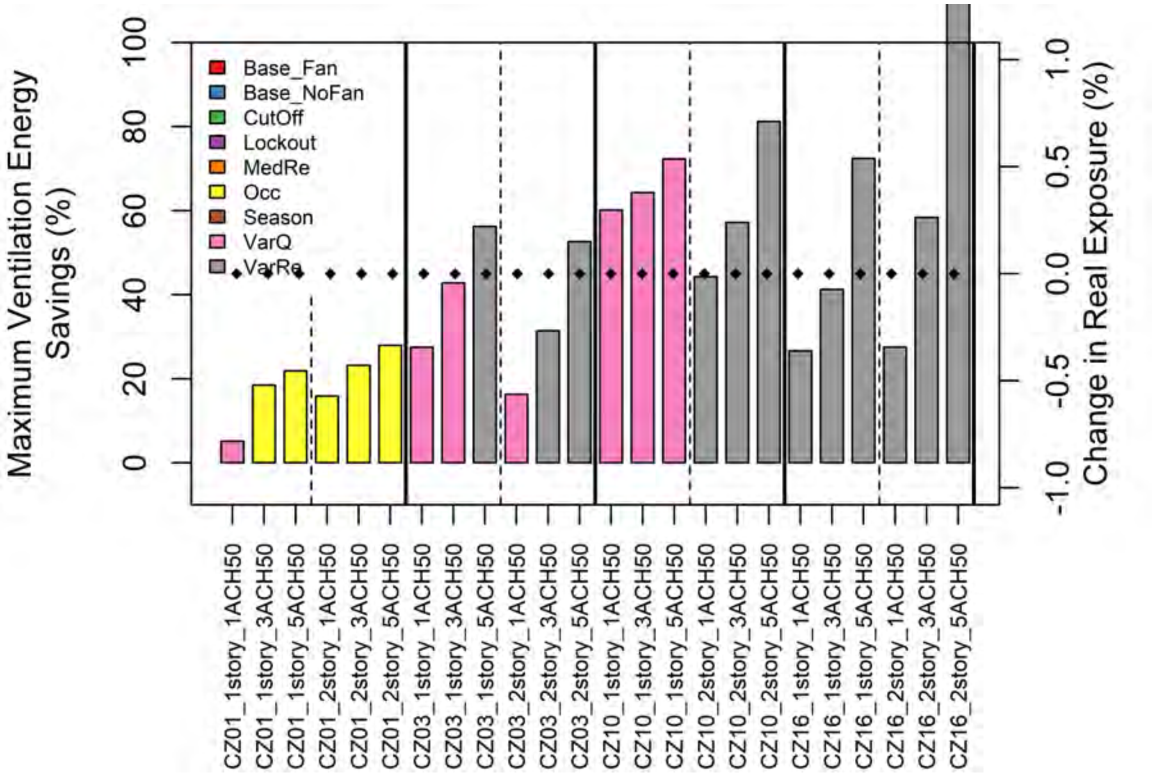

Figure 27 Normalized site energy relative savings. Maximum for each case.

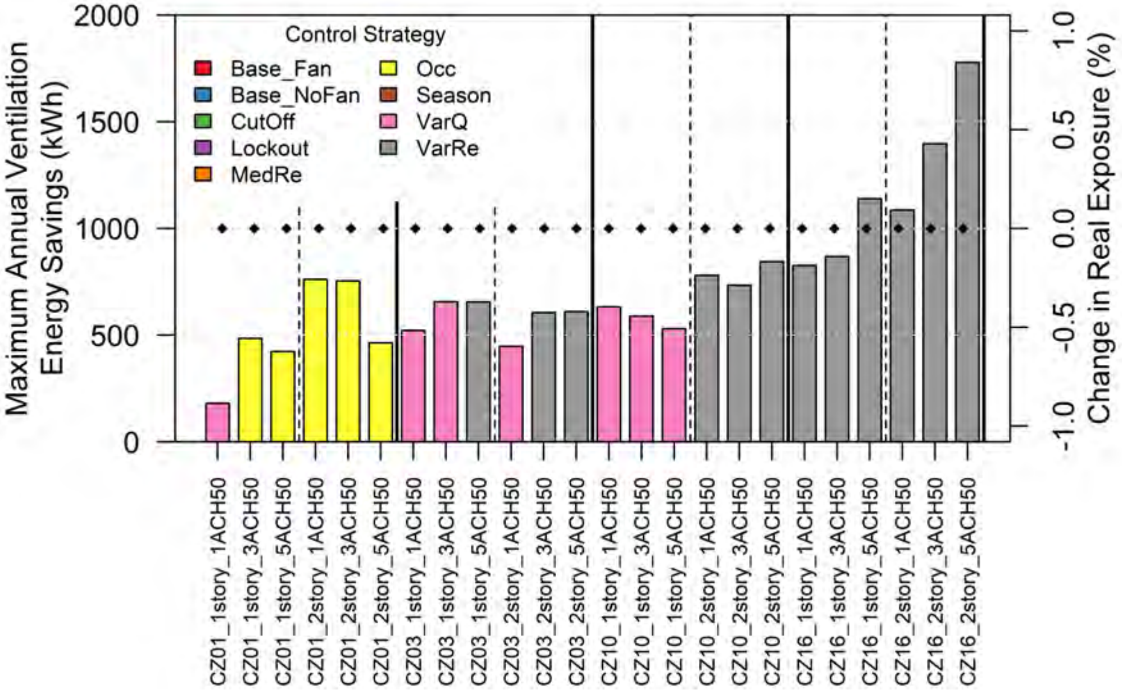

Figure 28 Normalized site energy absolute kWh savings. Maximum for each case.

Percent TDV ventilation energy savings are fairly consistent across CZ3, 10 and 16, while TDV percent savings are much lower in CZ 1 (<25%). Unlike the site energy assessment, the TDV percent savings do not show consistent increases with increasing envelope leakage. This trend is evident in some cases (i.e., CZ16 and 3), but is otherwise erratic. This could be due to the reduced dependency of TDV energy use on envelope leakage, which tends to have stronger impacts on heating energy, due to larger indoor-outdoor temperature differences. Yet, in most locations, absolute TDV kWh energy savings were still reduced as envelope leakage increases. Again, prototype impacts are mixed and lack clear trends. Notably, absolute TDV energy savings are nearly the same in CZ10 and in CZ16, which contrasts sharply with the site energy results, where CZ16 strongly dominated. As noted elsewhere, TDV energy strongly weights electricity consumption, particularly during peak cooling periods, and the VarQ controller’s ability to reduce peak cooling demand ensured its absolute TDV energy savings were similar to those in the much colder CZ16 cases.

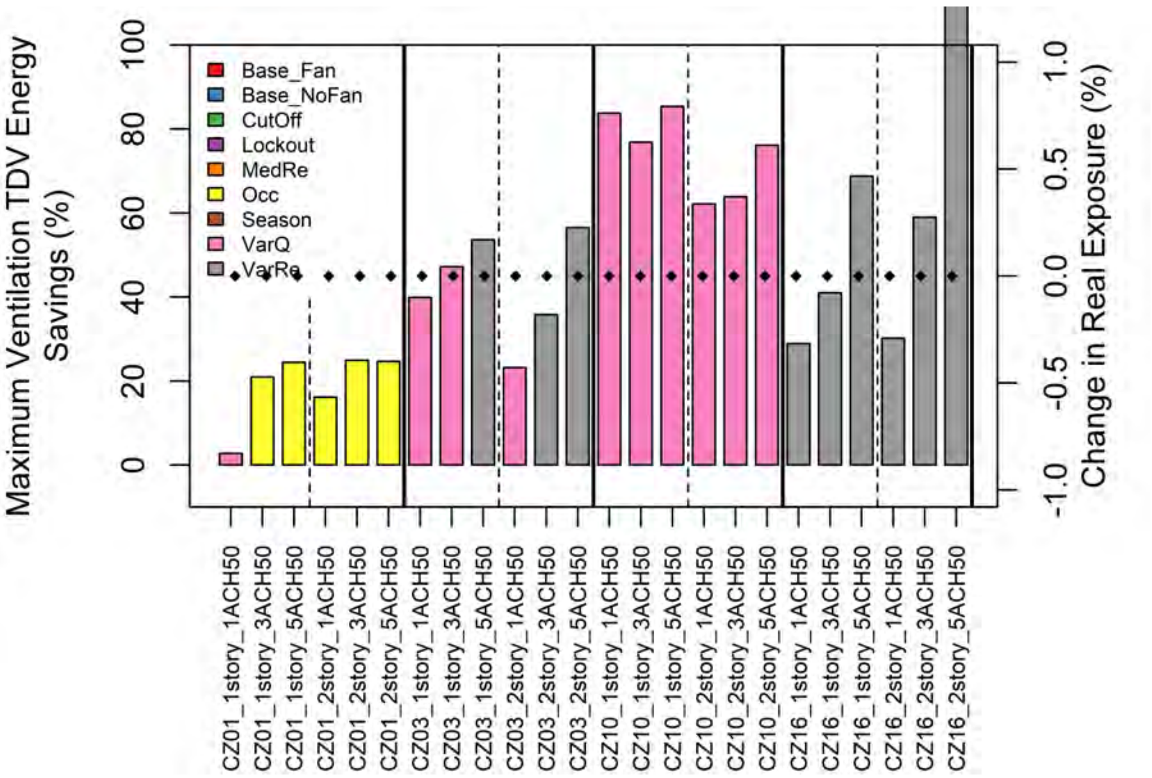

Figure 29 Normalized TDV energy relative savings. Maximum for each case.

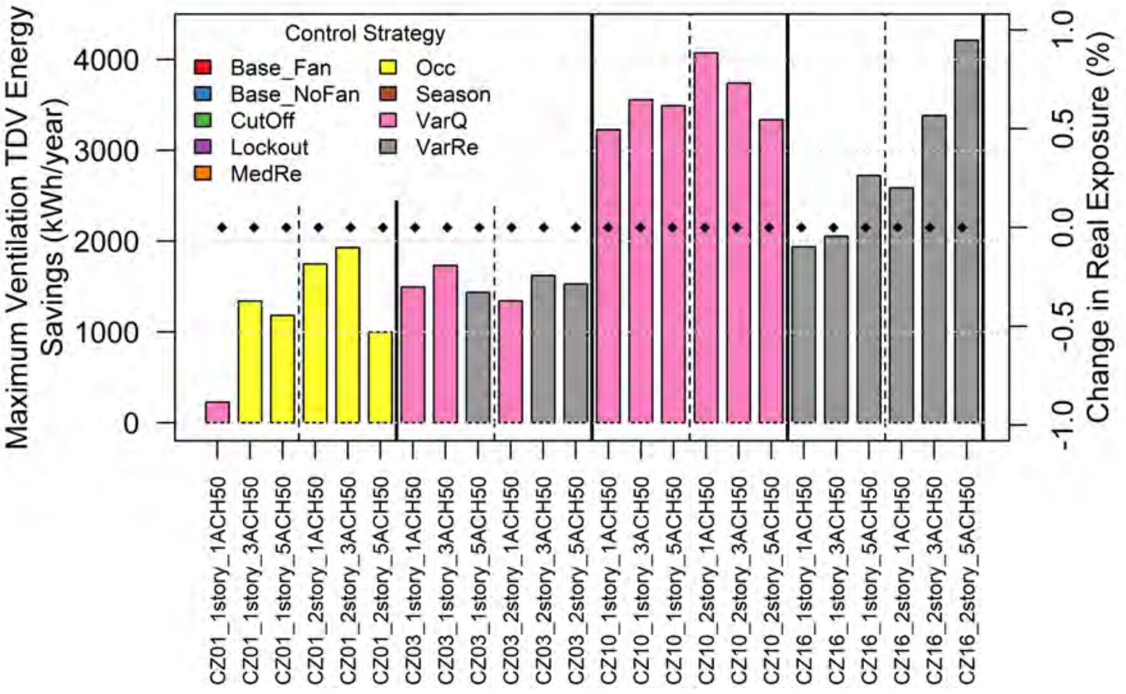

Figure 30 Normalized TDV energy absolute kWh savings. Maximum for each case.

Temperature Controls

Lock-Out Timer Control (Lockout)

For each case (combination of prototype, envelope leakage and climate) we show Lockout controller percent ventilation energy savings for site energy (Figure 31) and TDV (Figure 32) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 33) and TDV (Figure 34).

The results were almost unanimously negative for raw site energy savings, with 0-20% increased ventilation energy consumption in all cases, except CZ10 (Riverside) where marginal savings were estimated of less than 20% of ventilation energy. CZ10 is cooling dominated, and the Lockout control was somewhat effective at reducing cooling energy use, while it was not effective at saving heating energy. This could be due to a misalignment between the duration of the Lockout period (6-hours) and the periods of daily high or low outdoor temperatures. Or it could be due to the temperatures experienced during the non-Lockout hours of the day, which might penalize additional ventilation flows less during the cooling season compared with the heating season. In cases with increase HVAC site energy use, the additional total airflow required to maintain exposure below one overwhelmed the thermal energy benefit of the lockout period, because this increases airflow over all other hours, including the hours immediately before and after the lockout period, where in these California climates the temperature differences can still be substantial. Future work may investigate optimizing the length of the off period for the lockout strategy. There are no consistent trends with envelope leakage, and the infiltration accounting method (Qing vs. AIM-2) has very little impact on savings, positive or negative. When assessing raw TDV savings, the performance remains poor in most locations, with marginal savings around 20% in CZ10 1-story cases.

The normalized results are noticeably different, but the performance of the Lockout control remains marginal. Many more cases achieve positive ventilation energy savings, but they are always less than 20%, and the most airtight homes increase energy use. Performance in CZ10 is actually worsened for the airtight cases, while the leakiest homes increase savings slightly. Also, select 3 and 5 ACH_{50} cases in CZ1, 3 and 16 shift from increased consumption to very small savings. When normalized, we clearly see that the leakiest homes have the greatest percent ventilation savings, and while very similar, the AIM-2 infiltration accounting slightly outperforms the Qinf method.

These raw and normalized results suggest that a controller that shifts ventilation airflow between hours of the day will not be effective on its own, unless the diurnal temperature swings are quite large (as they are CZ10 during cooling season). When diurnal swings are large, the TDV energy benefit from cooling savings can be substantial. This indicates that this could be a simple and effective peak demand saving strategy. This timer-based control type has been shown to be part of an effective smart ventilation controller that combined other features, including occupancy detection and auxiliary fan sensing (Turner & Walker, 2012; Iain S. Walker et al., 2012). But in isolation, this strategy is not effective in most new California homes.

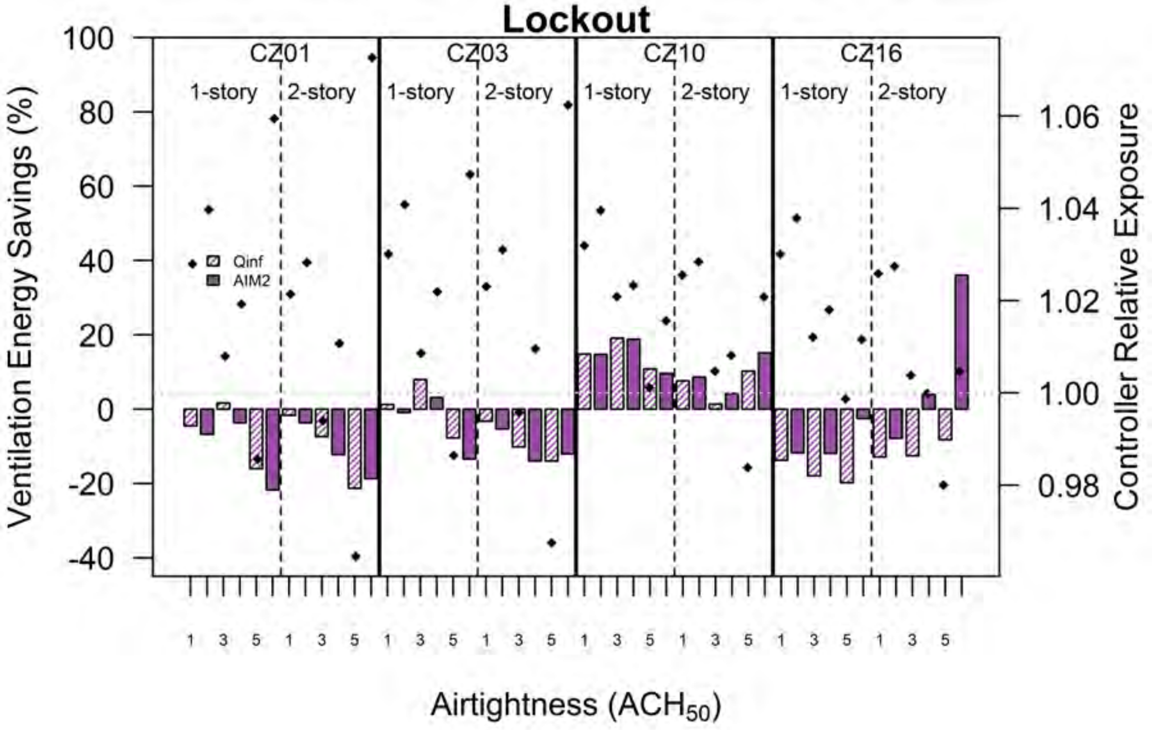

Figure 31 Lockout TSVC ventilation energy savings and controller relative exposure.

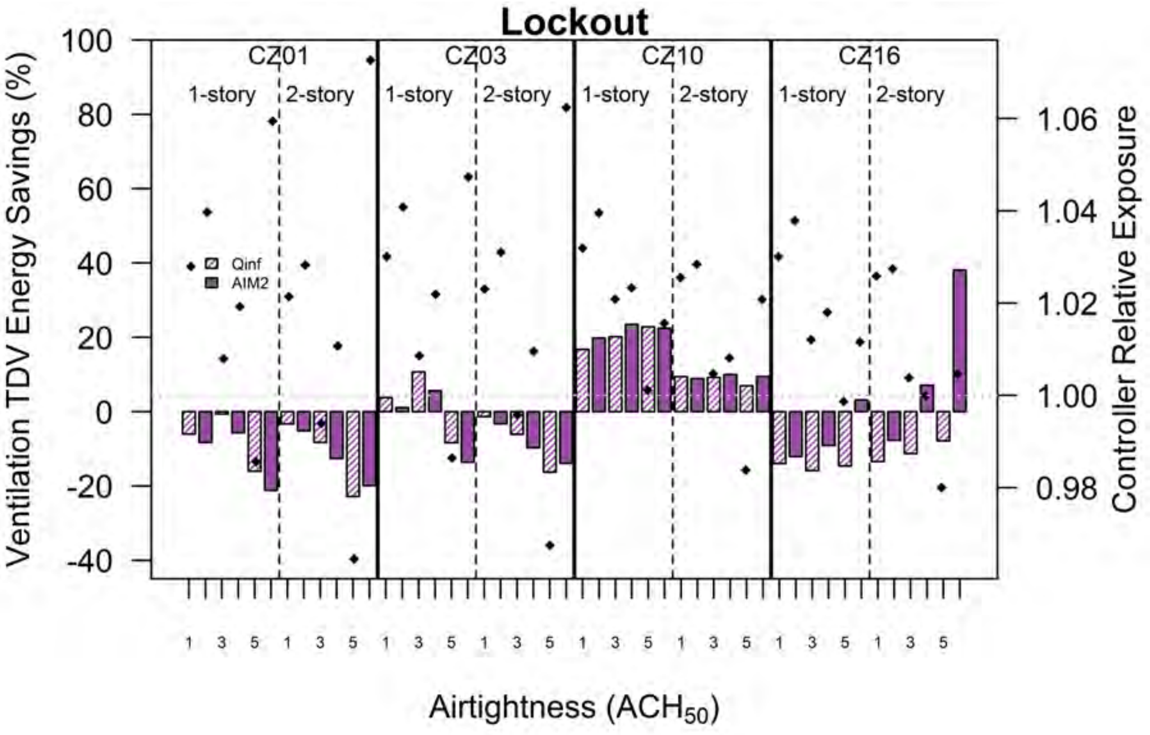

Figure 32 Lockout TSVC ventilation TDV energy savings and controller relative exposure.

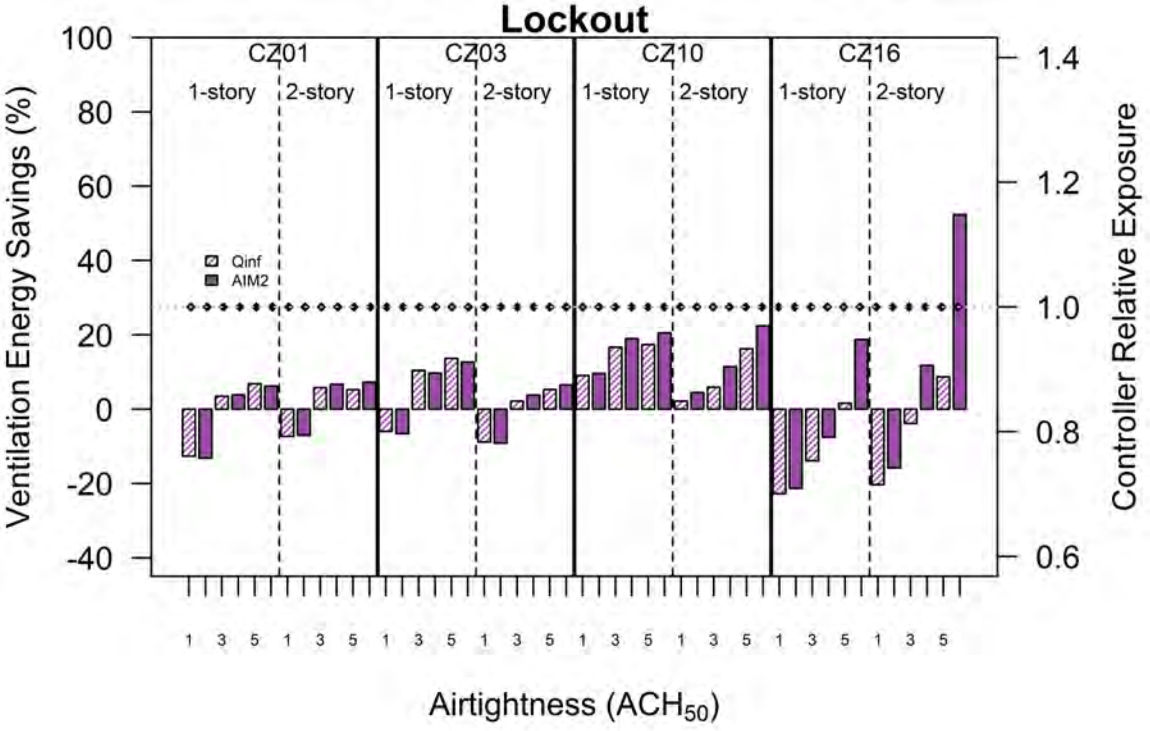

Figure 33 Lockout TSVC normalized ventilation energy savings.

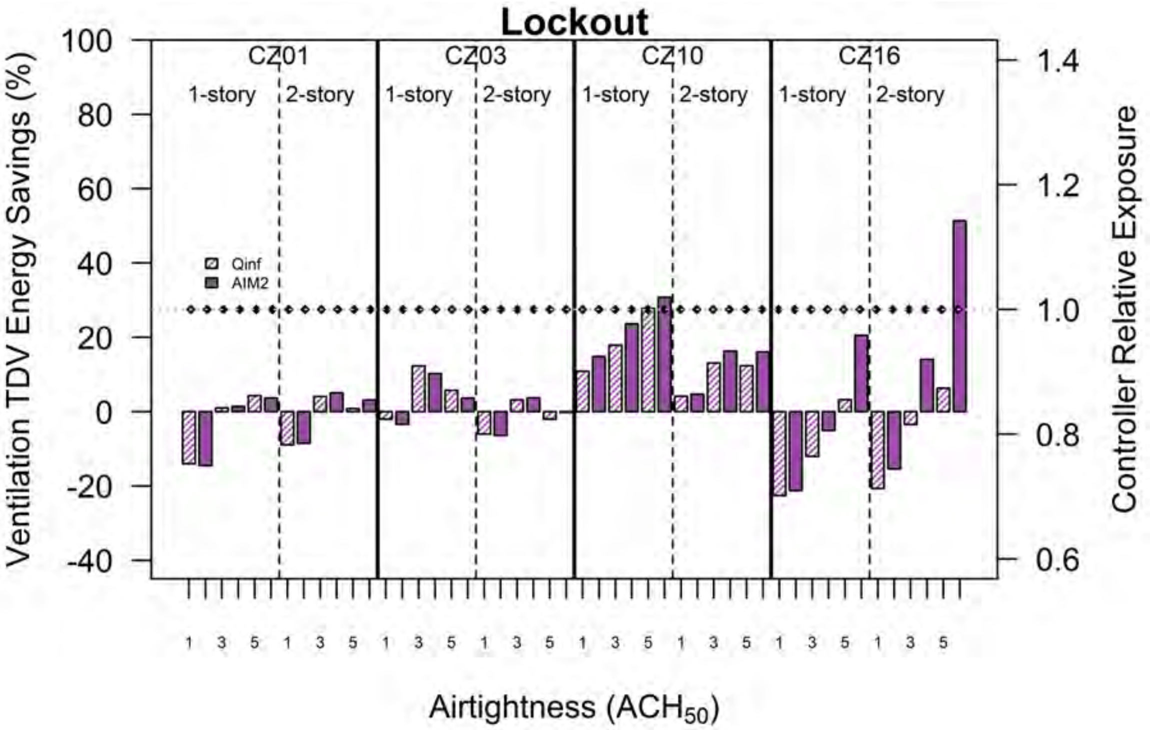

Figure 34 Lockout TSVC normalized ventilation TDV energy savings.

We also assessed the effect of varying the number of lockout hours between 4, 6 and 8 hours with the IAQ fan turned off. Longer lockout periods required larger IAQ fans to maintain exposure below one on daily and annual bases. For CZ10 (the only location with savings), we show the impact of varying lockout hours in Figure 35 for 1-story medium prototypes at 3 and 5 ACH_{50}. The savings clearly increase as the lockout period gets longer, with maximum savings in the 8-hour lockout controls. In locations with large diurnal temperature swings, an 8-hour lockout period appears best, though savings are still marginal, at 10% of ventilation energy.

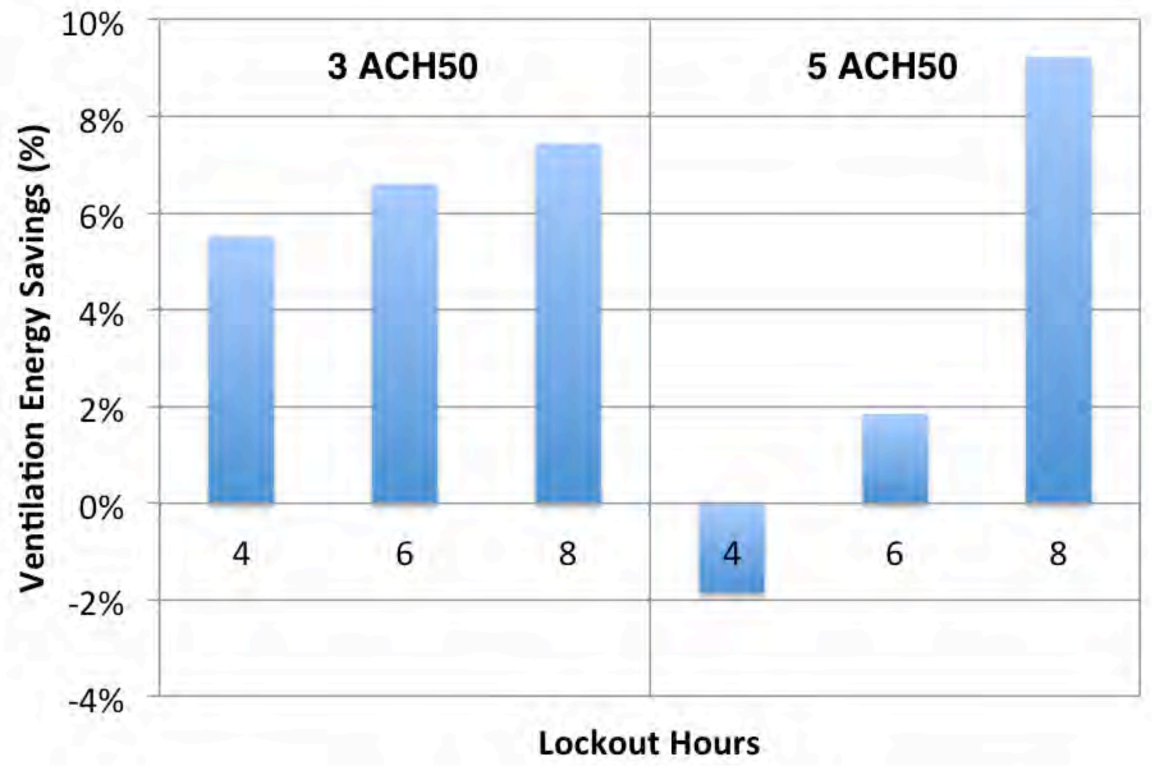

Figure 35 Effect of lockout period on Lockout TSVC performance in CZ10, 1-story medium prototypes with 3 and 5 ACH_{50} airtightness.

Running Median (MedRe)

For each case (combination of prototype, envelope leakage and climate) we show the Running Median controller percent ventilation energy savings for site energy (Figure 36) and TDV (Figure 37) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 38) and TDV (Figure 39).

Overall, the raw data results show that the 30-day running median controller had poor performance in most locations and prototypes, with increased energy consumption between 0 and 30% of ventilation energy. Once again, savings are evident in CZ10, as well as in some of the 2-story 5 ACH_{50} cases in other climate zones, most notably CZ16, where this controller saved almost 40% of ventilation energy in this prototype. No trends are evident by house prototype, envelope leakage, or infiltration accounting method. The raw TDV energy performance was similarly poor across all factors, with select cases in CZ10 having 20-25% savings.

When normalized by relative exposure, many of the increased consumption cases turn into ventilation savings, though almost universally below 20% of ventilation site energy. Percent savings are higher with leakier envelopes and no differences are observable between house prototypes. The infiltration accounting method is varied, with marginally better performance for AIM-2 with some notable exceptions, such as the 2-story 5 ACH_{50} home in CZ16.

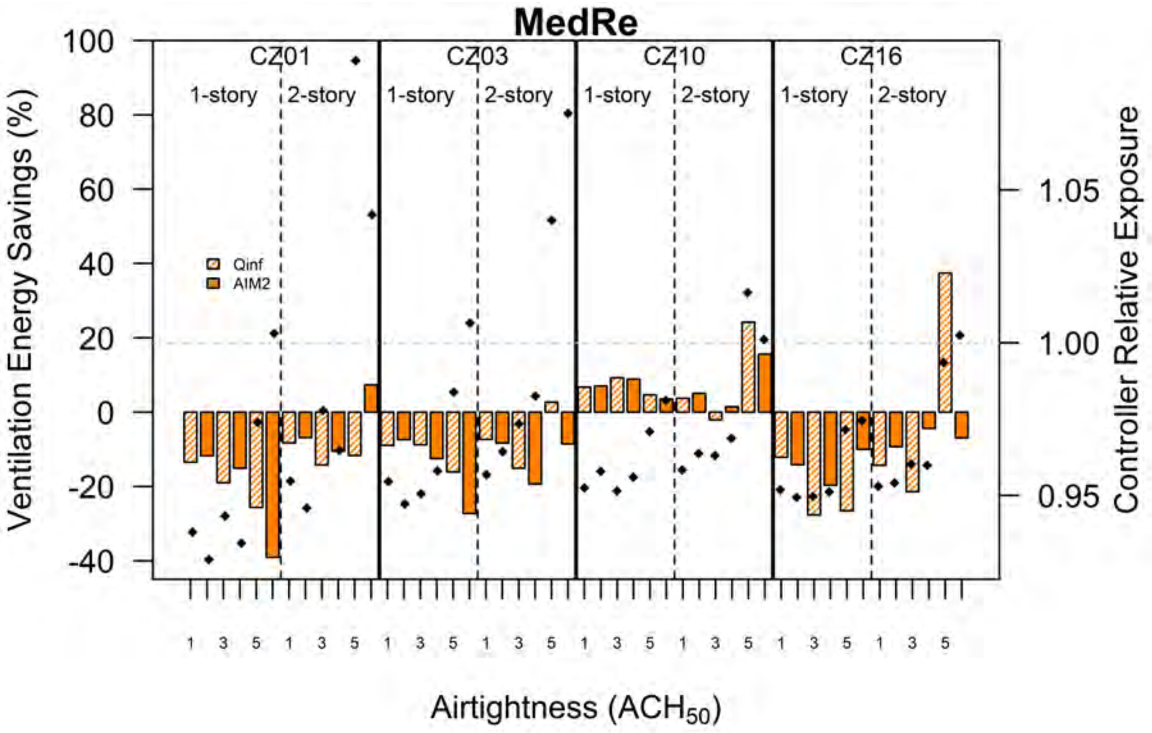

Figure 36 30-day running median TSVC ventilation energy savings.

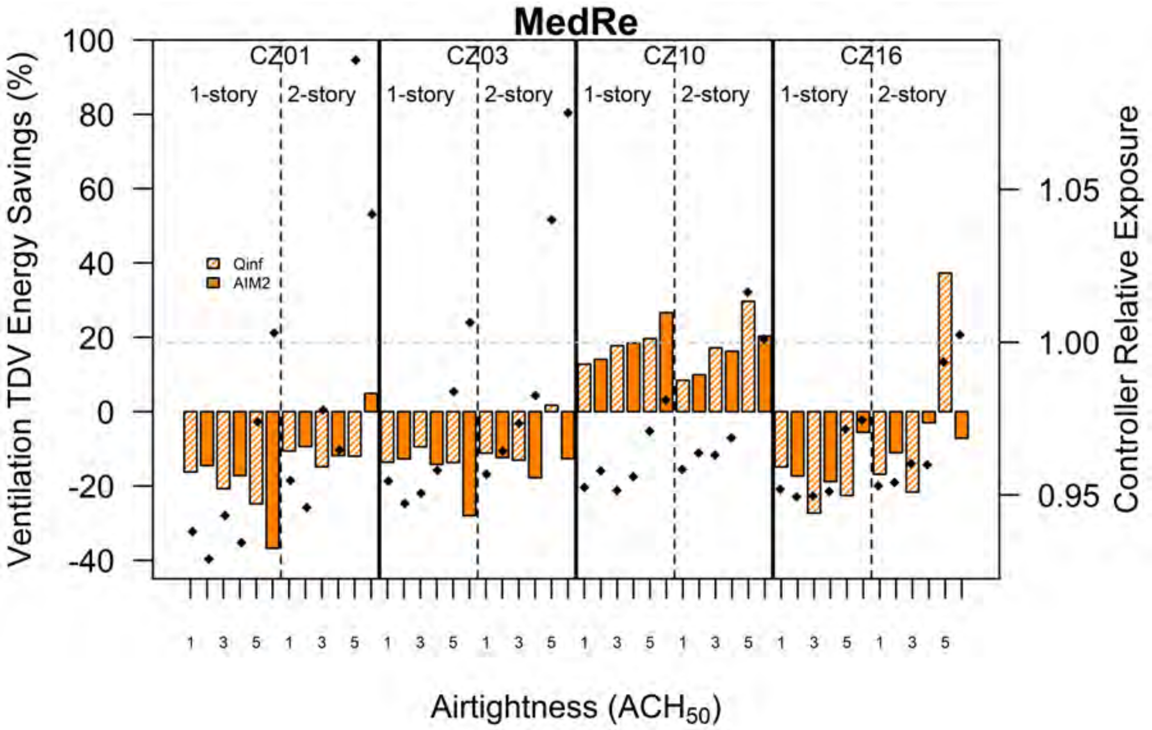

Figure 37 30-day running median TSVC ventilation TDV energy savings.

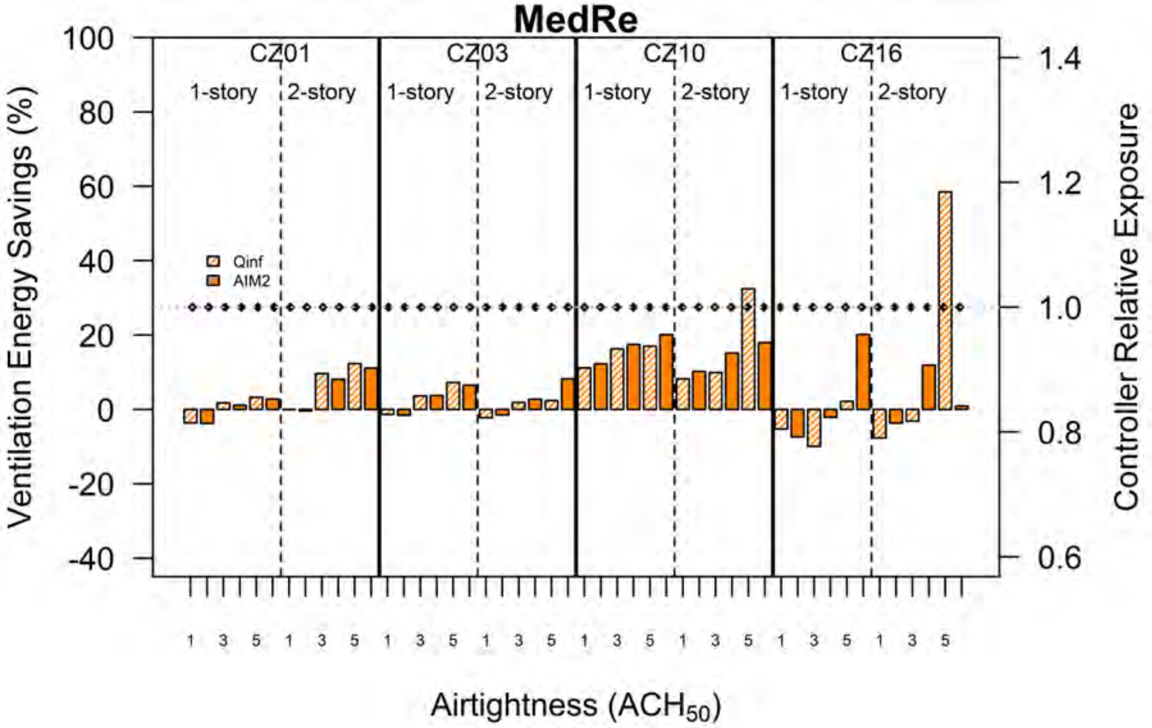

Figure 38 30-day running median TSVC normalized ventilation energy savings.

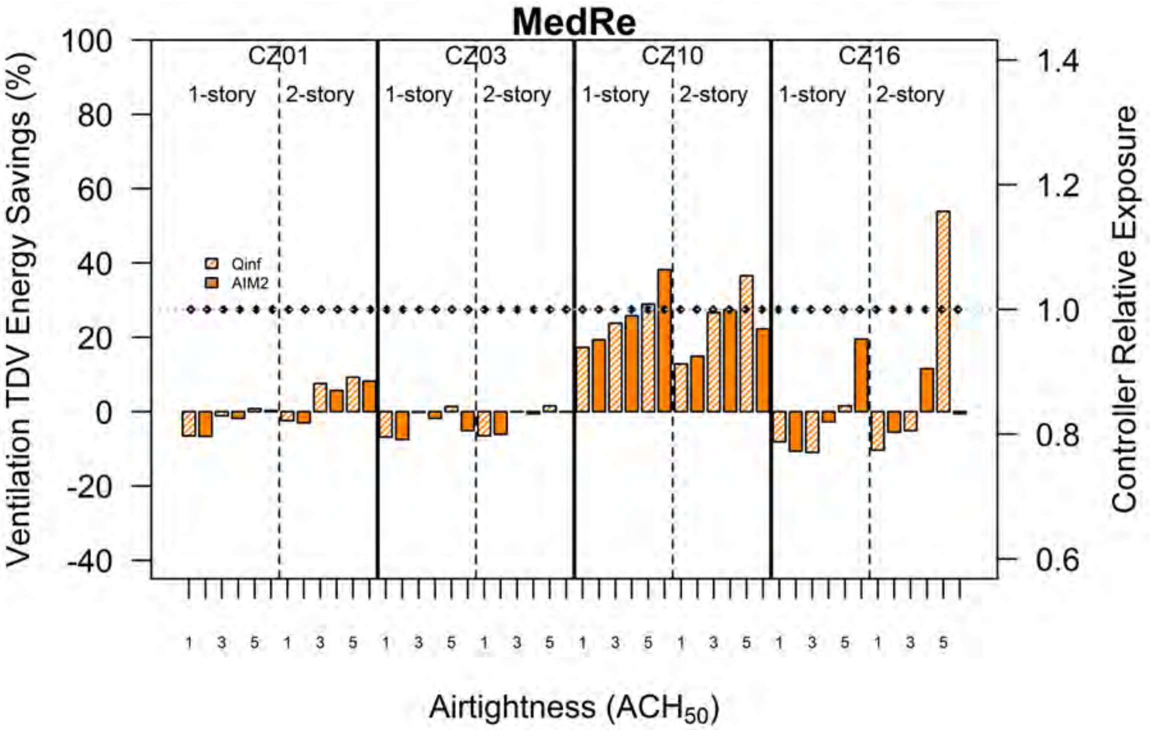

Figure 39 30-day running median TSVC normalized ventilation TDV energy savings.

We provide an example of the monthly controller exposure levels achieved by the 30-day Running Median TSVC for a 1-story medium 5 ACH$_{50}$ prototype in CZ10 with a fan size multiplier of 2 (see Figure 40). Notably, the median exposure for each month is not equal to 1, which results from the inability of the prior month's 30-day running median to adequately predict the distribution of temperatures for the following month. So, the monthly values skew high and low by between 5-10%. Similarly, over the year, the annual average exposure (dotted green line) is above the target exposure of 1.0 (dashed blue line). An illustrative time-series example is provided to illustrate controller behavior in Figure 41.

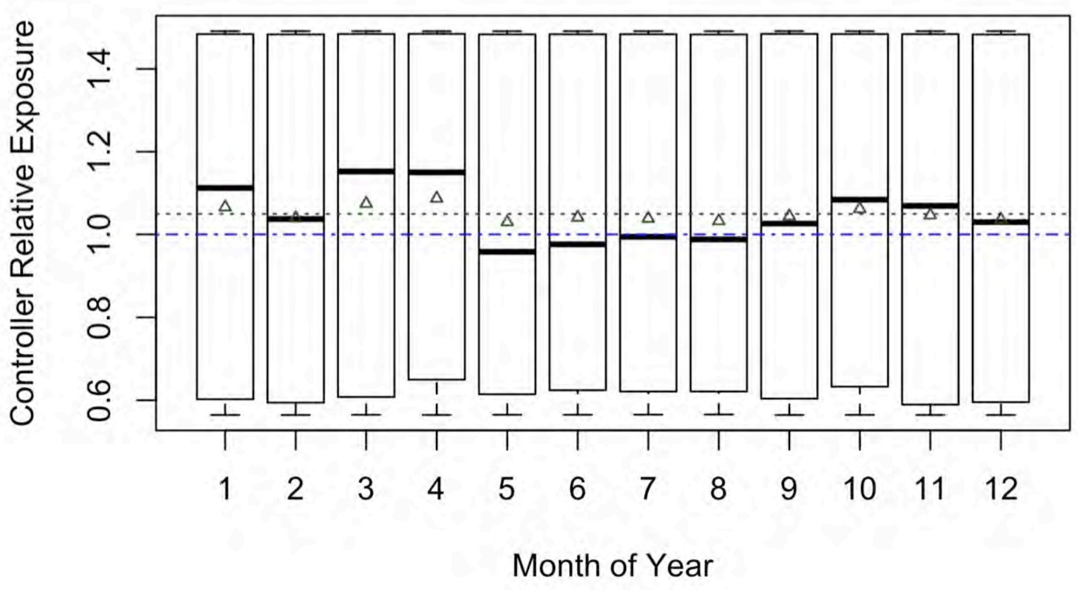

Figure 40 Monthly boxplot distributions of controller relative exposure for a 30-day Running Median example simulation in a 1-story medium 5 ACH_{50} prototype in CZ10 (Riverside). Blue dashed line is at 1.0 and the dotted green line is the annual average exposure achieved.

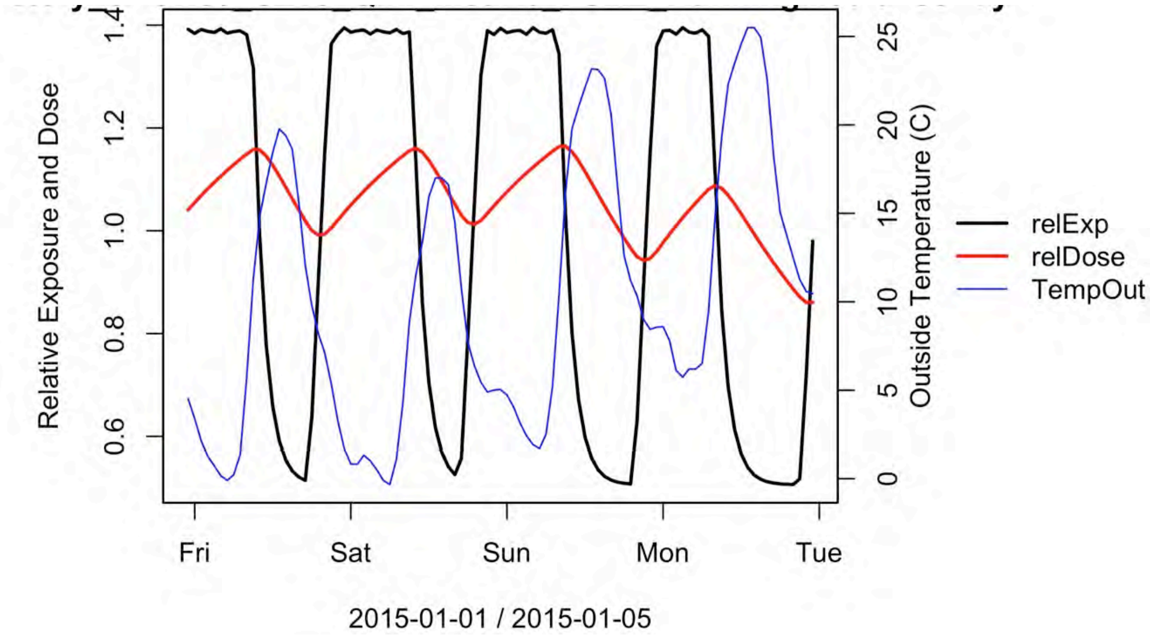

Figure 41 Example of the Running Median TSVC controller. 1-story medium, 3 ACH_{50} home in CZ10 with an FSM of 2. High RE target of 1.4 and low target of 0.5.

As noted above, we found that the running median controller was often not able to maintain equivalence with a continuous fan as designed per 0. In general, we needed to reduce the high RE target (governing the amount of under-ventilation) by 0.2 in order to get annual exposure below one. The reason for this is that the relative exposure is a self-referencing time-series, and it takes time to travel between different values, such as a high and low RE target. It just so happens that in these cases, the controller consistently reaches and maintains the high RE target, while consistently not reaching the low RE target. The result is that you no longer get an average value of one or less. This is illustrated in the example Figure 2 for a 1-story 3 ACH_{50} home in CZ10. The controller consistently achieves and maintains the high RE target of 1.4, but when it increases ventilation to achieve the low target of 0.5, it hardly, if ever, reaches that target. This occurs because the exposure increases more rapidly when the fan is off than it is reduced when the fan is on. The net-effect is to skew the average exposure above one. This will occur to some extent in any cases where the controller cycles between high and low targets on a daily basis.

This inability to reach the low exposure target becomes more of an issue as the natural infiltration rate (Qing) predicted using ASHRAE 62.2-2016 equations increases relative to the target ventilation rate (Total). The reason for this is that our approach to fan over-sizing uses the Fan Size Multiplier (FSM), which is applied only to the 62.2 sized baseline ventilation fan. But the FSM is used in some control types as part of the control algorithm. For example, the target high and low exposure targets used in the running median control are FSM and 1/FSM, respectively. This approach works very well in a very airtight home, where the fan airflow is nearly equal to the whole house airflow. But in the leakier homes, the ventilation fan is only a fraction of the target ventilation rate, so doubling the fan airflow fails to double the whole house airflow. These cases may never be able to achieve 1/FSM as an exposure target. Indeed, Figure 36 shows the controller exposure for the 30-day running median cases, and we see that the exposure is often above 1 for the 2-story 5 ACH_{50} cases. This results from the dynamics described in the prior paragraph, as well as in how the FSM is used to size fans and in the control algorithm itself.

Seasonal (Season)

For each case (combination of prototype, envelope leakage and climate) we show the Seasonal controller percent ventilation energy savings for site energy (Figure 42) and TDV (Figure 43) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 44) and TDV (Figure 45).

Overall, consistent raw savings were predicted with the Seasonal controller in nearly all climate zones and locations. Ventilation energy savings in most scenarios were roughly 20%, with select cases with increased consumption (in CZ3) and others with much higher savings (e.g., 2-story large homes with 5 ACH_{50} leakage in CZ10 and CZ16). There are no clear trends with envelope leakage or prototype, though the 2-story cases have marginally higher savings in some scenarios. The infiltration accounting method is again inconsistent in its effects. The AIM-2 method gives some benefit in CZ10 and 16, while the Qing approach is slightly better in CZ3. Relative exposure (the black diamonds) was very well controlled to the target of 0.97 in nearly all cases. The exceptions were the 2-story 5 ACH_{50} cases, where the noted issue about using the Fan Sizing Multiplier in the control algorithms increased average exposure, because the whole house airflow could not reach a level corresponding with the 1/FSM low exposure target. Notably, this effect is small. When this controller fails to meet the exposure below one requirement, it does so with annual average exposure at most of 1.04.

The raw TDV savings for each case show a strong increase in ventilation TDV energy use in CZ10 (Riverside), which is a cooling dominated location in terms of TDV energy, due to its high electrical cooling loads. The Seasonal controller increases the ventilation rate during the cooling season, in an attempt to reduce heating energy, while sacrificing somewhat higher cooling loads. In most locations, this still results in net-TDV savings, but in cooling-dominated locations, the TDV electricity penalty outweighs heating season benefits. In these cooling climates, TDV ventilation energy increased 20-50%.

Normalized ventilation percent savings are increased across the board, with clear trends towards greater percent savings in homes with leakier envelopes. The trend towards improved performance when using AIM-2 in CZ10 and 16 is clearer when normalized, as is the benefit of the Qinf approach in CZ3. The 2-story prototypes have much higher savings in the leakiest cases, reaching savings in the range of 50-100%. When normalized, TDV energy use still increases in nearly all CZ10 cases, due to the shift of ventilation airflows to the cooling season. CZ16 shows consistent normalized TDV energy savings with the Seasonal control, with increasing savings in leakier, 2-story cases using the AIM-2 infiltration model. The normalized TDV savings are erratic in CZ3, following no clear patterns.

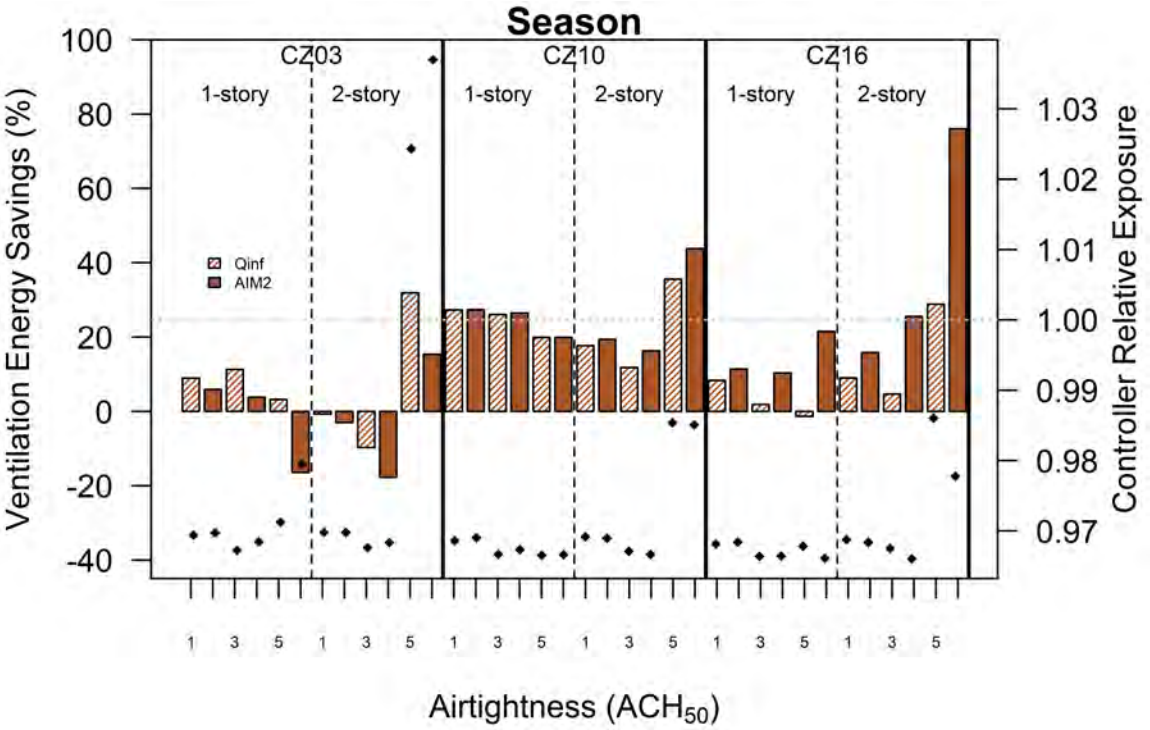

Figure 42 Seasonal TSVC ventilation energy savings. No cases simulated in CZ1, due to lack of cooling season.

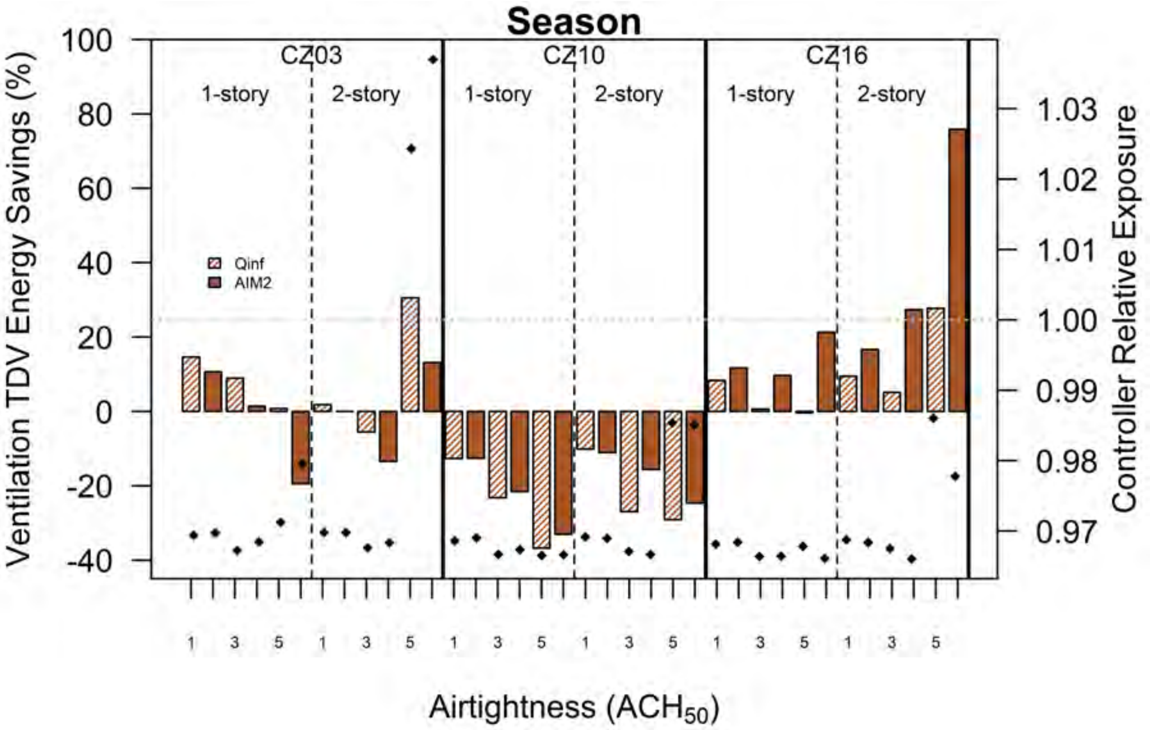

Figure 43 Seasonal TSVC ventilation TDV energy savings. No cases simulated in CZ1, due to lack of cooling season.

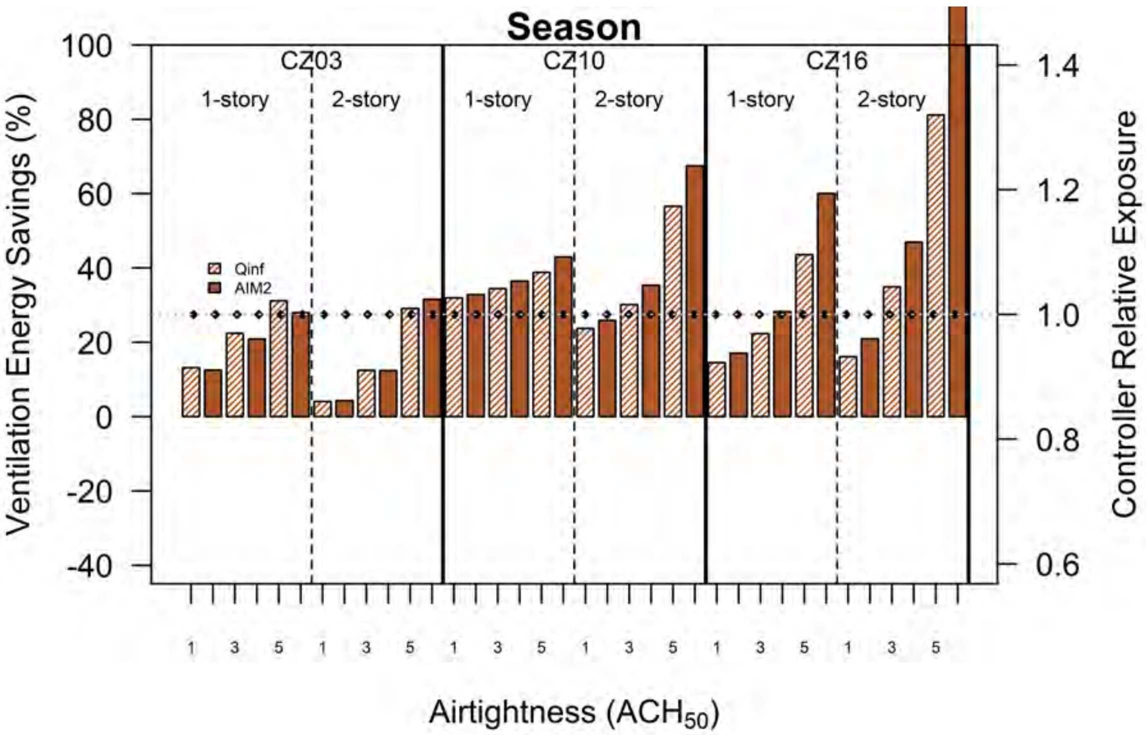

Figure 44 Seasonal TSVC normalized ventilation energy savings. No cases simulated in CZ1, due to lack of cooling season.

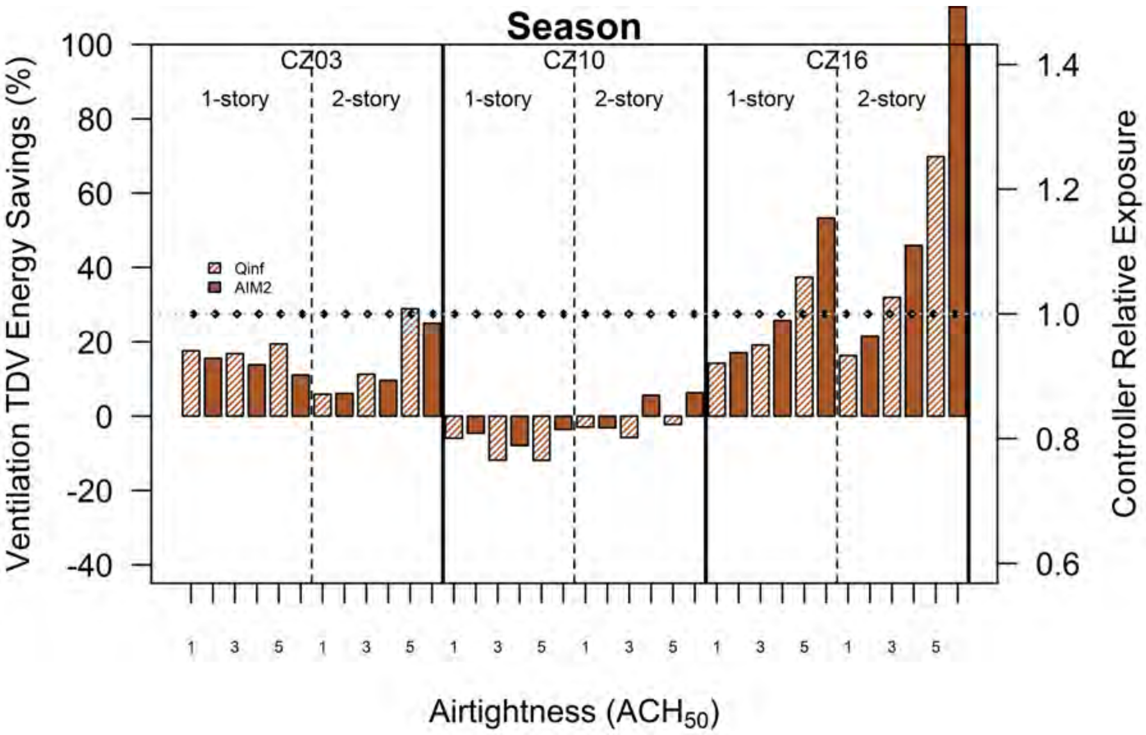

Figure 45 Seasonal TSVC normalized ventilation TDV energy savings. No cases simulated in CZ1, due to lack of cooling season.

We illustrate the simple and consistent operation of this TSVC using daily minimum, mean and maximum controller exposure values in Figure 3. This example case is a 1-story medium 5 ACH_{50} prototype in CZ10, heating season exposure target of 1.5 and cooling season target of 0.61. When in heating season, the 1.5 target is consistently maintained, with very little variability over the course of a day; same for the cooling season at the low exposure target. This predictable behavior ensures relatively straightforward estimation of the annual average exposure during design phase.

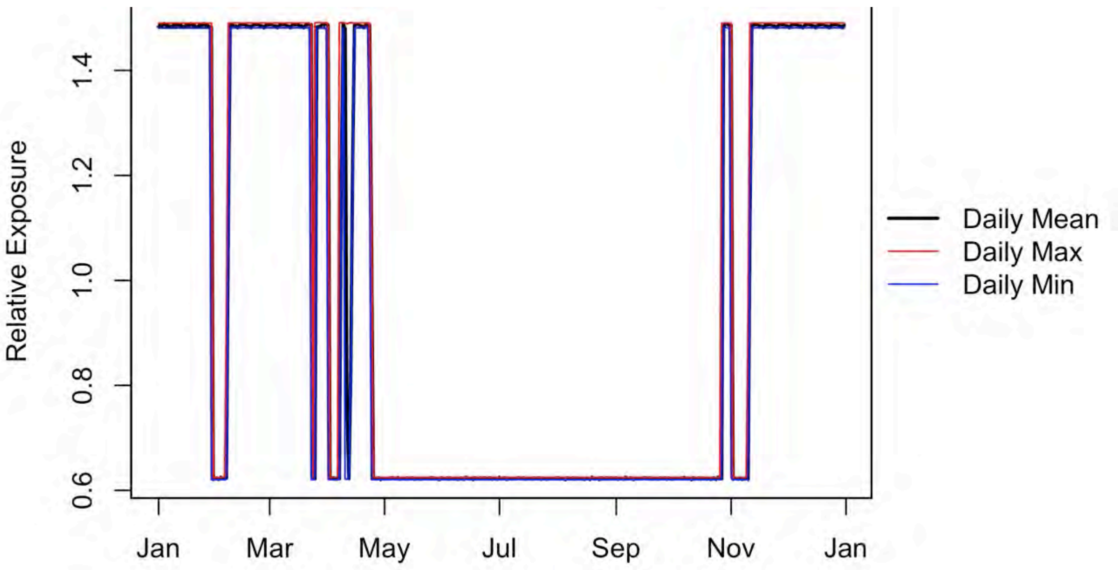

Figure 46 Seasonal TSVC illustration of daily minimum, mean and maximum values for controller relative exposure. 1-story medium 5 ACH50 homes in CZ10 with heating season RE target of 1.5 and cooling season target 0.61.

Optimized Cut-Off (CutOff)

For each case (combination of prototype, envelope leakage and climate) we show the CutOff controller percent ventilation energy savings for site energy (Figure 47) and TDV (Figure 48) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 49) and TDV (Figure 50).

The cutoff control was able to maintain equivalence and save ventilation energy in the majority of cases, with savings between 20 and 80% of ventilation site energy in CZ10 and 16. Savings worsened with increasing envelope leakage in CZ1, and savings improved with leakage in CZ 3, 10 and 16. As with the Seasonal controller, the AIM-2 infiltration model improved savings in CZ10 and 16, while the Qinf model gave better savings in CZ3. The 2-story homes had greater savings in CZ16, but prototype effects were otherwise mixed. Performance remained solid for raw TDV ventilation energy savings in CZ10, but

TDV savings were marginal in CZ3 and 16. As with most controllers, its performance was poor in CZ1 homes.

The normalized site and TDV energy savings were improved across the board. Again, when normalized, increased envelope leakage clearly was associated with increased normalized percent savings. Similarly, the AIM-2 infiltration model improved performance in CZ10 and 16, and Qinf was best in CZ3 cases. Prototype effects were notable in CZ16, where the 2-story cases saved much more normalized energy. Normalized TDV savings generally averaged in the range of 30-70% across CZ3, 10 and 16.

In addition to good energy performance, the CutOff TSVC has the further benefit that the peak exposure experienced by the occupants is much lower (see Figure 79), generally just a few tenths above the seasonal average exposure target.

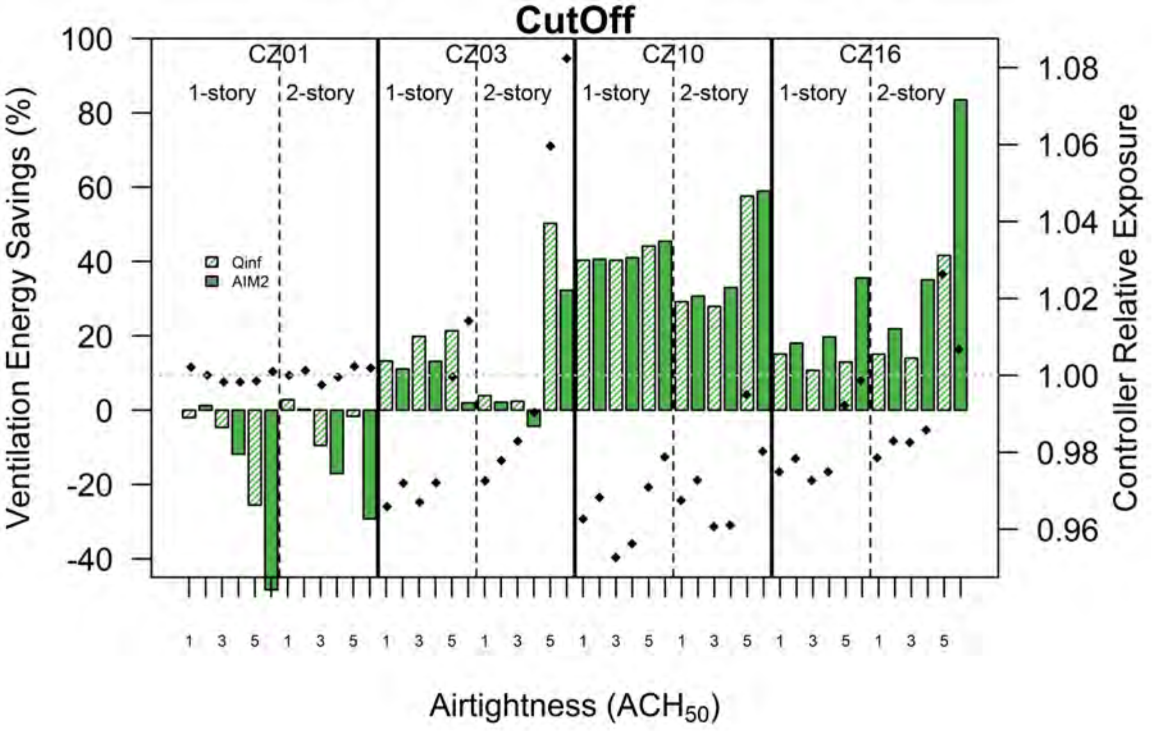

Figure 47 Cutoff TSVC ventilation energy savings.

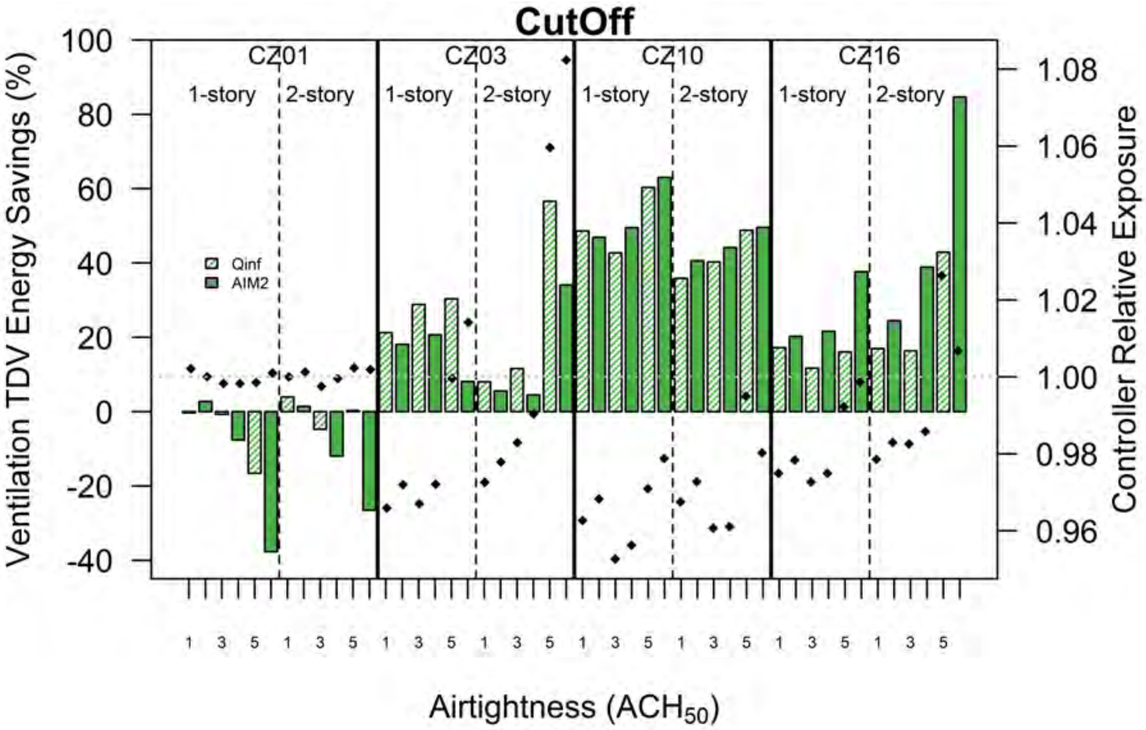

Figure 48 Cutoff TSVC ventilation TDV energy savings.

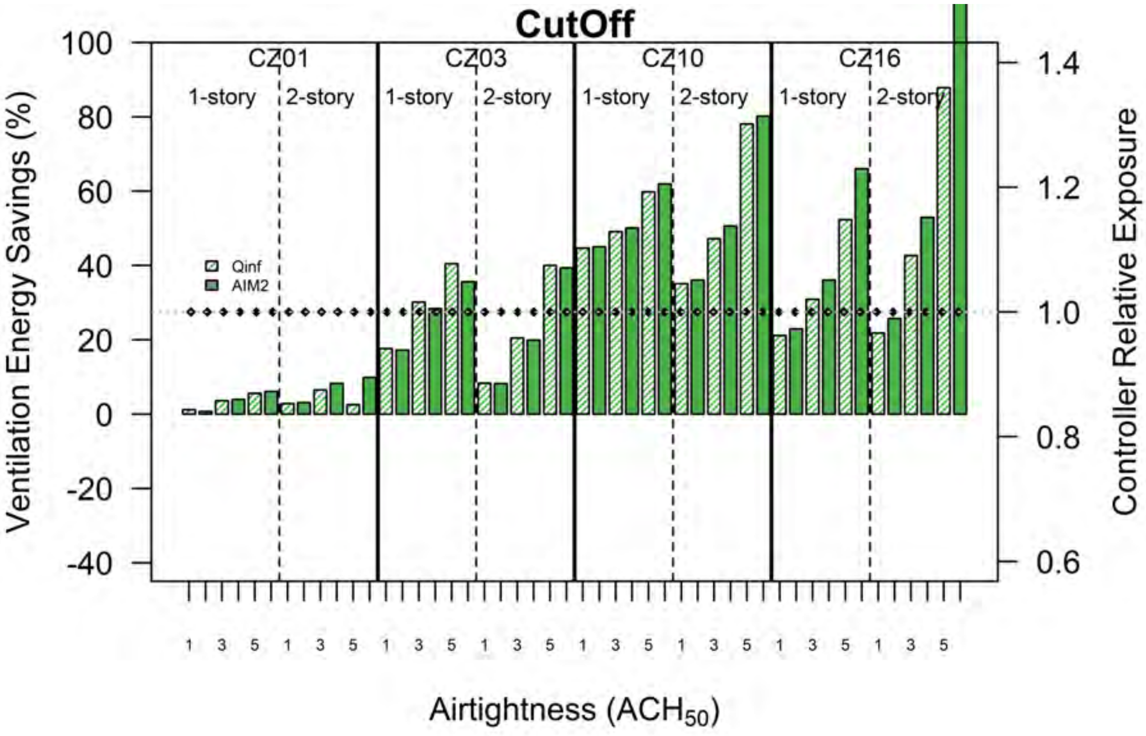

Figure 49 Cut-Off TSVC normalized ventilation energy savings.

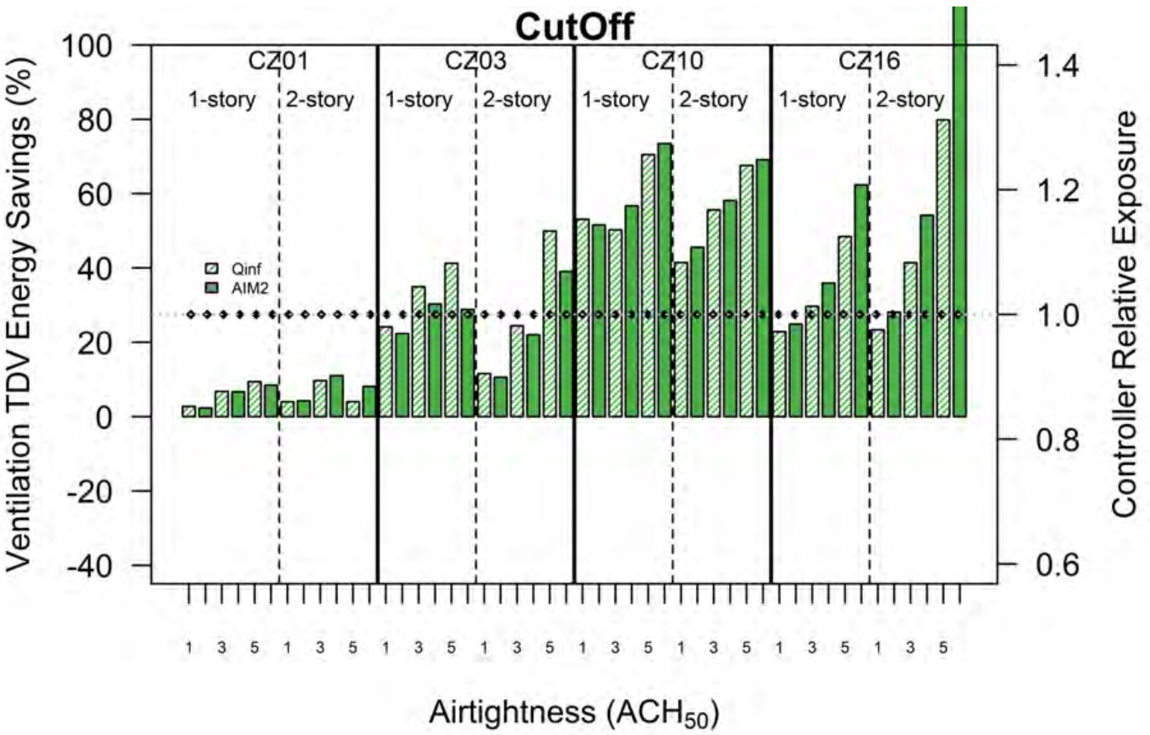

Figure 50 Cut-off TSVC normalized ventilation TDV energy savings.

The monthly distribution of controller exposure is shown for an example case in Figure 51 for a 1-story 1 ACH_{50} home in CZ10. Heating season mean exposure target was 1.5 and cooling season was 0.62, and the green triangles show monthly means. Here we see the clear pattern of increasing exposure (reducing ventilation) during the heating months and reducing exposure (increasing ventilation) during the cooling season. The monthly averages align pretty well with the seasonal targets, and the peak exposure values are well controlled to the limits of 1.8 in heating and 1.16 in cooling.

A time-series illustration of this same exact case is provided in Figure 52 with controller exposure, dose and outside temperature (dashed green line represents the heating season temperature cutoff for increased exposure). We see that during the heating season, the controller steadily maintains the peak exposure target of 1.8 unless the outside temperature exceeds 16.7°C, at which point the controller increases ventilation and targets exposure of 1/FSM (0.5 in this case). This successfully reduces ventilation for the maximum amount of time, while still keeping the annual average exposure below one.

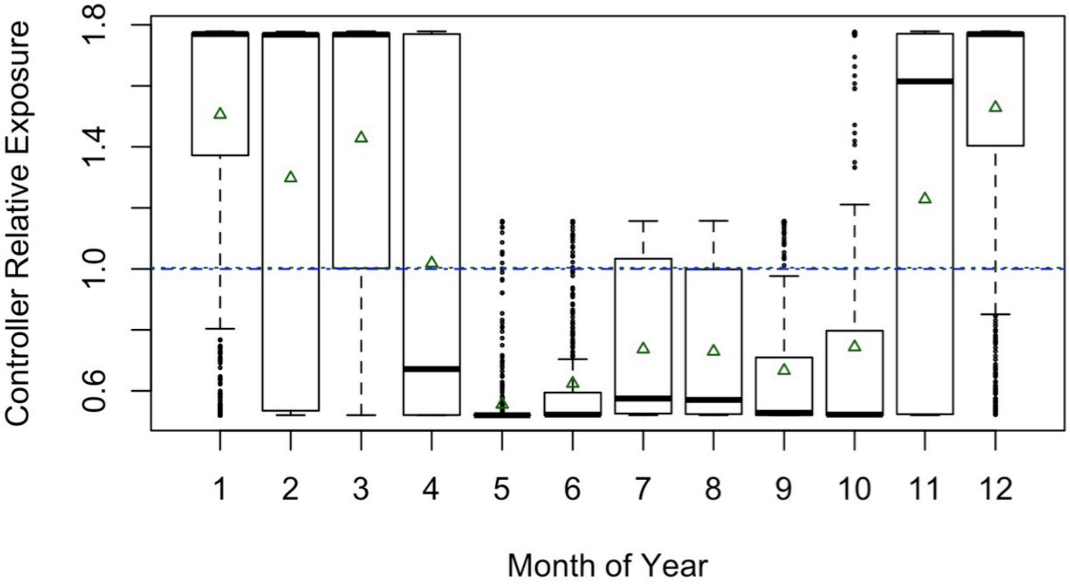

Figure 51 Monthly boxplot distributions of controller relative exposure for the Cutoff TSVC in a 1-story 1 ACH$_{50}$ home in CZ10. Heating season mean exposure target was 1.5 and cooling season was 0.62. Green triangles show monthly mean.

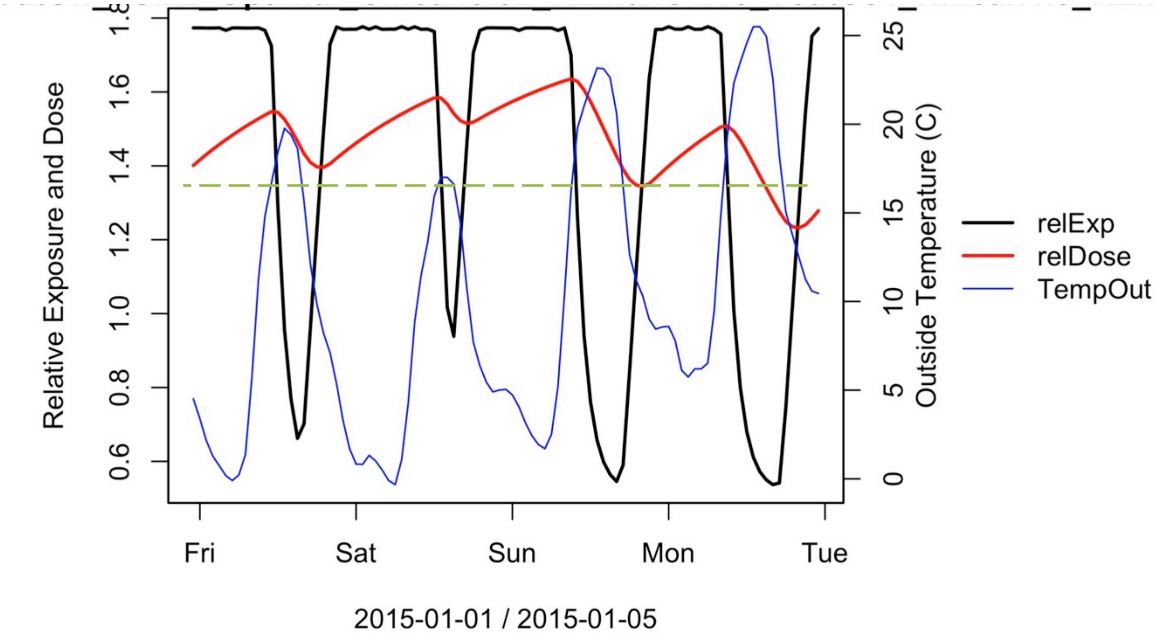

Figure 52 Time-series illustration of Cutoff TSVC controller exposure, dose and outside temperature in a 1-story 1 ACH$_{50}$ home in CZ10. Low exposure target (high ventilation rate) is targeted when outside temperature (blue line) exceeds 16.7°C (dashed green line).

Variable Airflow (VarQ)

For each case (combination of prototype, envelope leakage and climate) we show the VarQ controller percent ventilation energy savings for site energy (Figure 53) and TDV (Figure 54) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 55) and TDV (Figure 56).

The VarQ TSVC had the second largest weighted average ventilation site energy savings (48%) and the highest TDV savings (61%). It also had among the highest peak cooling demand savings, shedding between 0 and 300 watts during the 2-6pm peak period on the ten hottest days of the year. This controller reduced occupant exposure and improved IAQ in nearly all cases relative to the baseline continuous fan. The VarQ controller had by far the highest peak exposures, because it allowed the IAQ fan to be completely turned off during some outdoor conditions. The peak exposures could be drastically reduced, by setting a minimum target airflow of 5 L/s instead of 0 L/s. The VarQ controller also suffered from relatively more cases that failed to meet the annual exposure requirement, with roughly 30% failure rate vs. roughly 20% for some of the other well-performing controllers. That being said, when it failed, the VarQ generally exceeded 1.0 by only 1-5%, well within the range achieved by the continuous baseline IAQ fans. Relative to the VarRe or CutOff controllers, the VarQ controller also requires more user inputs in order to generate the optimum control parameters. This makes specification of the controller more complex and variable with house parameters, such as airtightness, climate zone, etc.

Raw percent site savings were greatest in CZ10, with consistent savings levels across envelope leakages and infiltration assumptions. Aside from climate zone, house prototype was clearly an important determinant of VarQ performance, with greater savings in the 1-story prototypes, in both CZ10 and 3. Raw percent TDV savings were also greater in 1-story prototype homes and otherwise varied little across envelope leakage levels and infiltration assumptions. Notably, the controller exposure was well below 1.0 in several of the CZ16 cases. Even when below 0.90 the energy savings were indistinguishable from similar cases with exposures near 1.0.

When normalized by relative exposure, the site and TDV savings all increased substantially. This was the first control type to show meaningful energy savings in CZ1, when normalized. As with other controls, when normalized, the percent savings increased with envelope leakage, infiltration model assumptions had little impact, and prototype performance was similar, with the exception of the leakiest cases in CZ16, where 2-story savings were substantially larger than in 1-story. This is notable, because the raw savings were stable across leakage levels, and normalization introduced clear differences with leakage. Normalized TDV percent savings were sometimes flat across leakage levels (CZ3) and other times followed the familiar pattern (CZ16). It could be that the increasing savings with increasing envelope leakage has more to do with normalization of the baseline cases, rather than of the control cases. The baselines have clear patterns of higher exposure in leakier homes, due to superposition fan sizing models used in

62.2-2016 (see 0). So, smart control savings may be increasing with leakage, because the baseline case energy consumption consistently increases when normalized, which increases the apparent savings.

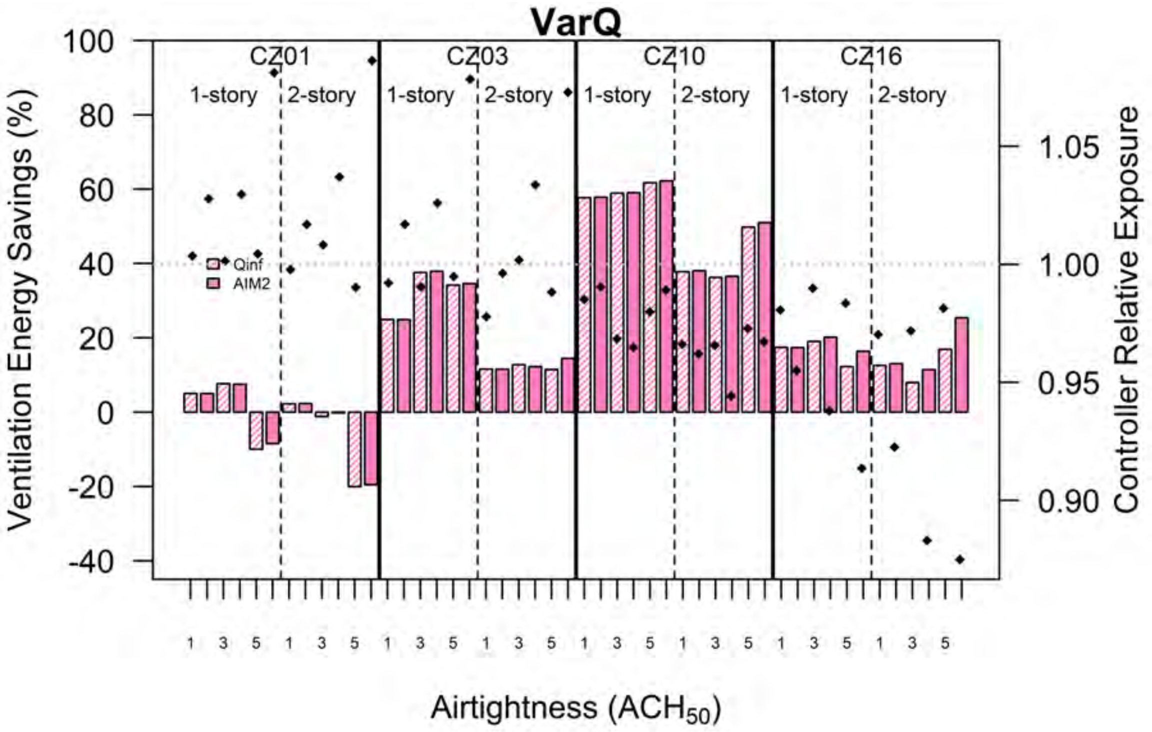

Figure 53 Variable airflow TSVC ventilation energy savings.

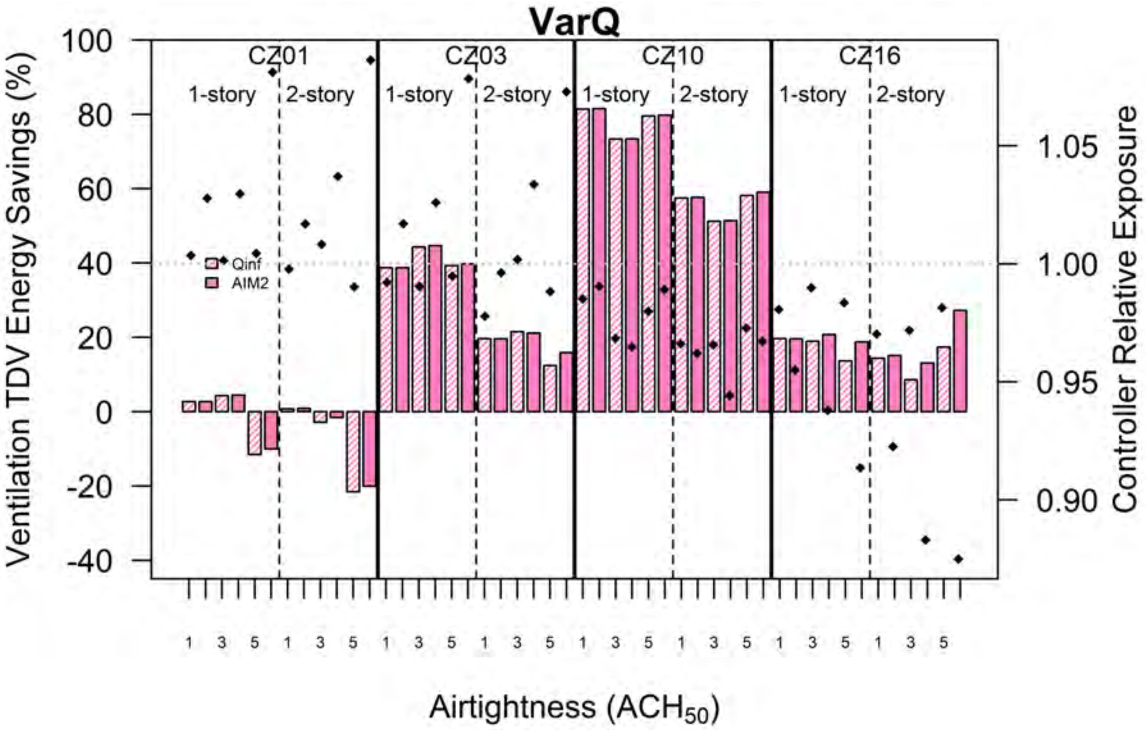

Figure 54 Variable airflow TSVC ventilation TDV energy savings.

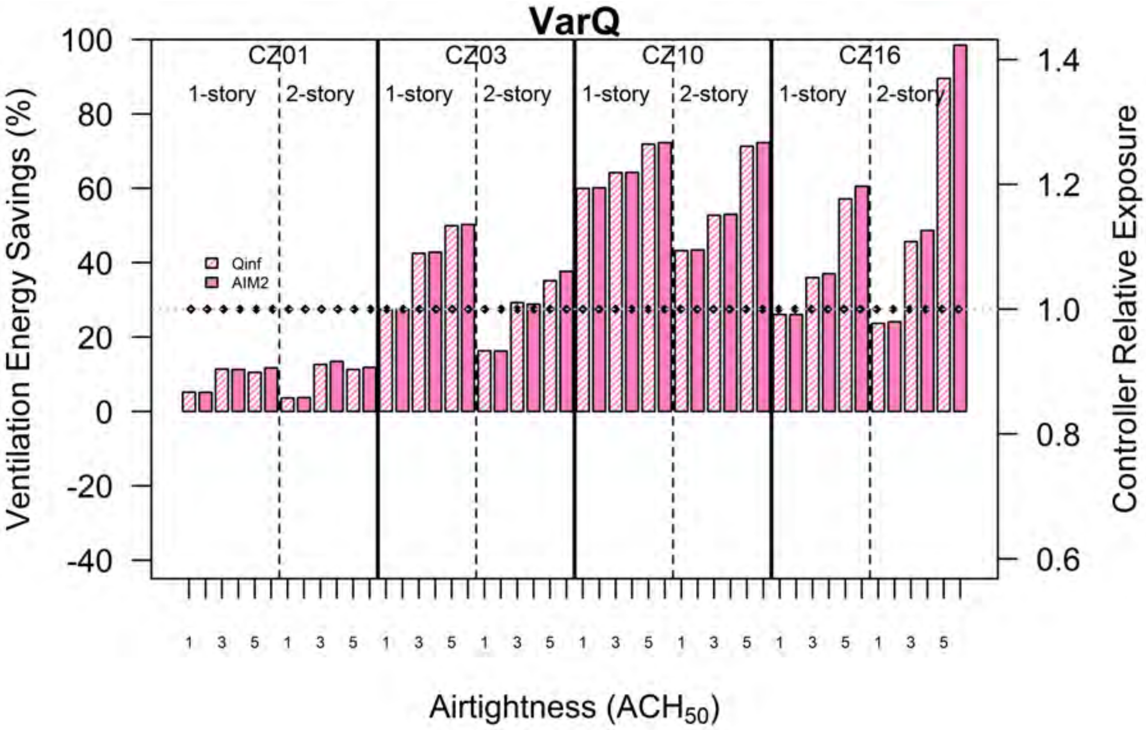

Figure 55 Variable airflow TSVC normalized ventilation energy savings.

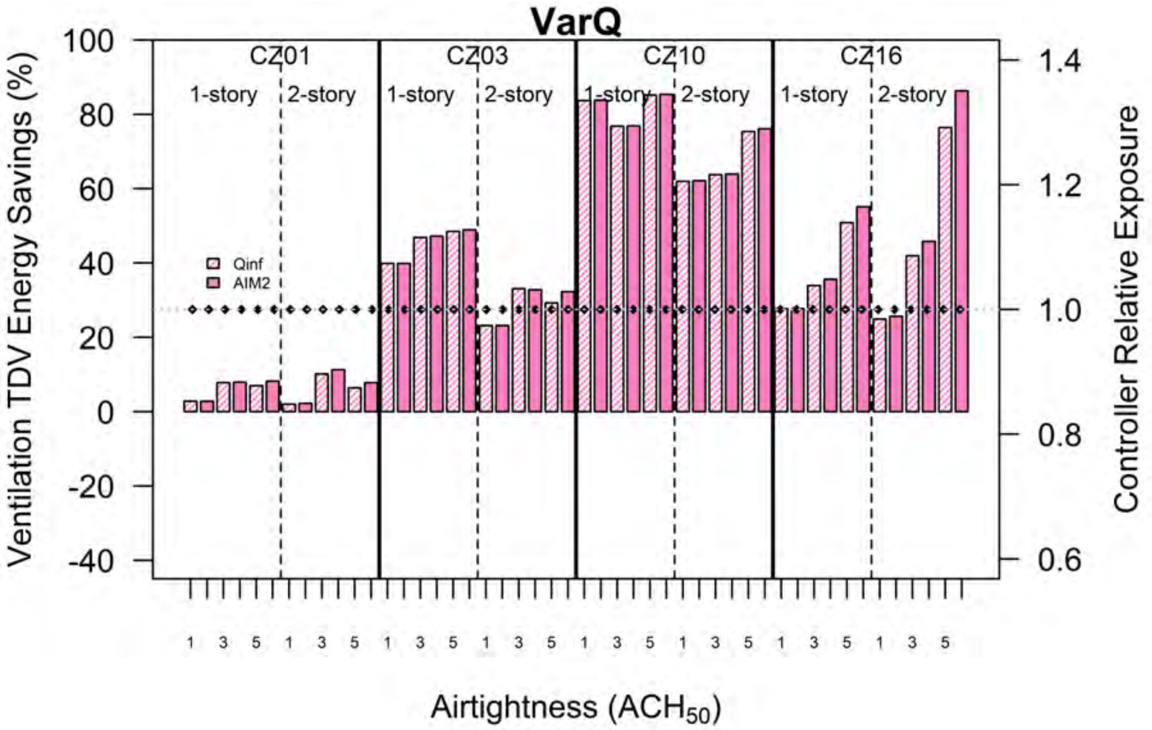

Figure 56 Variable airflow TSVC normalized ventilation TDV energy savings.

The VarQ controller also does the most seasonal shifting of ventilation, with the highest average exposure values in heating periods and cooling periods. The monthly distributions of controller exposure are plotted for an example case of the VarQ controller in Figure 57, for a 1-story 5 ACH_{50} home in CZ16 (Blue Canyon). The monthly controller exposure values are fairly high. Even for similar monthly average exposures (as in the Cutoff controller in Figure 51), the VarQ allows much higher peak exposures during most months of the year. Notably, the 5 ACH_{50} case shown has lower peak relative exposure values than would be found in the more airtight 1 and 3 ACH_{50} cases, because the leakier home has greater background natural infiltration when the fan airflow is curtailed during extreme temperatures.

An illustrative example time-series plot is provided to shown VarQ controller behavior in Figure 58 for a 1-story 5 ACH_{50} home CZ10 (Riverside) with a fan size multiplier of 2. This plot shows the real and controller estimates of relative exposure, along with the house airflow and outside temperature. We see that for most hours of the day, the VarQ controller keeps the house airflow at a low number, with minimal fan airflow and some infiltration. When the outside temperature increases, the IAQ fan airflow ramps up proportionally until it is at full airflow around 80 L/s.

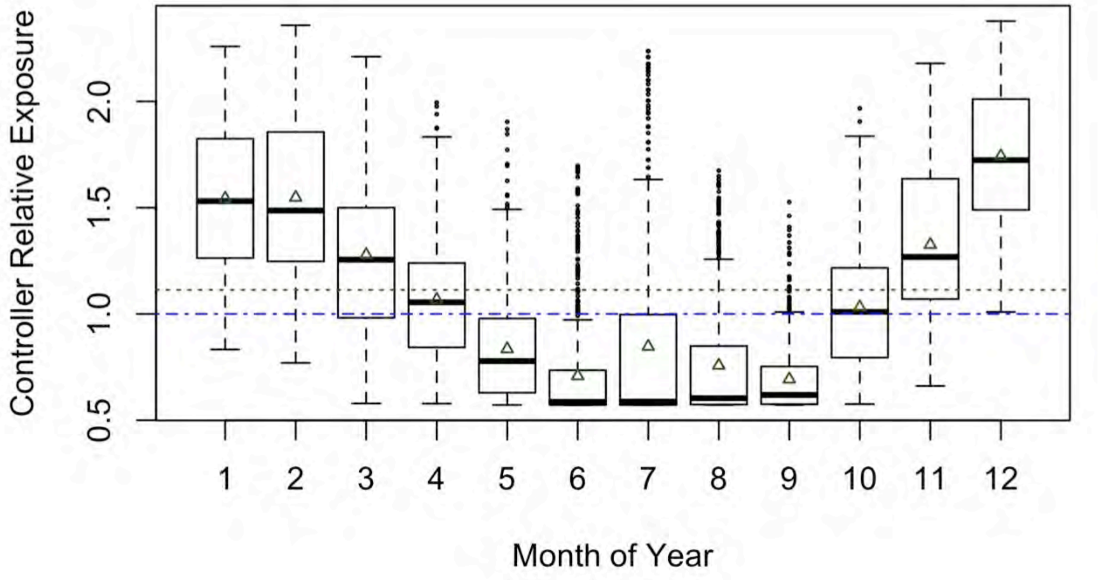

Figure 57 Monthly distributions of controller relative exposure for the VarQ TSVC controller in a 1-story 5 ACH_{50} home in CZ16 (Blue Canyon). Blue dashed line is the target annual exposure and the dotted green line is the actual average exposure.

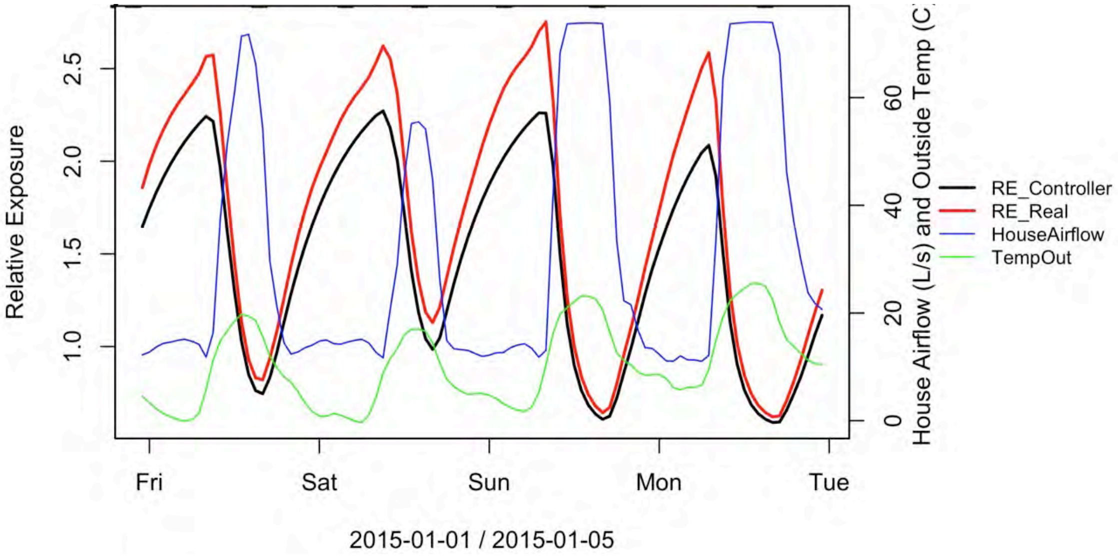

Figure 58 Time-series illustration of the VarQ controller in a 1-story 5 ACH_{50} home in CZ10 (Riverside), including controller and real exposure, along with house airflow and outside temperature.

Variable Exposure Target (VarRe)

For each case (combination of prototype, envelope leakage and climate) we show the VarRe controller percent ventilation energy savings for site energy (Figure 59) and TDV (Figure 60) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 61) and TDV (Figure 62).

Similar to the VarQ TSVC, the VarRe controller performed very well across climate zones and house types. Site ventilation savings are in the 20-60% range, while TDV savings typically range from 30-50%. The TDV savings are quite consistent across climate zones 3, 10 and 16. CZ3 and 16 show improved raw site savings when envelope leakage increases (and worsened savings in CZ1), while savings in CZ10 are flat across leakage levels. Again, the AIM-2 infiltration model has obvious performance benefits in CZ10 and 16, while performance in CZ3 is improved using the Qinf infiltration assumption. Prototype has little impact on the raw percent site savings.

Again, the ventilation percent savings are improved when normalized by exposure. As with VarQ, the VarRe control was able to achieve meaningful savings in CZ1 when normalized to ensure the same IAQ. Again, normalized site energy savings clearly increase with envelope leakage, and the other patterns are similar to those described for the prior control strategies.

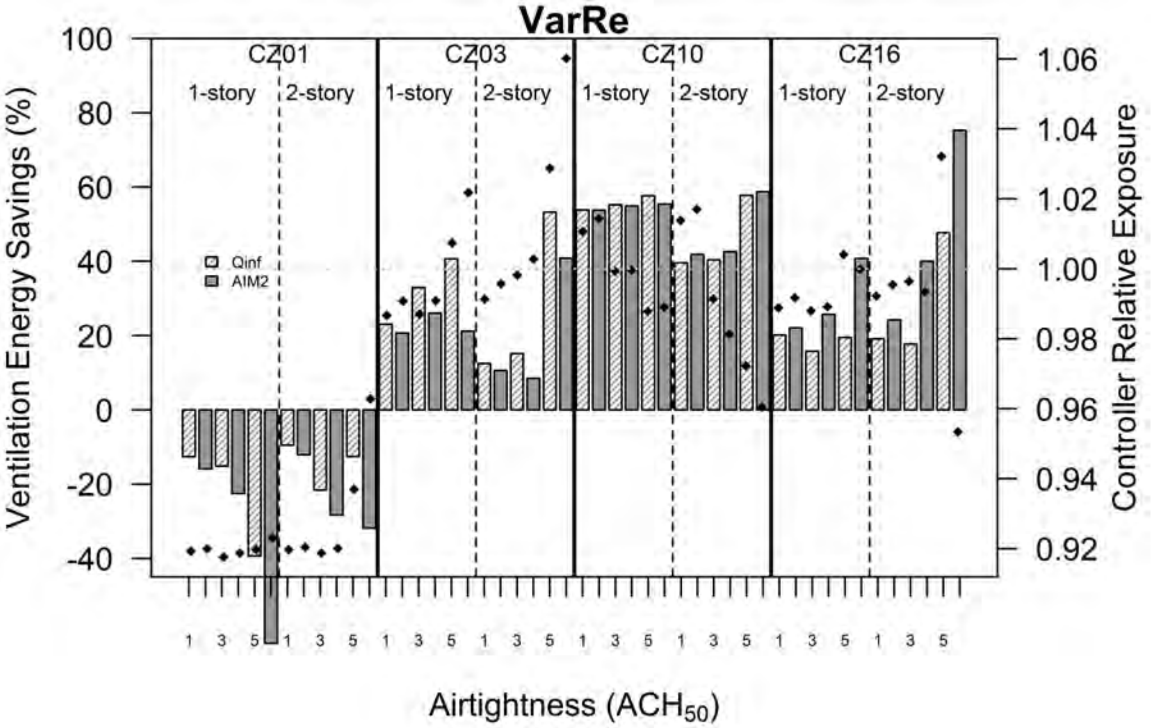

Figure 59 Variable exposure TSVC ventilation energy savings.

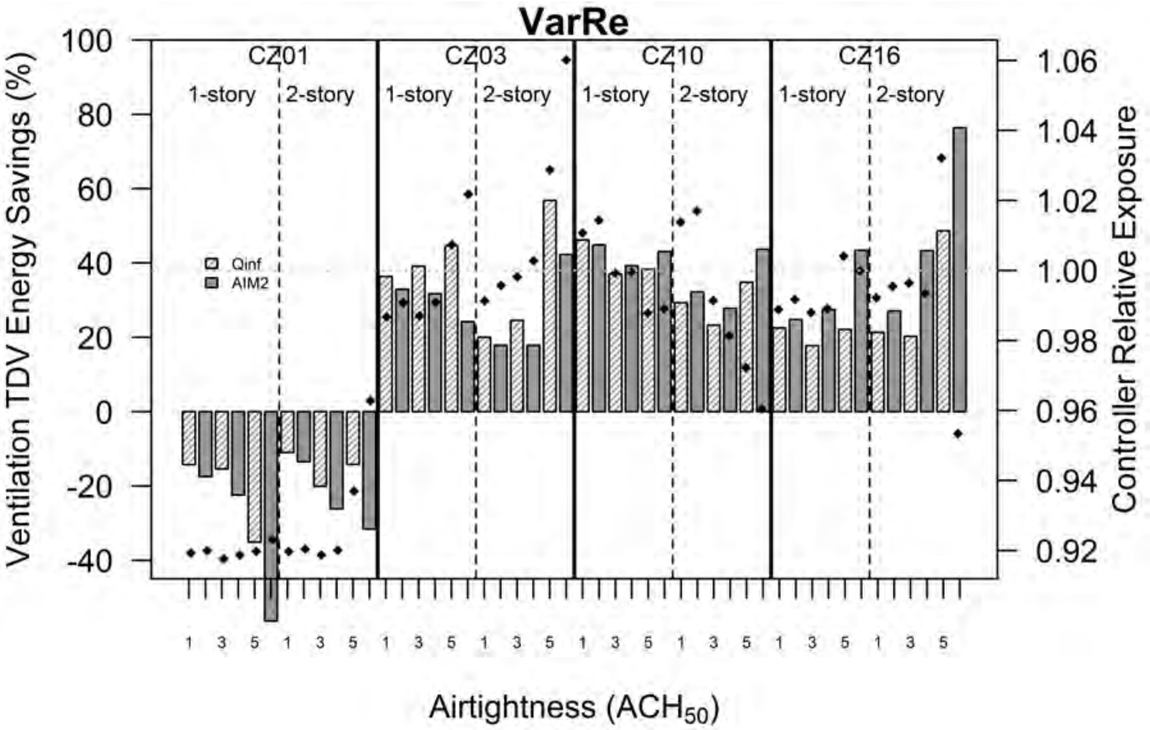

Figure 60 Variable exposure TSVC ventilation TDV energy savings.

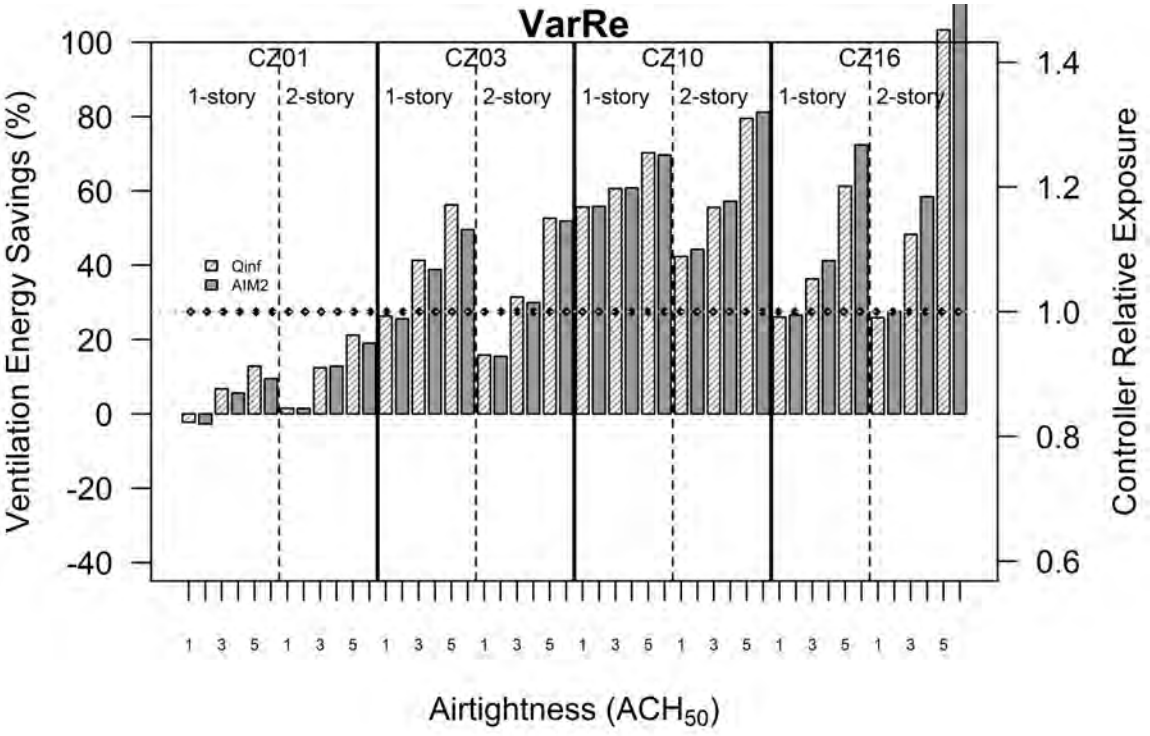

Figure 61 Variable exposure TSVC normalized ventilation energy savings.

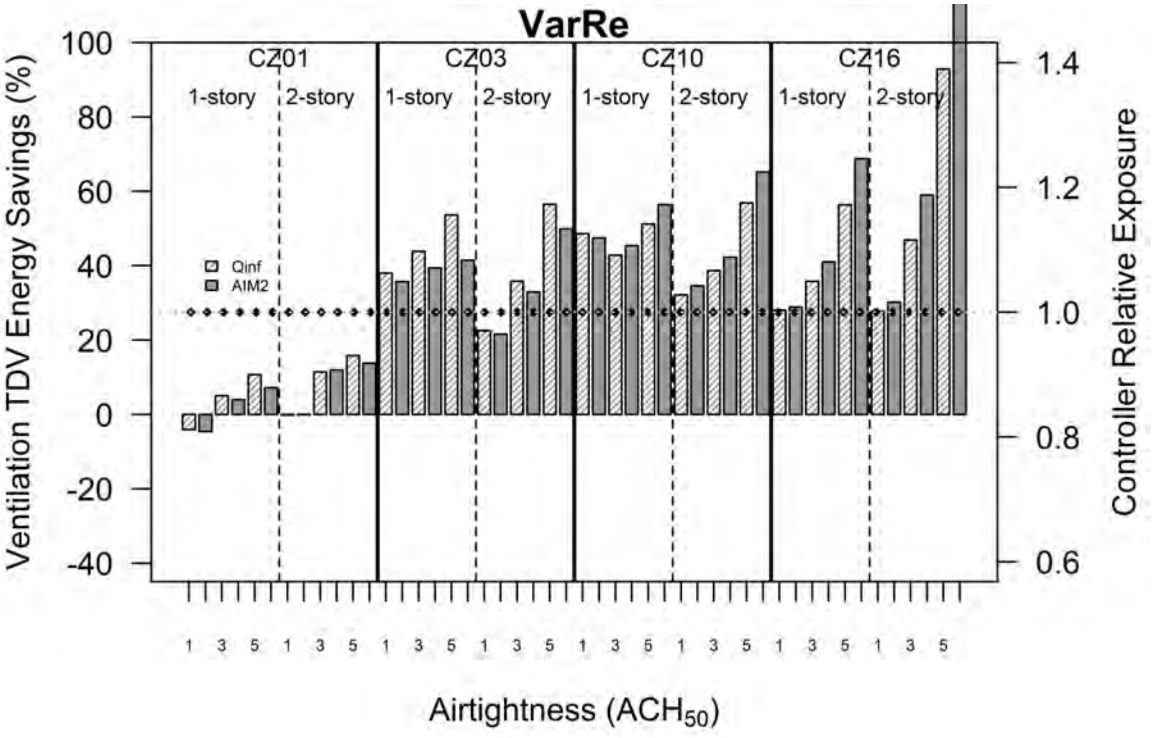

Figure 62 Variable exposure TSVC normalized ventilation TDV energy savings.

The monthly distribution of controller exposure values (Figure 63) for the VarRe controller is very similar to that used for the VarQ TSVC. Exposure and ventilation are shifted seasonally, with high exposure and low airflow during the heating months and vice versa during cooling periods. The peak exposure values are lower in the VarRe than in the VarQ, because the fan is never just turned off, rather a high exposure value maintains a low ventilation rate.

An example time-series plot is also provided to show controller behavior in Figure 64 for a 1-story 1 ACH_{50} home in CZ10 with a peak heating season exposure target of 4.1 (unusually high). We see that the exposure values (real and controller) are inversely proportional to the outside temperature, with peak exposure occurring at the lowest temperature (around 0°C). The controller functions as intended, to shift almost all house ventilation to warmer periods of the day and year (in heating season).

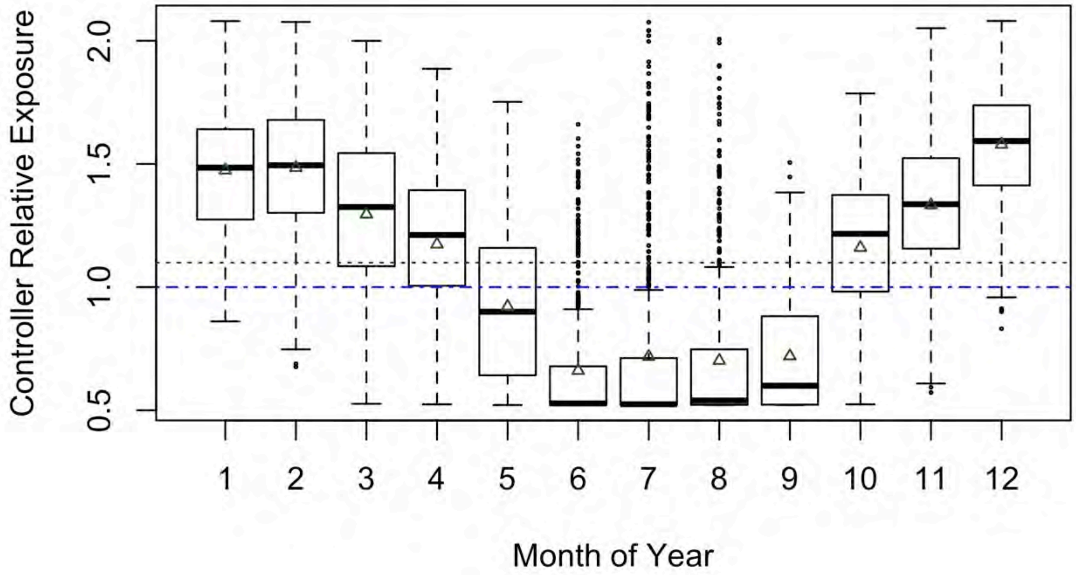

Figure 63 Monthly boxplot distributions of controller exposure for the VarRe TSVC in a 1-story 1 ACH_{50} home in CZ16 (Blue Canyon). Peak exposure targets of 2.1.

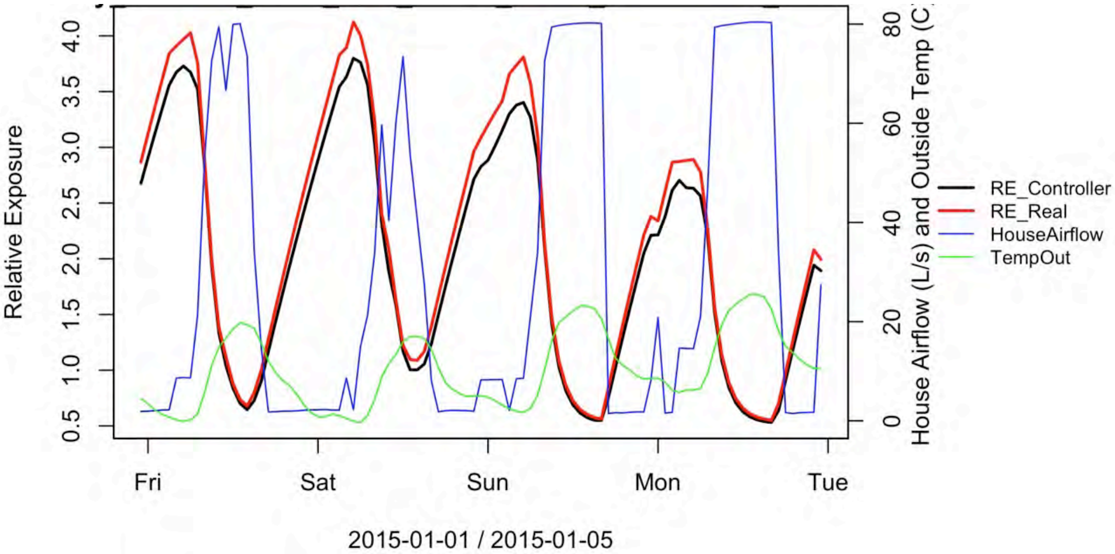

Figure 64 Time-series illustration of the VarRe TSVC controller in a 1-story 1 ACH_{50} home CZ10 (Riverside), with a fan size multiplier of 2 and a peak heating exposure target of 4.1. Includes real and controller exposure, along with whole house airflow and outside temperature.

Occupancy Controls

For each case (combination of prototype, envelope leakage and climate) we show the Occupancy controller percent ventilation energy savings for site energy (Figure 65) and TDV (Figure 66) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 67) and TDV (Figure 68). All cases assume the standard OSVC control (ventilation off while unoccupied), with 1st shift, 9-hour daytime absences on weekdays.

Overall, the savings from OSVC were much lower than those achieved using TSVC approaches. This is not surprising, given that the energy associated with ventilation is entirely dependent on the temperature difference between the house and outside. A temperature-aware controller should perform better. 1st shift occupancy controllers effectively behave opposite of our temperature controllers—they reduce ventilation during the mildest times of day (mid-day) and increase ventilation during the more extreme periods (evening/night). These effects are coupled with the fact that our OSVC accounts for pollutant emissions during the unoccupied period, which means that a high ventilation rate recovery period is needed at the start of occupancy. The net-effect is that total ventilation airflow is not reduced very much (overall median of 2.4% reduction in whole house airflow). Past DCV approaches did not account for unoccupied emissions and therefore dramatically over-predicted how much ventilation rates could be reduced while maintaining equivalent exposure. The limited energy savings predicted here align well with those made across U.S. climates by Less & Walker (2017), where Occupancy control savings were substantial only in the most cooling-dominated locations (e.g., Miami, FL).

While the OSVC is very consistently able to deliver annual integrated occupied exposure below one, it saves little energy, with some exceptions (most notably the 2-story 5 ACH_{50} case in CZ 16 with nearly 50% savings). In fact, the controller is just as likely to increase ventilation energy, as it is to save energy. This occurs because in many cases, the OSVC fails to reduce ventilation rates, while it succeeds at shifting ventilation over the hours of the day in a way that increases the net-ventilation load on the HVAC. During heating season, the OSVC reduces ventilation during the mildest, most beneficial times of day (roughly from 9-5pm). During the cooling season, the OSVC does reduce ventilation during hot times of day, but it also massively increases the ventilation rate as soon as occupants return home (at 5pm), which is still a very hot time of day; in fact, it is the peak time of day for cooling load and grid stress.

Normalized percent site savings improved substantially, reversing all cases of increased consumption. There is a clear pattern across all climate zones of increasing savings with more envelope leakage and in 2-story homes. In nearly all cases, the use of the AIM-2 infiltration model improved normalized performance relative to the Qinf approach. TDV savings remained erratic even when normalized, with greater TDV savings in leakier, 2-story homes, and some notable cases with increased normalized TDV energy use in tight homes in CZ10.

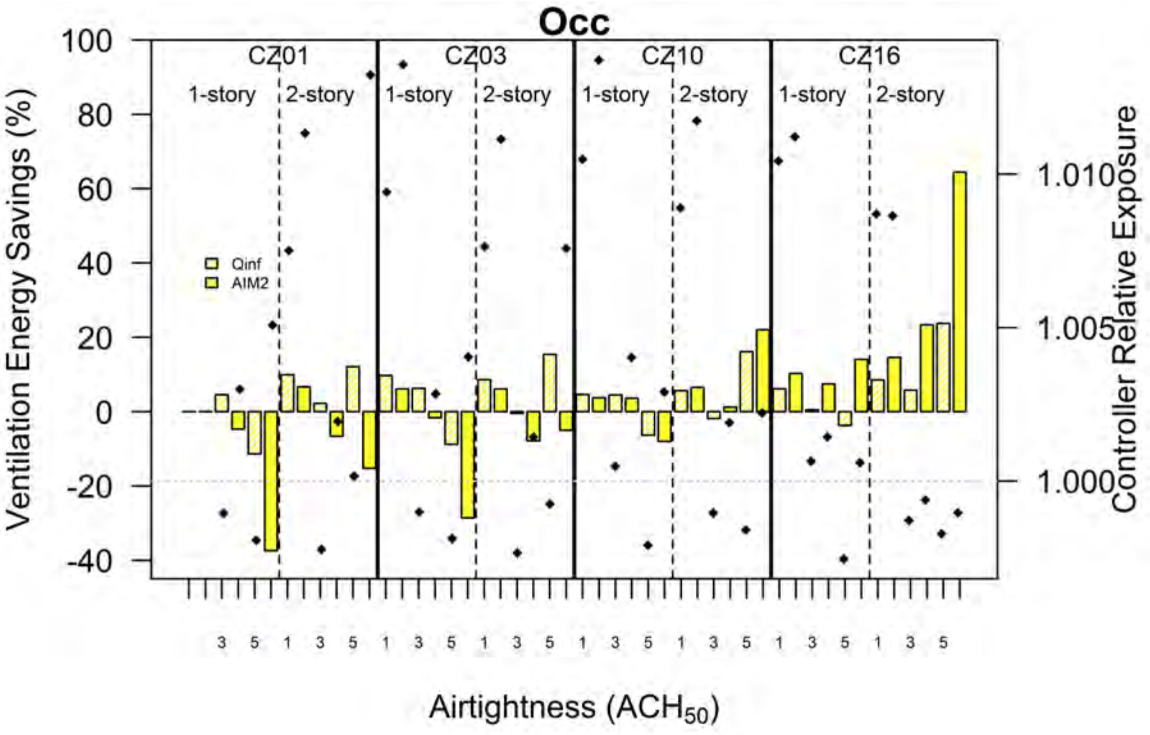

Figure 65 Occupancy SVC ventilation energy savings.

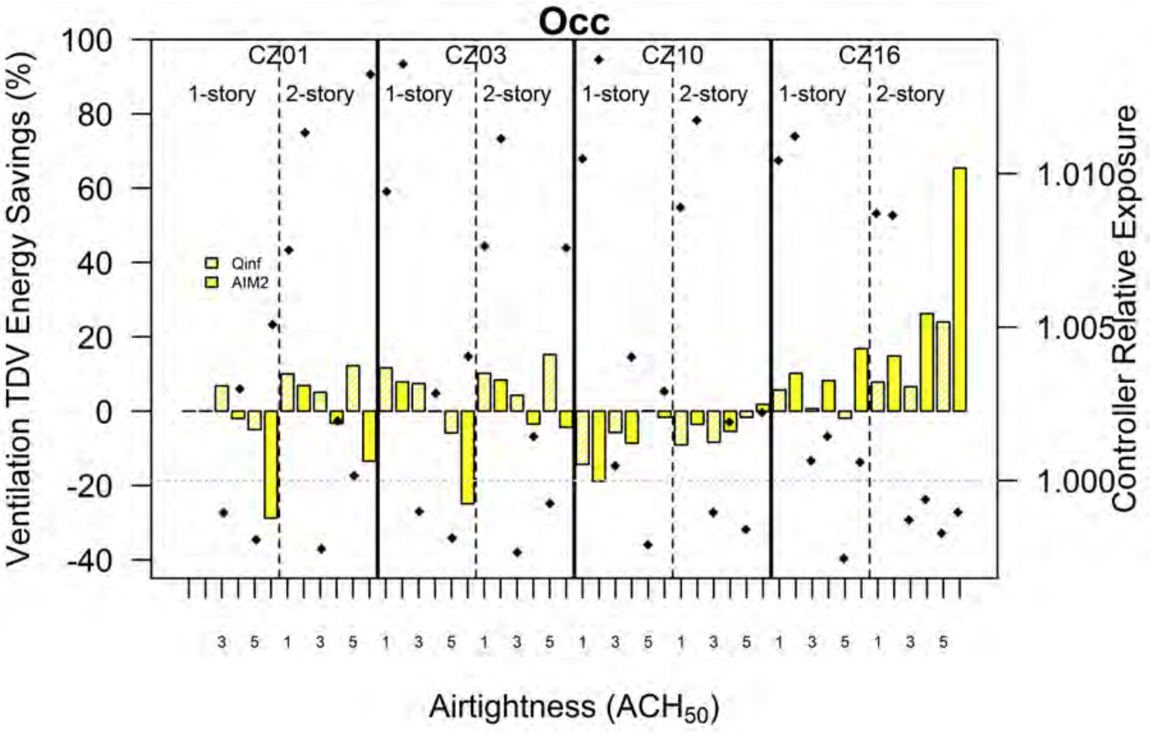

Figure 66 Occupancy SVC ventilation TDV energy savings.

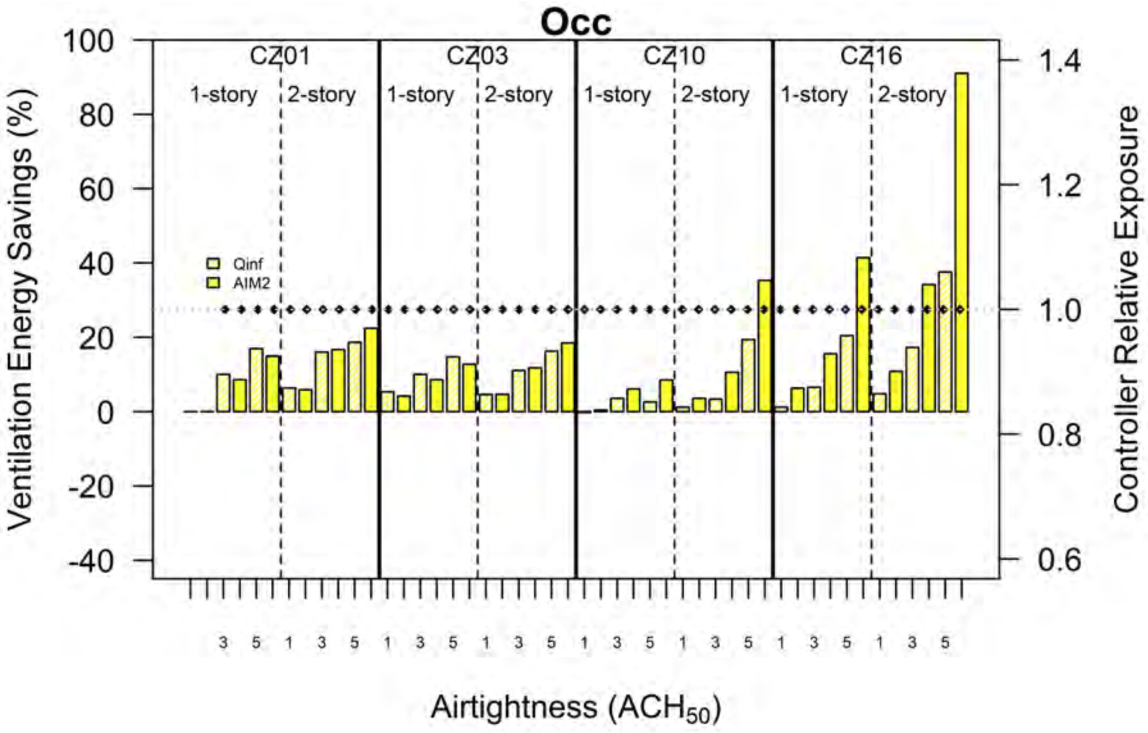

Figure 67 Occupancy SVC normalized ventilation energy savings.

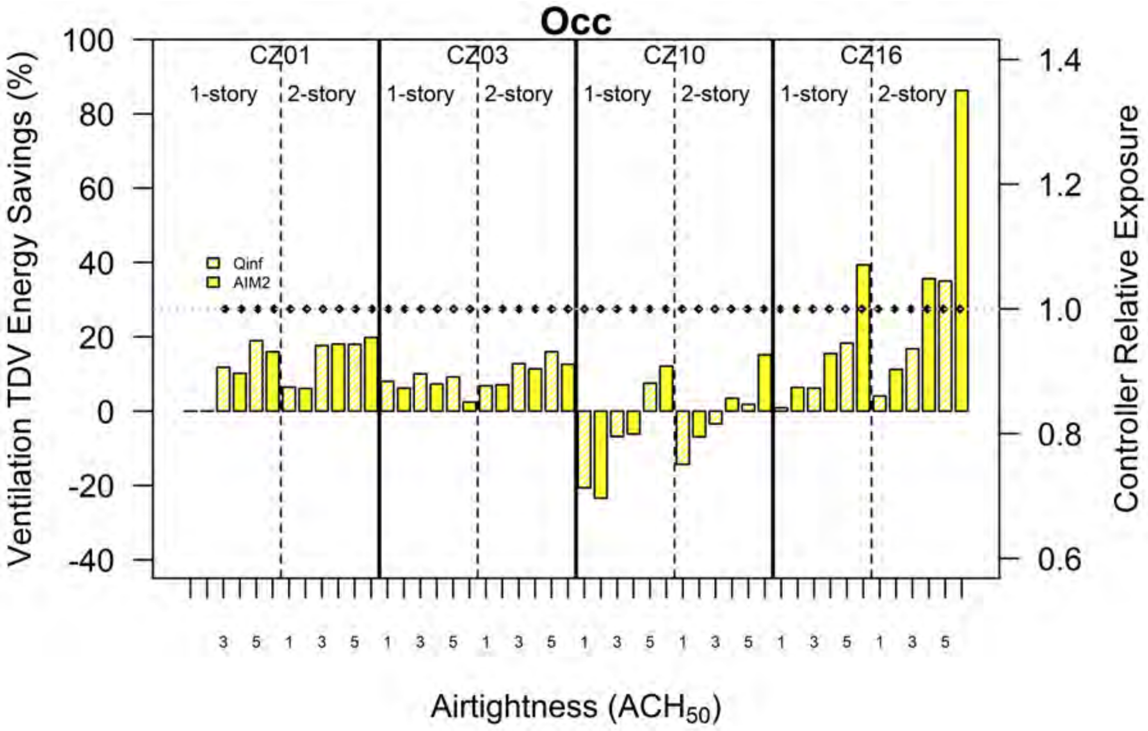

Figure 68 Occupancy SVC normalized ventilation TDV energy savings.

An illustration of the Unocc SVC is provided in Figure 9. The day begins with the IAQ fan maintaining relative exposure (*relExp*, red line) near 1. Light grey highlighted periods show IAQ fan on periods, and the aqua region shows the unoccupied mid-day period. The relative dose (*relDose*, blue line) tracks the running average of the relative exposure and is fixed at almost exactly one. The unoccupied period is marked by relative exposure increasing to a peak around 2.7 when the occupants return home. The relative dose increases slightly when occupants return home, and it is reduced back below one during the recovery period. The IAQ fan is off during the entire unoccupied period, and then it is on continuously until the recovery period ends when both relative exposure and relative dose are less than one (approximately 23:00). This same pattern is repeated each day of the week with an occupant absence.

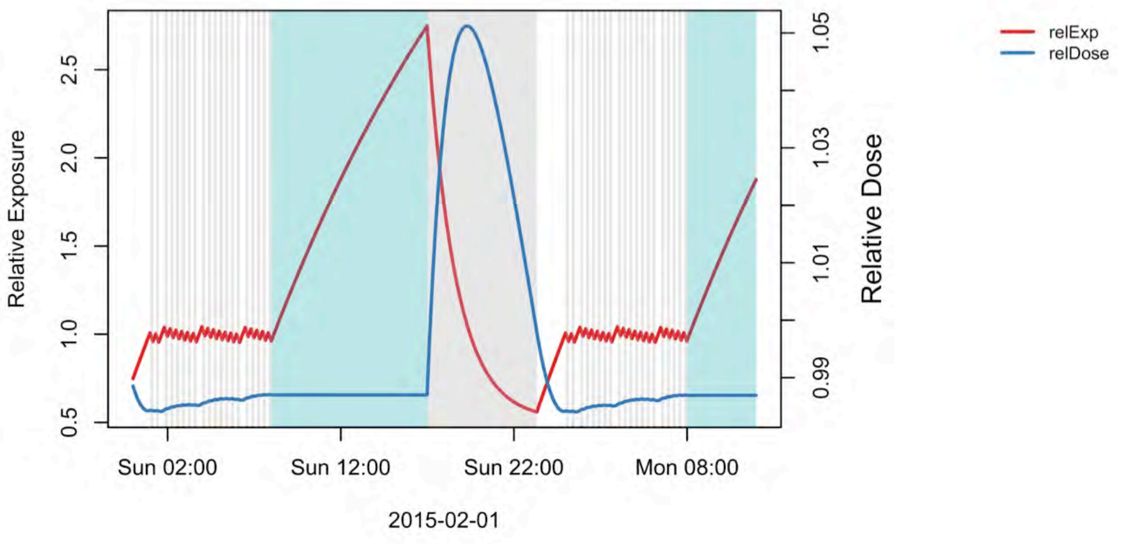

Figure 69 Illustration of Occupancy control operation with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey, unoccupied period in aqua.

Variations on the Occupancy Controller

As described in Section 0, we tested three variations on the Occupancy SVC. First, is the standard control, where the fan is turned off during unoccupied periods, and the controller then increases ventilation during occupancy to ensure daily integrated occupied exposure is below one. Second, we tested a 1-hour pre-occupancy flush out where the ventilation system operates at full airflow during the hour prior to occupancy, and then the controller takes over and controls daily integrated occupied exposure below one. Finally, we tested a controller where the IAQ fan is turned to 35% of the 62.2-2016 baseline fan airflow during unoccupied periods, and then the controller ensures daily-integrated occupied exposure less than one. The median ventilation site energy savings for each of these variations is summarized by climate zone in Figure 70 (see Figure 71 for TDV ventilation savings). We show only raw, non-normalized savings to illustrate these variations in the occupancy controller.

Overall, the 1-hour flush out pre-occupancy provides the highest ventilation energy savings (CZ16 exception), though median savings are still very low, with median values of 3-10% depending on climate zone (10-25% savings in CZ16). TDV ventilation savings are similar, with the 1-hour flush out still performing the best. TDV energy increases in CZ10 for all three variations on the Occupancy controller. The 1-hour flush saves the most energy because it allows the largest reduction in total ventilation airflow relative to the baseline continuous fan. The median reduction in whole house airflow was 3.7% for the 1-hour flush cases, while only 0.9 and 1.11% for the standard OSVC and the 35% OSVC. The daily airflow requirements for an equivalent control decrease as the peak exposure goes down, and the 1-hour flush out cases had median peak exposure of 1.7, compared with 2.4 and 1.8 for the standard OSVC and the 35% OSVC. The 35% unoccupied airflow strategy does reduce peak exposure similarly to the flush out, but it fails to reduce overall ventilation rates, because the airflow is higher during unoccupied periods. The flush out is a much more efficient (in terms of airflow) way to reduce peak exposure.

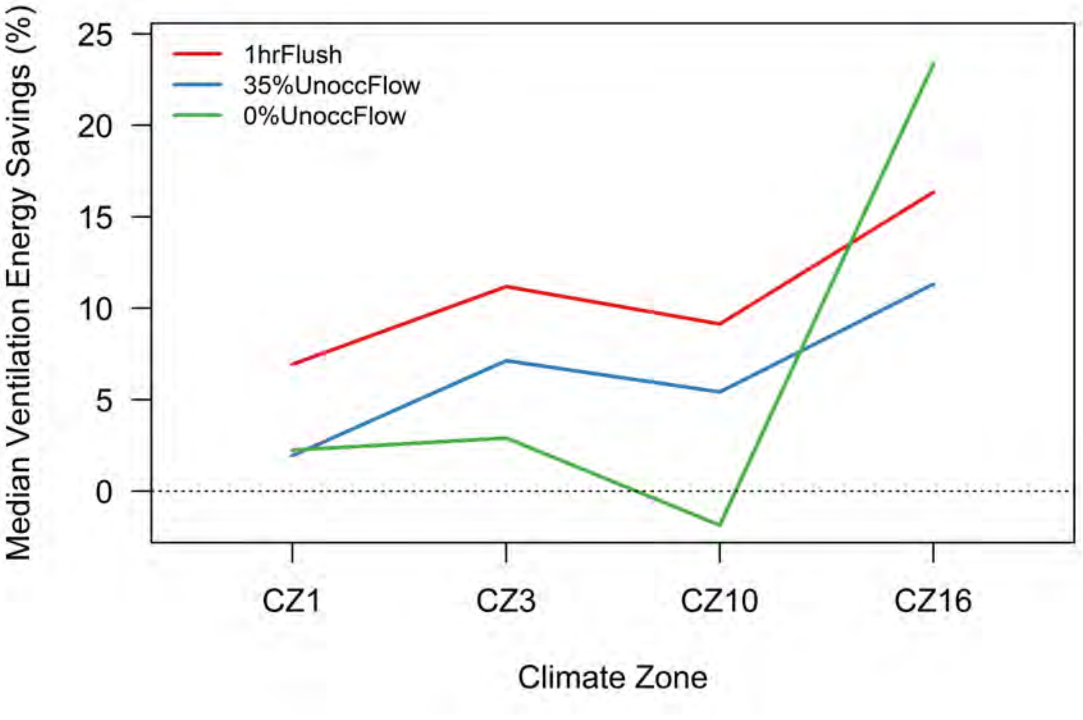

Figure 70 Median ventilation site energy savings for the Occupancy SVC control with no flush pre-occupancy, a 1-hour flush and with low unoccupied ventilation airflow.

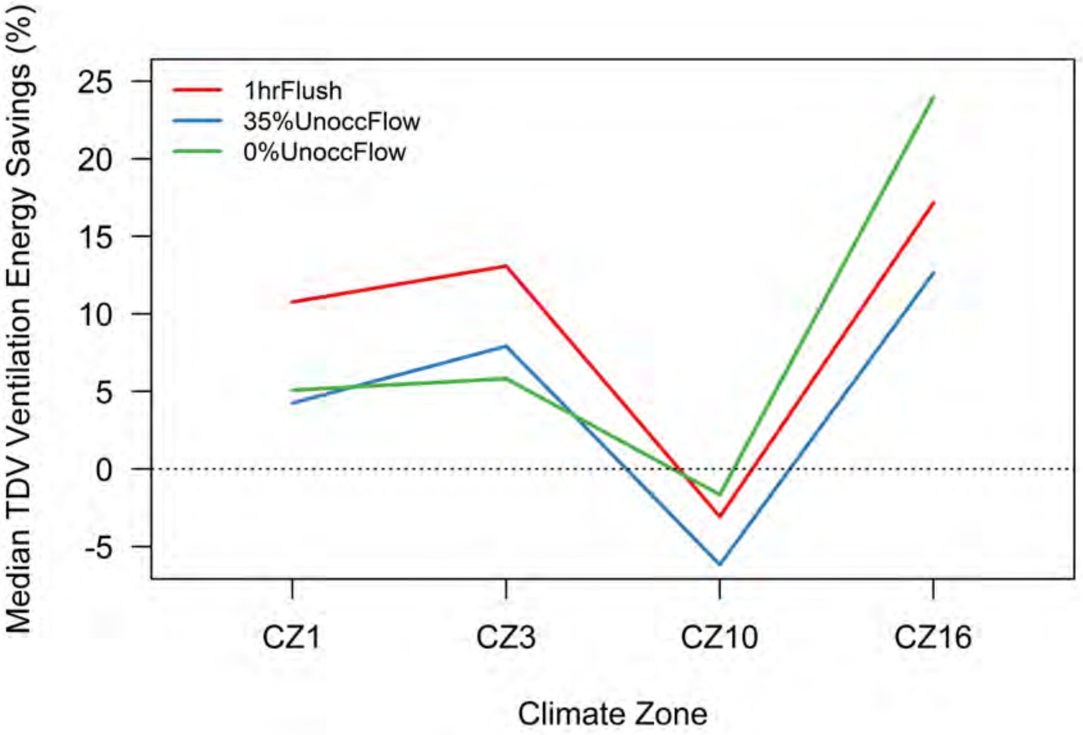

Figure 71 Median ventilation TDV energy savings for the Occupancy SVC control with no flush pre-occupancy, a 1-hour flush and with low unoccupied ventilation airflow.

Addition of Auxiliary Fan Sensing to TSVC and OSVC

All temperature and occupancy controls were tested with an auxiliary fan sensing capability, which built upon the original controls to simply account for other exhaust airflows in the controller's air exchange estimates. This allows the controllers to operate the main IAQ fan less (or at lower airflow), because it is aware of other concurrent airflows. For example, if the VarQ controller calculates that the IAQ fan must operate at full capacity, but the clothes dryer is operating, the controller then reduces the IAQ fan flow accordingly. We show only non-normalized results for the auxiliary fan add-on controls.

The overall median ventilation site energy savings for compliant cases are shown for each control type in Figure 72, with and without auxiliary fan sensing (TDV savings are shown in Figure 73). Here we see roughly a 10-15% average boost in ventilation savings when adding auxiliary fan sensing to the existing controls. For individual cases, the incremental benefit of auxiliary fan sensing decreases as the overall savings increase. For the best-performing cases, adding the auxiliary fan sensing adds a small 3-5% additional benefit. For the worst performing cases, auxiliary fan sensing could add 14% savings. Auxiliary fan sensing provided greater TDV benefits, because it largely allowed reduced ventilation rates during peak hours when occupants returned home and used auxiliary ventilation devices for cooking and bathing. The VarQ controller had less incremental TDV energy benefit from auxiliary fan sensing, because aggressive reductions in ventilation airflows during peak demand periods were inherent in its control schema.

There is some variability by control type, but that is not due to fundaments of the controls and how they interact with auxiliary fan sensing. Rather, these groupings include different homes, because sometimes the inclusion of auxiliary fan sensing changed the compliance status of the case (annual exposure below one). In fact, with the exception of the Lockout control, inclusion of auxiliary fan sensing always increased the fractions of control cases that were compliant with the exposure below one requirement. These different groupings shift the medians up and down. For example, it looks like the VarRe gets much more benefit from auxiliary fan sensing than do the VarQ cases, which results from including different cases in the median estimate.

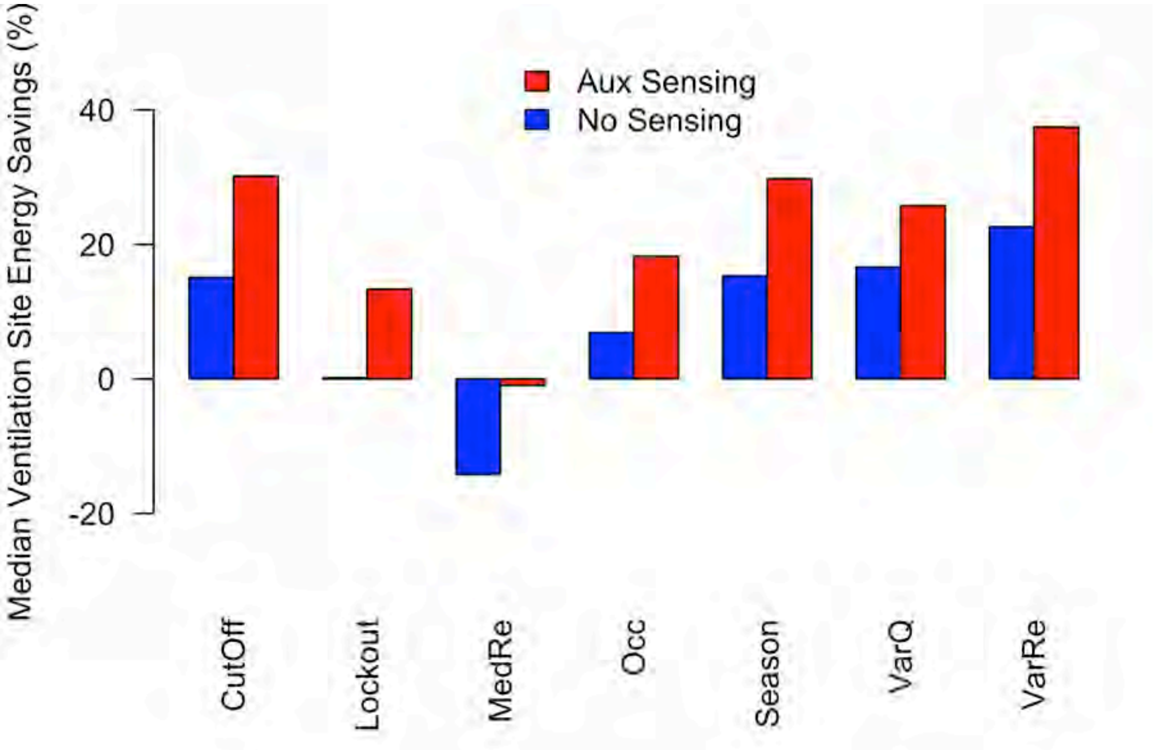

Figure 72 Median ventilation site energy savings for compliant SVC with and without auxiliary fan sensing.

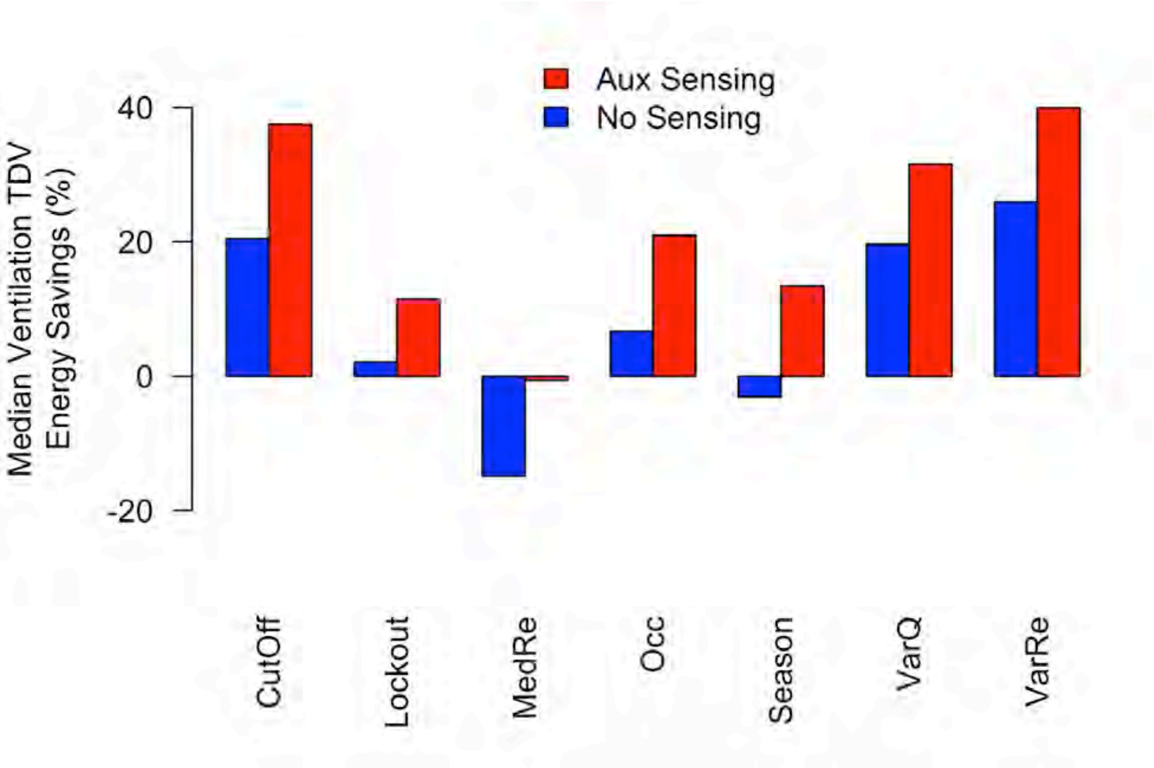

Figure 73 Median ventilation TDV energy savings for compliant SVC with and without auxiliary fan sensing.

We noted above that auxiliary fan sensing reduced controller exposure, but what is more notable is how it increased real exposure. We show these changes in Figure 74. On average, controller exposure is reduced by about 1% (from 0.998 to 0.987), or less, when using auxiliary fan sensing, which makes more cases/controls compliant. These small changes occur because of the non-linearities when combining unbalanced mechanical ventilation with infiltration (the calculations for fan sizing do not exactly match the calculations for recombining mechanical flows and infiltration) and issues such as timing of when auxiliary fans are operating and the ventilation fan is being turned on and off by the various control strategies. But this feature also consistently increases the real exposure, by 7% on average (from 0.897 to 0.966). Fully 75% of the control cases still had real exposure below one (though they were higher than without auxiliary fan sensing), and real exposure was at most 1.1. So, auxiliary fan sensing does contribute to meaningful energy savings of roughly 5-15%, but it does so by reducing the overall air exchange rate and increasing occupant exposure to contaminants. This is allowed by the ASHRAE 62.2-2016 ventilation standard, but may not be advisable. In more real terms, an actual home using a smart controlled ventilation fan with auxiliary fan sensing would have a 7% higher formaldehyde concentration than if it did not use the fan sensing feature.

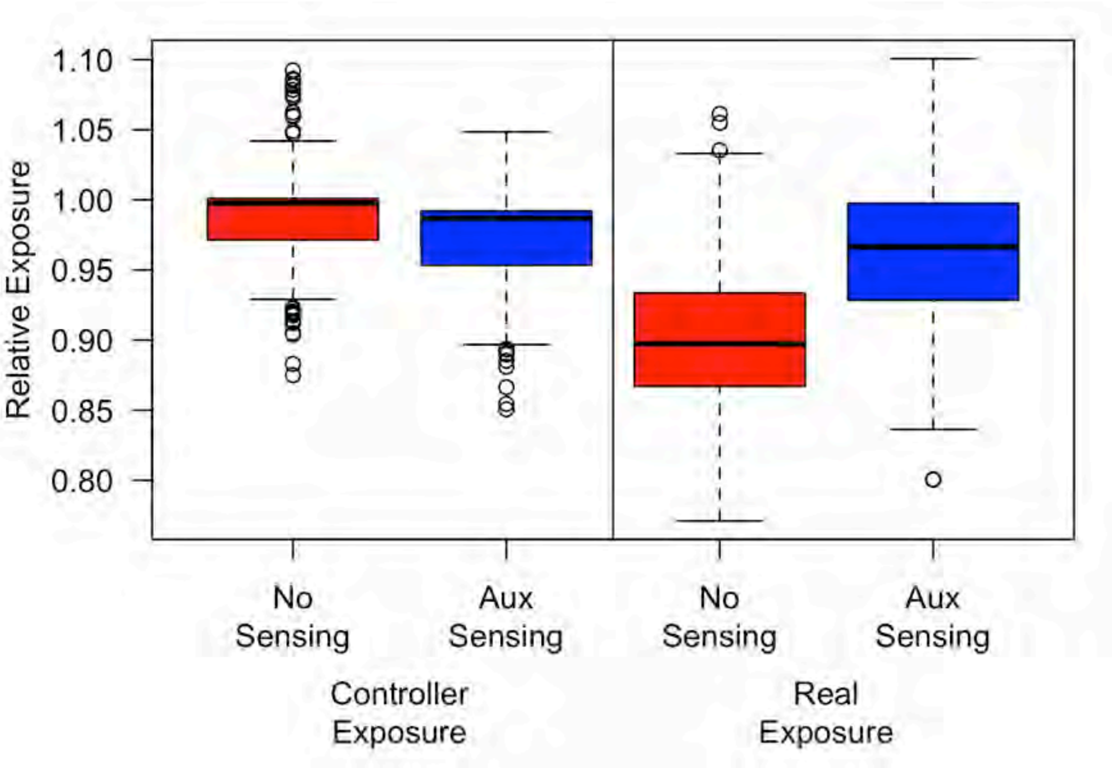

Figure 74 Controller and real relative exposure, compared by auxiliary fan sensing status.

Discussion

This discussion focuses on the impacts that the smart controllers had on relative exposure, IAQ and house ventilation rates. We begin by describing the margins of failure for non-62.2 compliant cases where relative exposure was >1.0 (Section 0). Next we describe the impacts of smart controls on: reductions in exposure (Section 0), increases in peak exposure (Section 0) and changes to exposure during occupied and unoccupied hours of the year (Section 0). We describe the daily vs. seasonal shifting of exposure for different control types (Section 0). House airflow is discussed in terms of increases in ventilation rates with SVC (Section 0) and comparisons of the energy impacts of SVC with those of envelope air sealing (Section 0). Finally, we discuss next steps for inclusion of smart ventilation controls within the realm of demonstrating Title 24 energy code compliance (Section 0). A further discussion of simulation parameter sensitivity is summarized in 0.

Failure Margins for Non-Compliant Controls

A substantial minority of smart control cases failed to meet the requirement of ASHRAE 62.2-2016 that annual average relative exposure be less than or equal to one. While these failures are unfortunate and show the potential inconsistent exposure in controls that shift ventilation seasonally, it is important to note the margins by which the control exposure exceeded 1.0. We show the distributions of failure margins aggregated by control type in Figure 75. When most controllers failed, they failed by relatively small average margins of 0 to 3% (i.e., 1-1.03 exposure). These controllers did not satisfy the ventilation standard, but they did have annual exposures commensurate with those achieved by continuous baseline ventilation fans sized to ASHRAE 62.2-2016 (see the Base_Fan cases in Figure 75 on the far left).

We struggled in this project with how to determine if a control case was equivalent to the continuous fan. We ultimately have deemed all cases with controller exposure above 1.0 by any margin whatsoever to have failed. This is in accordance with the requirement in the ASHRAE standard.

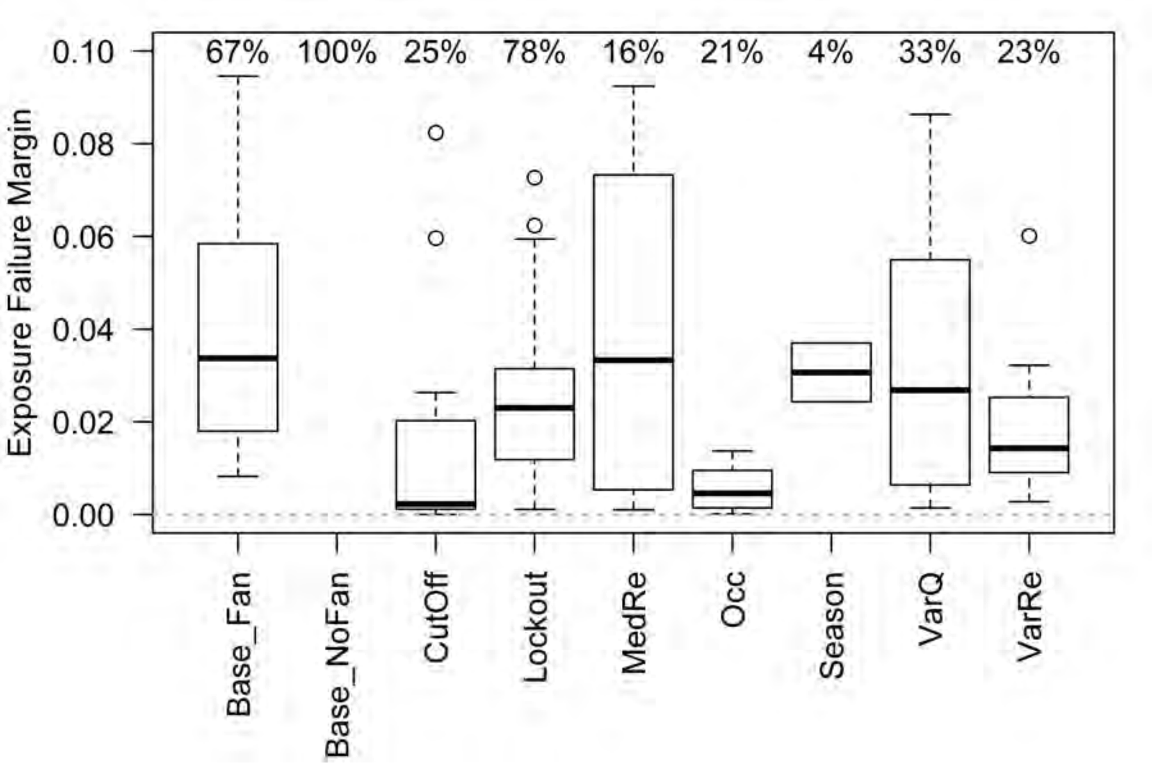

Figure 75 Margin of failure for simulations failing to meet equivalence requirement of controller relative exposure <= 1.0. Fraction of cases that failed indicated in text at the top.

Reductions in Exposure

Overall, the SVC reduced the real and controller relative exposure when compared with the continuous fan baseline simulations, which translates to improved IAQ for the smart control cases. The distributions of reductions in real and controller relative exposure are shown by boxplots in Figure 76 and Figure 79. Across the board, smart controls reduced real relative exposure by between 0 and 20% (averaging between 5 and 10%), while reductions in controller exposure were somewhat smaller, ranging from 0 to 15% reductions relative to the continuous fan baselines (averaging between 3 and 5%). We also illustrated these reductions in the plots of the best-performing controllers for each home (see Figure 18). The top-performing controllers, in addition to reducing ventilation energy, also improved IAQ by reducing pollutant exposure between roughly 0 and 15%.

Smart controls reduced real and controller relative exposure for two main reasons. First, most baseline continuous fan cases had exposures between 1 and 1.09, which means they were under-ventilated relative to the 62.2-2016 whole house target airflows. This bias in 62.2 fan sizing is discussed in 0. Second, the smart controls were designed to achieve controller exposures below one, which meant a design target in most controllers of 0.97 to account for imperfections in controller design and operation. As a result, many controllers inadvertently had annual exposures well below 0.97, reducing the exposure even further relative to the baseline fan cases.

This systematic bias towards high exposure in the reference baseline cases and low exposure in the control cases was the critical factor that led us to normalize the energy savings results and to present them in parallel with raw simulation results in Section 0.

We recommend that future assessments of smart ventilation controls designed to comply with ASHRAE 62.2-2016 follow a similar normalization method to ensure apples-to-apples IAQ and energy comparisons. This should be done for both baseline and smart control cases. Furthermore, we suggest that the ASHRAE standards committee responsible for 62.2 should change the superposition models embedded in the standard, so that they are a forwards-backwards identity. This would ensure that one arrives at the same value, whether sizing a fan (Qfan) using a target whole house flow (Qtot) and infiltration estimate (Qinf), or using the resulting fan flow and infiltration estimate to calculate whole house flow for use in exposure calculations. Hurel et al (2016) provide all superposition models as identities, including those currently in 62.2. The equations would become marginally more complex when estimating whole house flow for use in exposure calculations. This would eliminate the systematic bias towards high exposure in baseline cases, but it would not necessarily impact the varying exposures achieved by a smart controller.

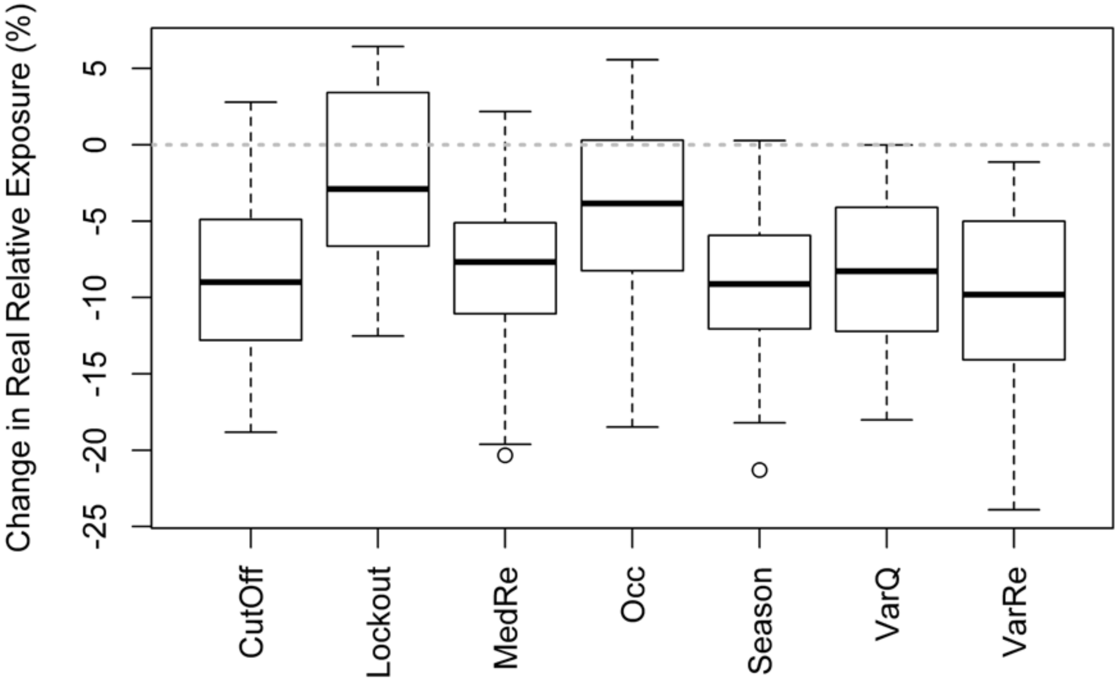

Figure 76 Reduction in real relative exposure, by smart control type.

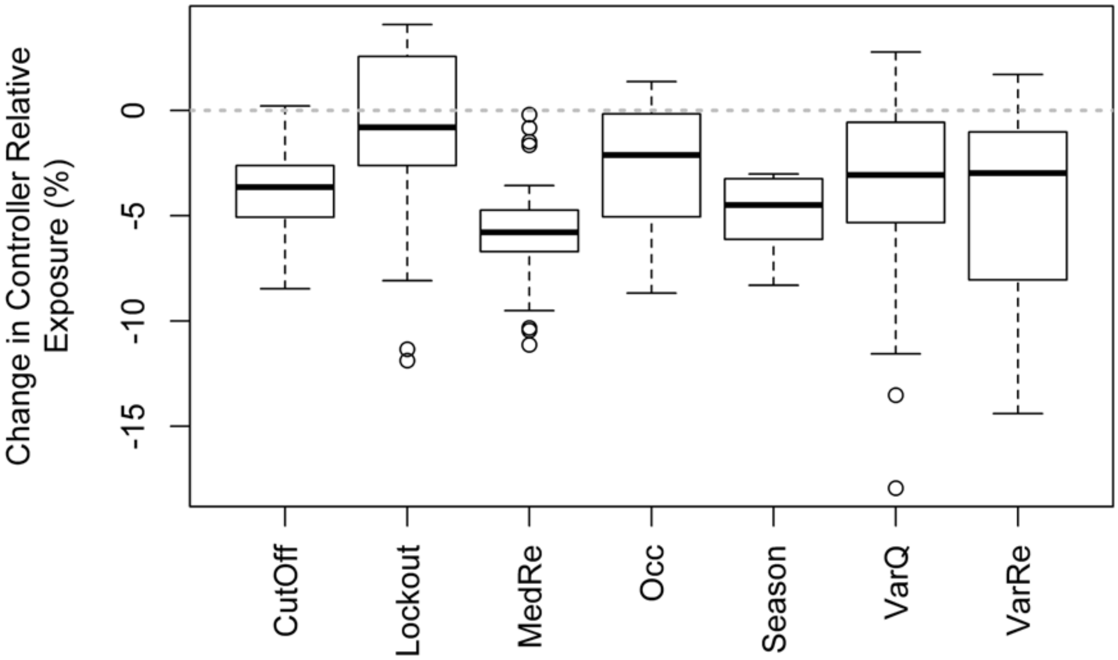

Figure 77 Reduction in controller relative exposure, by smart control type.

Consistent with this, we also compare the controller exposure and the real exposure for every simulated case in Figure 78, along with the unity line dashed in grey. We note that for nearly all simulated cases, the real exposure is less than the exposure predicted by the ventilation controller, which makes all of our estimates essentially conservative in terms of IAQ impact. This is due to other airflows not accounted for by the controller, which the real exposure includes (e.g., local exhaust devices, and in Qinf cases, time-varying infiltration). Notably, the seasonal shifting smart controls (e.g., VarQ, VarRE, CutOff and Season) achieved the lowest real exposure, and the difference between controller and real exposure was also greater for these controls.

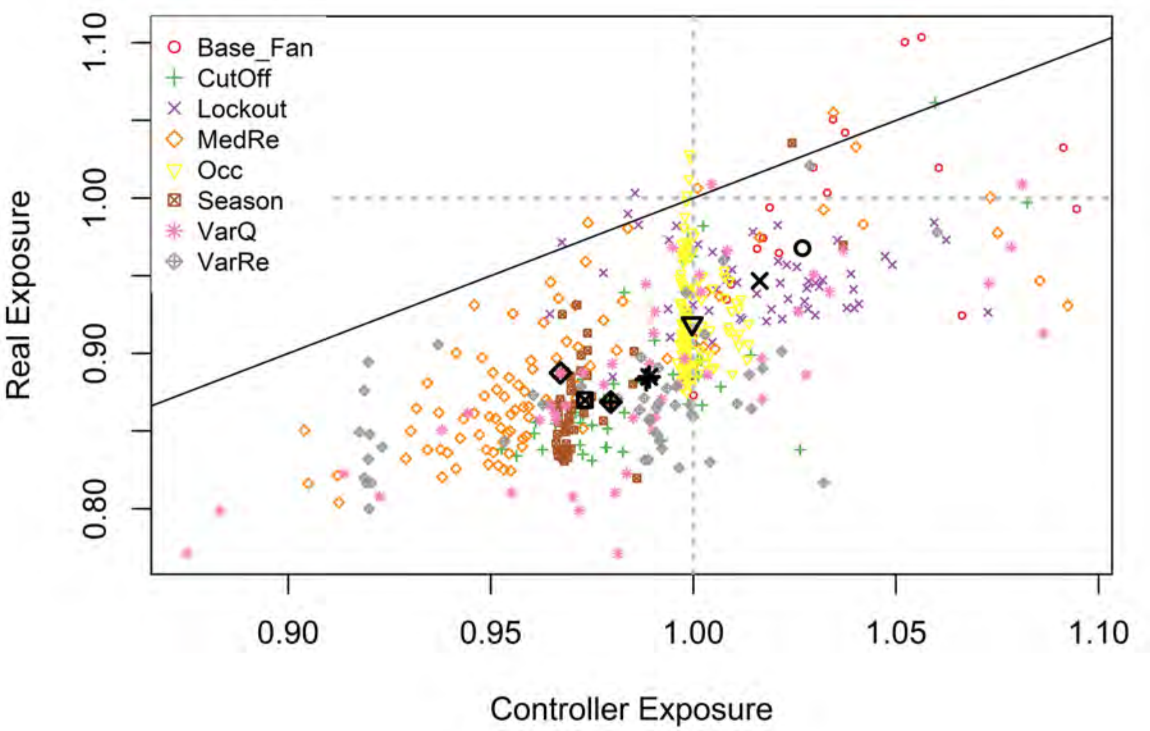

Figure 78 Controller vs. real relative exposure.

Increased Peak Exposure

While most smart controls saved energy and improved IAQ, they also increased peak exposure to the occupants, resulting from reduced air exchange rates when hot or cold outside. The peak annual one-hour relative exposure values are shown for each control type in Figure 79. For reference, the ASHRAE 62.2-2016 ventilation standard allows a peak exposure of 5 when demonstrating compliance through Appendix C. The big outlier in Figure 79 is the VarQ smart controller, which has much higher peak exposures than its counterparts, with a peak exposure in one case that exceeded the limit of 5 (note that this is because, unlike a real-time controller, this control strategy does not perform exposure calculations and, therefore, cannot limit peak exposure). The nearest counterpart for the VarQ is the VarRe controller. They work on similar principles, with a similar control structure, yet the peak exposures are much lower in the VarRe controller, averaging below 2 and at most 3.5. The reason VarQ experiences high exposure excursions is that the controller will actually just turn the ventilation fan off if it is cold or warm enough outside. In contrast, the VarRe controller simply targets an increased exposure level (lower ventilation rate) during those same periods. The VarQ controller could easily be adjusted to target a low airflow rather than 0 at extreme conditions, which would eliminate this issue. The Cutoff controller is also worth noting, because it was one of the top energy performers, and its peak exposures are very low—averaging below 1.5 and always below 2. The Cutoff control was actually optimized by targeting a low peak exposure, but doing so for as many hours of the year as possible (as opposed to a high exposure target for fewer hours). Overall, we expect peak exposures in these situations to worsen with increasing airtightness and in more mild climates. But some controls are good at limiting these peaks (VarRe and Cutoff), and others are not (VarQ).

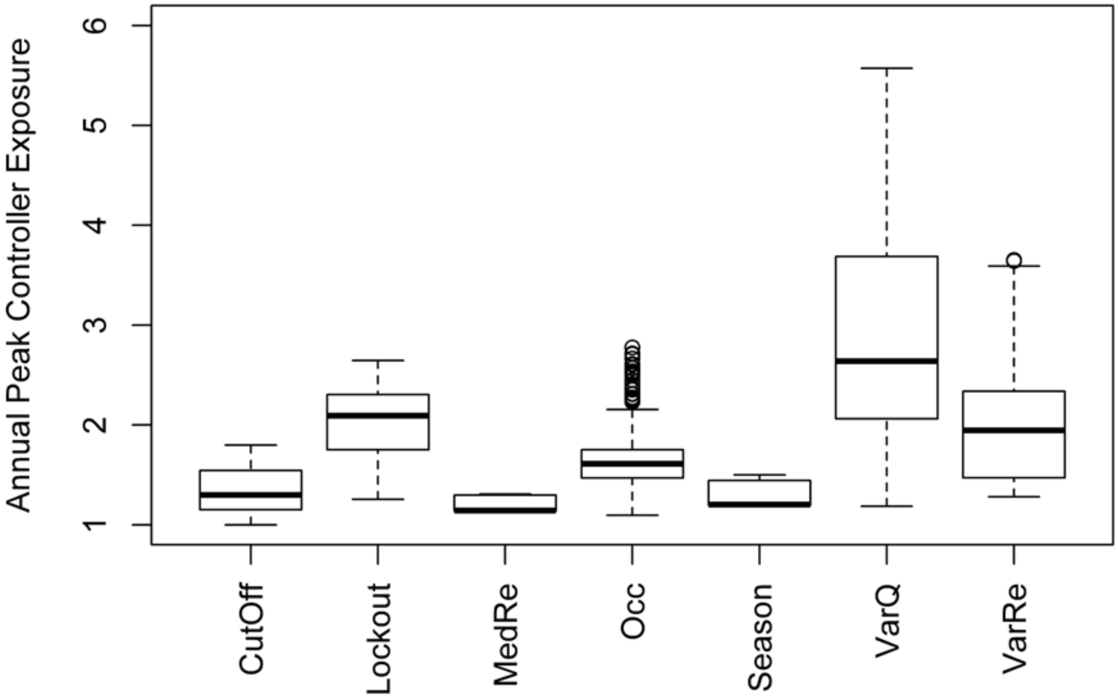

Figure 79 Annual peak one-hour controller relative exposure.

Occupied vs. Unoccupied Exposure

We have noted elsewhere that the Occupancy and Temperature SVC behave in different ways, with the temperature-based controls generally reducing ventilation during the coldest/hottest periods and increasing it at other times. Over the course of a day in the heating season, we expect our TSVC to increase ventilation during the warm, daytime hours when the home is unoccupied. The same controllers then reduce the ventilation rate during colder nighttime hours when occupants are present. We expected that this approach might bias the TSVC towards a net-increase in occupant exposure, because the controls (and the ASHRAE 62.2-2016 standard) weight exposure equally during occupied and unoccupied hours.

To assess this, we applied a standard occupancy schedule to our TSVC results, using the same 9-hour, 1st shift absence as in the Occupancy SVC cases. We then averaged the time-series controller and real exposure values for all occupied and unoccupied hours to assess this potential bias. For each control type, we calculated the median occupied and unoccupied control exposure across all cases, and these overall values are shown in Figure 80. Clearly, the occupied and unoccupied hours had quite similar controller exposure values across all control types, except for the Occupancy SVC, which purposefully maintains high exposure during unoccupied periods. In fact, for most of the TSVC, occupied exposure was slightly less than unoccupied exposure (except VarRe). In any case, the values are essentially indistinguishable over the course of the year. This pattern is the same when assessing real exposure by occupancy status. These results may reflect a balancing of TSVC behavior over the course of heating and cooling seasons. During cooling season, we expect increased ventilation during occupied, nighttime hours and reduced airflow during the hot, unoccupied daytime hours. This might balance out the expected biased pattern in the heating season. Finally, it is worth noting that all TSVC actually achieved lower occupied exposure on average than the Occupancy SVC did. We strongly conclude that the TSVC pose no risk of biasing occupant exposure high, even though the controls are unaware of the occupancy status.

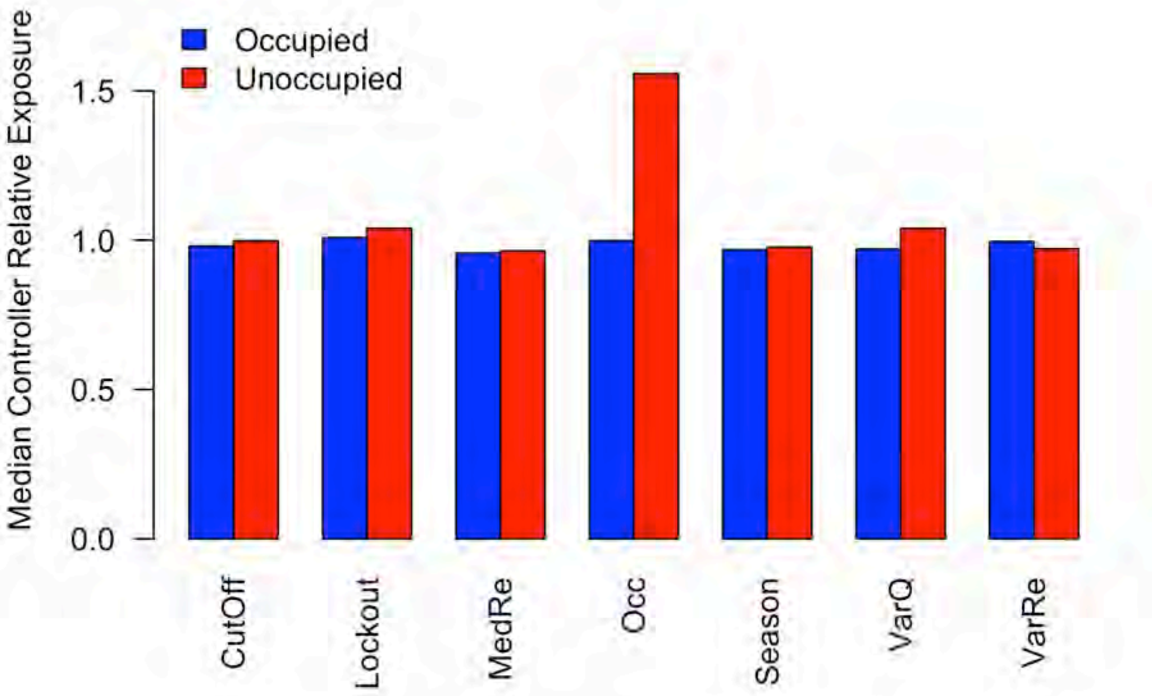

Figure 80 Comparing controller exposure by occupancy status for all smart controls (medians calculated within each control group).

Daily vs. Seasonal Controllers

The smart controls developed and tested in this work differed in the time horizons over which they maintained equivalent exposure with 62.2-2016.

The worst energy performance was for the two control types that targeted equivalent exposure on a daily basis—the Lockout and the Occupancy controls. In these controls, the mean occupied exposure was required to be less than or equal to 1.0 each day of the year. This ensured that the yearly exposure would also be less than 1.0. This approach allowed shifting of airflows only across hours of the day, which limited their effectiveness. A possible exception to this is the Lockout controller, which appears to reduce cooling energy use during summer periods (See end-use savings plots in Figure 17). This could be because the 6-hour lockout period covers the hottest summer daytime hours, and the increased ventilation rate during other hours does not increase the net-load. In heating, the 6-hour period covers the coldest hours, but the remaining hours with high ventilation rates offset the savings and increase the net-heating load.

The next-worst performing control was the Running Median (MedRe) controller, which used a 30-day time period for ensuring equivalent exposure. This controller was intended to ensure that each month's mean occupied exposure was less than or equal to 1.0, which again ensured annual exposure was also below 1.0. The MedRe was able to shift ventilation airflows between days and weeks of the month, but not between months/seasons. This additional flexibility gave it a marginal advantage over the daily Lockout and Occupancy controls.

Finally, the controls with the greatest energy savings were those that targeted equivalent exposure on an annual basis—Seasonal, CutOff, VarQ and VarRe. These controls were able to shift ventilation airflows across months and seasons of the year, and whether by-design or through optimization, they all reduced ventilation airflows during the heating season and increased them during the cooling season. The Seasonal control was the simplest approach that did this seasonal shifting, and it did nothing other than reduce ventilation in winter and increase it in summer. This worked well in many contexts, but it had predictable TDV energy penalties, due to the emphasis on peak period electricity consumption in TDV assessments. But by far the best-performing strategies—CutOff, VarQ and VarRe—built upon this seasonal shifting of ventilation flows by also varying airflow within each season to take advantage of mild periods and to avoid ventilating during especially hot or cold times.

While the energy benefits were clear, there are also notable downsides to these seasonal-shifting control strategies.

First, it is simply very challenging to design and optimize an annual controller that will achieve exposures below one. Despite careful design and optimization to select control parameters, the simulated controller exposures were often substantially different than the simplified estimates used in the design-phase. For example, the VarRe controller sets an exposure target for every time-step of the simulation based on the season and outside temperature, and it then identifies the maximum RE target such that annually the target exposure values will average to 0.97. The problem is that any given target exposure value cannot necessarily be met at the time-step it is calculated, because when the target moves rapidly (as it does with diurnal temperature patterns), it takes time for the controller to adjust the exposure (up or down) to the reach the target value in the actual home. It is this lag in the changing exposure values relative to the targets established by the controller that makes these control types unstable and difficult to predict precisely.

Second, some are concerned that the seasonal-type controls maintain seasonal average contaminant levels well above those in the reference condition. These high levels are then offset by low concentrations during other seasons. While consistent with the annual requirements of ASHRAE 62.2-2016, the potential implications of this seasonal shifting are still unknown. For example, we simply do not know if the health and perceived IEQ are actually the same between a case with indoor formaldehyde held constant at 20 ppb, versus varying seasonal levels of 10 and 30 ppb (for 50% of the year, each). Any health detriments between 20 and 30 ppb may very well not be offset equally by health benefits from maintaining 10 ppb during the other season. This may be especially the case for indoor contaminants, such as irritants, odors or moisture.

Yet, this seasonal variability in indoor contaminant levels (and ventilation rates) already happens in actual homes due to a variety of effects, whether intended or not. First, many indoor VOCs are emitted at higher rates with increasing indoor temperatures. So, the cooling season will commonly see higher chemical emissions and measured concentrations. At the same time, many homes operate windows manually to provide ventilation during the cooling season, leading to higher average ventilation rates during these times. Furthermore, all homes experience time-varying infiltration rates, which in real homes will drive time-varying concentrations; again generally lower in particularly hot or cold periods. If anything, the seasonal smart controllers tested in this work will increase ventilation rates when chemical emissions are at their highest (during cooling season), potentially providing further value that is not reflected in our calculations based on a generic, continuously emitted contaminant. All homes experience time-variability in indoor contaminant levels, many seasonally. Our SVC simply exhibit this behavior purposefully.

Changes in Air Exchange Rate

Except for the Occupancy SVC, all smart ventilation controls increased the annual average air exchange rate of the home, which they must do in order to both dynamically vary the ventilation rate and maintain equivalent exposure (Nazaroff, 2009). Successful smart controllers increased whole house air exchange rates by anywhere from 0 to roughly 60%, averaging around 40% for the most successful controls. This counterintuitive result is possible, because the controllers shift airflow based on temperature, and the increased flows occur when weather is mild, with reduced energy impact. We show the distribution of increases in annual mean air exchange rate for each control type in in Figure 81. Notice how the occupancy controller saves energy by reducing the average ventilation rate relative to the baseline case. Some occupancy control cases increased the ventilation rate relative to the baseline cases, because the baselines have mean relative exposures greater than one, while the control cases are all less than one (i.e., 62.2-2016 compliant).

We have shown that increasing the house ventilation rate can be done while saving large amounts of energy relative to a continuous fan, but there are downsides as well. First, a larger fan is needed, with larger ducting, more potential noise, etc. Second, increasing the ventilation rate by up to 40% increases IAQ fan energy by at least that same fraction, which can substantially eat into ventilation savings, unless the controller is well designed and the fan power is low. Third, in locations with compromised outdoor air quality (i.e., Ozone in the central valley foothills, or $PM_{2.5}$ in downtown Oakland), this has the potential to greatly increase indoor concentrations of outdoor contaminants, mainly particulates and products of combustion (oxides of nitrogen). Finally, in hot-humid climates, increasing the ventilation rate by 20% will almost certainly transport more moisture into the home, leading to potential comfort problems and concerns about mold growth. This will be exacerbated by the overall trend with most of our TSVC to increase the ventilation rate drastically during the summer, while reducing it during the winter. The cooling season has the highest outdoor humidity in hot-humid climates, so this is likely a poor ventilation pattern for moisture control in humid environments.

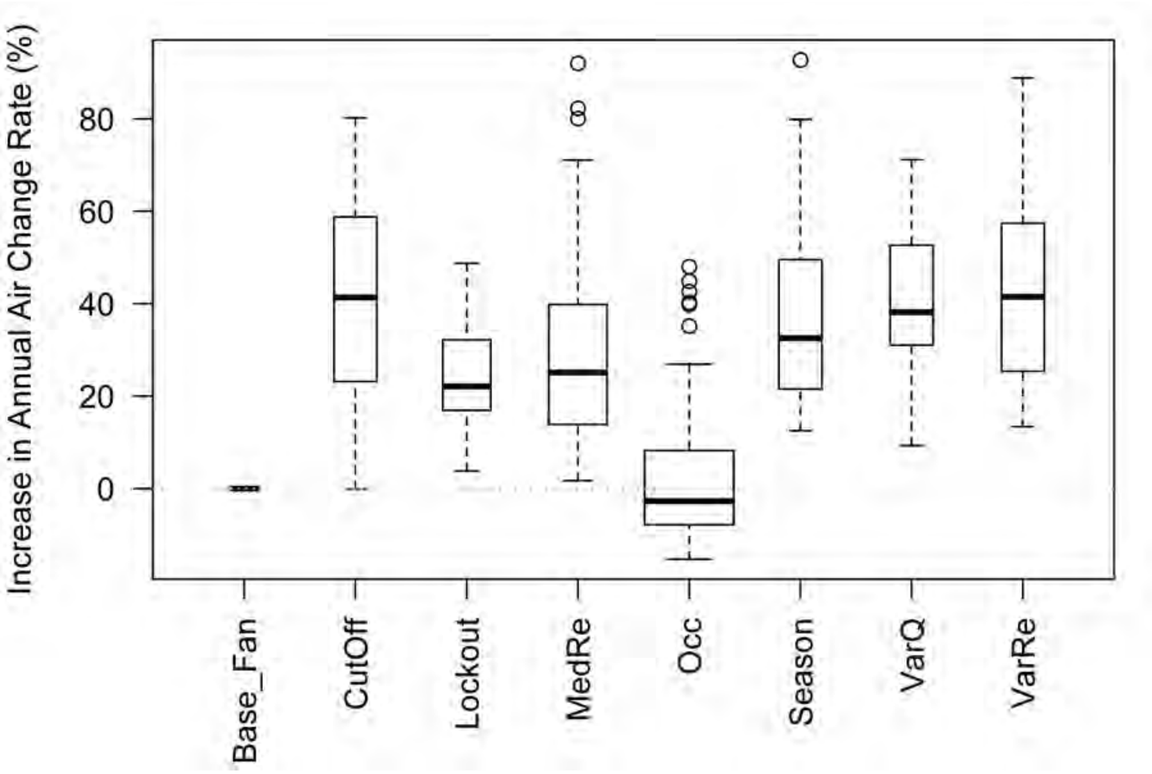

Figure 81 Increase in annual mean air change rate distributions by control type, ALL cases.

Smart Controls vs. Airtightening

We are also interested in how smart ventilation controls compare with air sealing a home; maybe similar energy performance can be attained by selecting the optimum airtightness for a given prototype and climate zone, and the added complexity of smart controls are not needed. Overall, our results show that in all but one scenario, a 62.2-compliant smart ventilation control will be a better energy conservation approach than airtighening, assuming that the home is ventilated in compliance with ASHRAE 62.2-2016. Notably, energy savings from air sealing the building envelope are the result of reduced ventilation rates, increased relative exposure and poorer IAQ. In contrast, the SVC save more energy and do so while reducing exposure and improving IAQ relative to the constant fan baseline cases.

In Figure 82 we show the total HVAC raw site energy consumption predicted for the baseline fan and best-performing smart controls at each airtightness level for the 2-story large prototype homes located in CZ10. The bars are colored by control type and are shaded (slanted lines) according to the infiltration accounting method (Qinf vs. AIM-2) with the least energy use for the given controller (see TDV energy in Figure 84). We see that of the baseline continuous fan cases, the 3 ACH_{50} home uses the least site HVAC energy. But there are smart controls at each airtightness level that use less energy than this constant fan minimum case. The VarRe control in a 3 ACH_{50} home with AIM-2 infiltration uses the least HVAC energy of all, followed very closely by the VarQ control in the 1 ACH_{50} home also using AIM-2 infiltration accounting. For this prototype and location, either the Qinf or AIM-2 infiltration assumptions give good performance.

In this study, we used the ASHRAE 62.2-2016 fan sizing method, which increases the required fan airflow as infiltration airflows are reduced with more airtight envelopes. The core idea of this sizing method is that it ensures the same whole house ventilation rates across differing levels of airtightness, climate zones and house types. This method is not perfect, but in general, there is little benefit to air sealing a home in California when ventilating in this manner, because the ventilation rate is designed to be fixed independently of the envelope leakage. Some benefit can be received, because the airtight home with a larger fan will have lower ventilation rates during very hot, cold or windy periods, compared with the leaky home with the smaller fan. This benefit is small in mild California climates. A recent statewide assessment (Chan et al. 2019) of this phenomenon suggests weighted average HVAC energy savings of 1-2% when imposing a 3 ACH_{50} airtightness limit on new CA homes. When fan size is not adjusted by envelope leakage, the savings increase marginally to the range of 3-5% of total HVAC energy use.

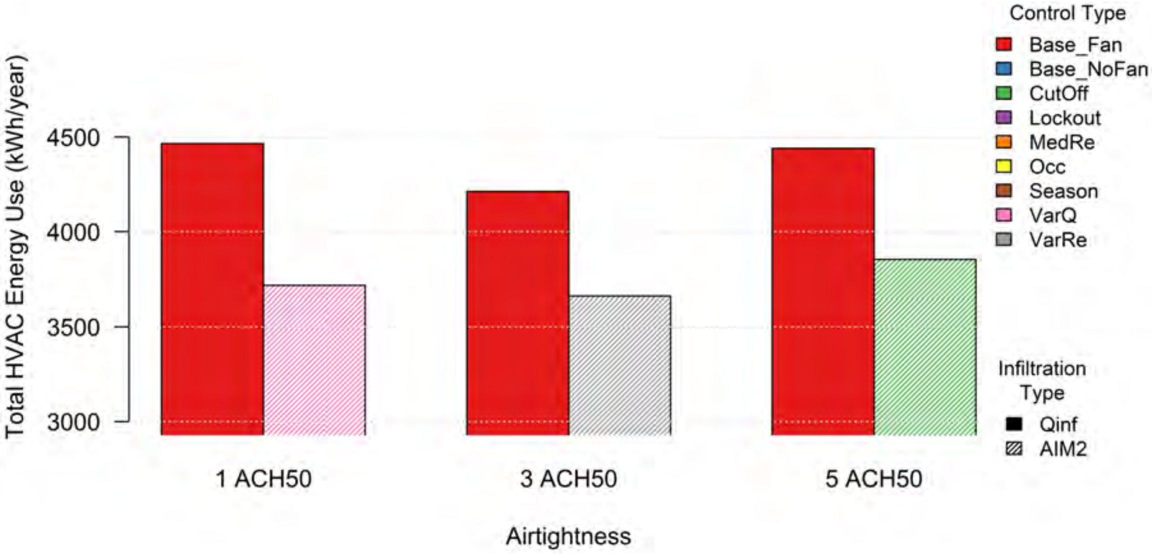

Figure 82 Total HVAC energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 2-story homes in CZ10 (Riverside).

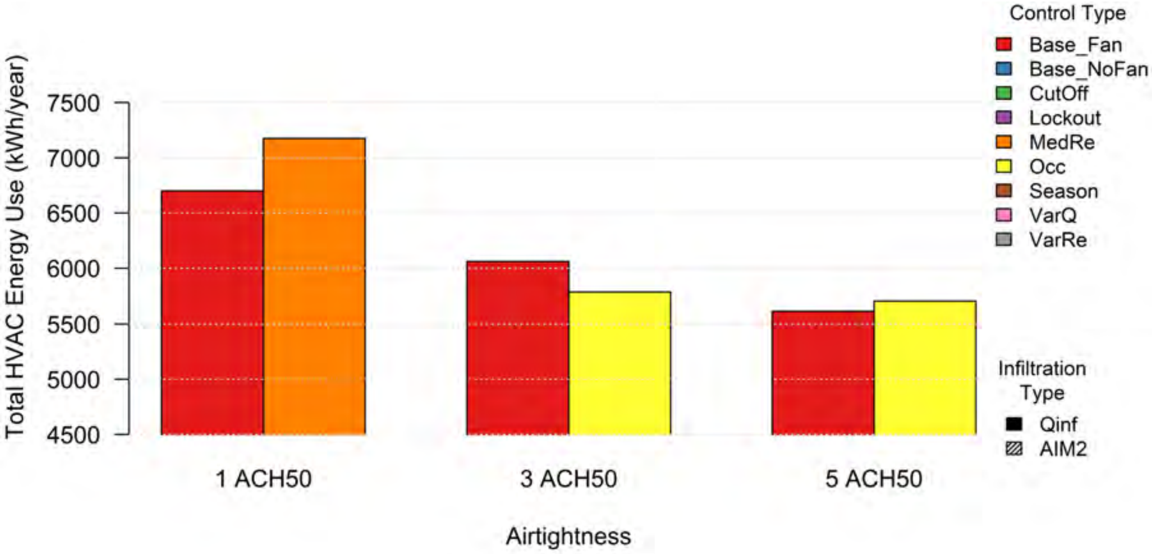

Figure 83 Total HVAC energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 1-story simulations in CZ1 (Arcata).

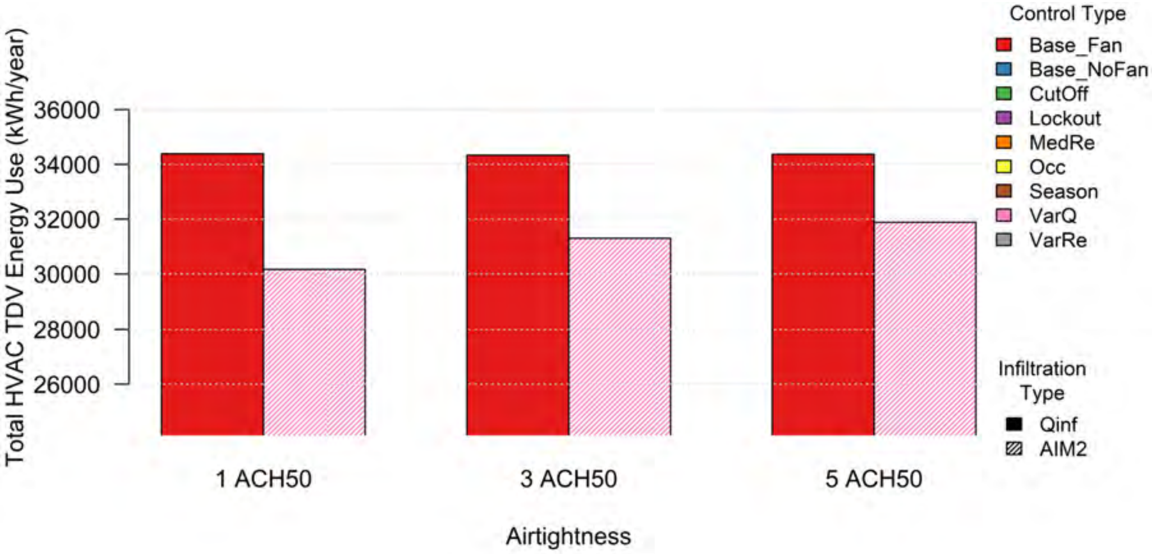

Figure 84 Total HVAC TDV energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 2-story simulations in CZ10 (Riverside).

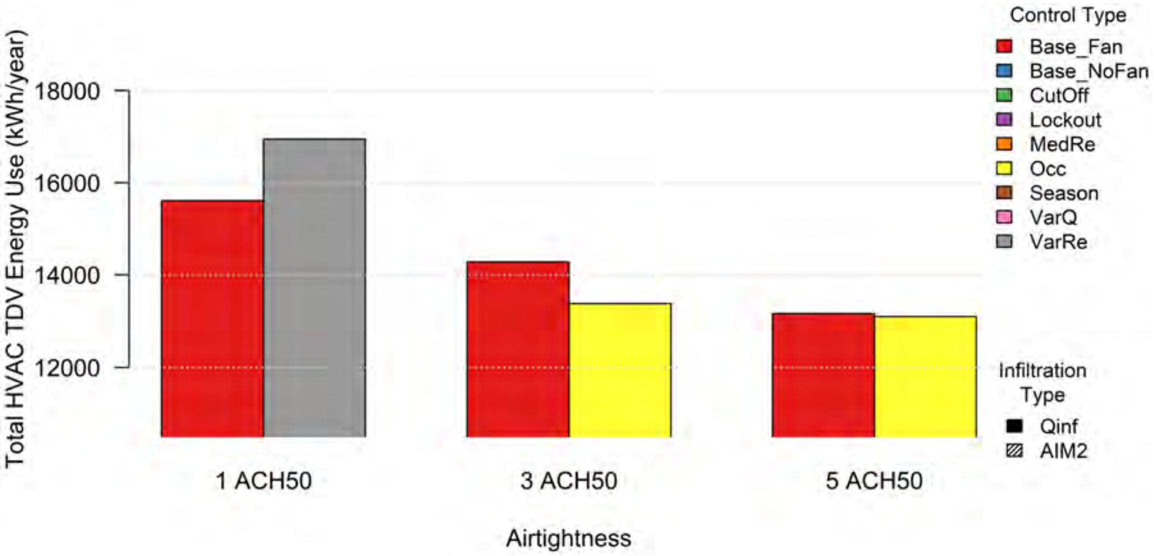

Figure 85 Total HVAC TDV energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 1-story simulations in CZ1 (Arcata).

Title 24 Next Steps

The 2019 Title 24 has adopted parts of the ASHRAE 62.2-2016 ventilation standard, including the ability to demonstrate compliance for time-varying ventilation using relative exposure (i.e., smart ventilation controls in Normative Appendix C). But there is no current method in the Title 24 to account for the energy savings or to get compliance credit for such systems.

One option would be to incorporate the ability to model dynamic ventilation systems and relative exposure into CBECC-Res, or allow the use of pre-calculated scheduled mechanical ventilation airflows (rather than the current fixed fan airflow). This is required to reflect the diversity of results found across house types, climates and envelope leakage rates in our work. This is also the only way to provide adequate market flexibility for future changes to control schemas by manufacturers, new code requirements, etc.

Another option is to use third-party compliance verification where a particular SVC approach is simulated using agreed upon assumptions and scenarios and gets an energy use multiplier that can be used in compliance calculations. The Energy Commission would also need to develop requirements or guidelines for manufacturers to use in demonstrating the compliance of their systems with the code requirements. This would include which housing types to model, ventilation system types, climate regions, and other such variables.

Notably, the reference case in our simulations was a continuous fan sized to the ASHRAE 62.2-2016 ventilation standard, but the 2019 Title 24 will require that IAQ fans in residences are sized differently. The new Title 24 fan sizing method is the same as ASHRAE 62.2-2016, but it fixes the envelope airtightness used in predicting annual effective infiltration at 2 ACH_{50} for all homes (homes that are tested below 2 ACH_{50} must use the lower number and increase the required fan size). Overall, this will increase the baseline fan sizes compared with our current simulations. This represents an additional opportunity for smart ventilation controls, because they can demonstrate energy savings relative to a baseline with higher ventilation energy consumption. Energy savings will increase, though improvements in IAQ through smart controls will be reduced or eliminated.

Finally, as discussed in Section 0, the superposition models used in ASHRAE 62.2-2016 are biased towards high exposure in constant fan cases using unbalanced fans. We suggest that this be fixed in ASHRAE 62.2 itself, but absent that, the CEC could consider amending the calculation procedures used in California. Specifically, we would recommend the equation used to estimate whole house airflow for exposure calculations in Normative Appendix C of the Standard be changed so that it is an identify (i.e., the same forwards-backwards) with the fan sizing equation. As outlined in Hurel, Sherman, & Walker (2015) Table 3, if the fan sizing superposition method currently in 62.2-2016 is used (i.e., Simple inverse sub-additivity) the matching forward calculation method should be used to estimate whole house airflows, as follows:

$$Q_{tot} = \frac{Q_{fan}}{2} + \sqrt{\frac{{Q_{fan}}^2}{4} + {Q_{inf}}^2} \tag{8}$$

Summary

Controller performance varied substantially by climate zone, airtightness and house prototype, therefore we cannot provide simple state-wide estimates of energy savings, nor can we identify which controllers are best optimized for state-wide use. Instead we were able to provide guidance on which control approaches are best suited to different climates.

The most successful smart controls shifted ventilation rates seasonally, rather than over the course of the day or month, and they used parameters pre-calculated using an optimization routine. These controls reduced weighted average site ventilation energy use by 41 - 51% (413 - 505 kWh/year; 12 - 15% of whole house HVAC energy), while TDV weighted average ventilation energy reductions were more varied and variable, at 36 - 61% (1,615 - 2,743 kWh/year; 6 - 10% of whole house TDV HVAC energy). Peak demand during the 2-6pm period on the hottest days of the year was reduced through use of the smart controls, with peak load reductions of 0 - 300 watts. We believe that specific peak controls could achieve even greater reductions in demand. The vast majority of site energy savings were for heating end-uses (>90% of total savings), while TDV energy savings were split fairly evenly between heating and cooling. On average, the smart controls reduced occupant pollutant exposure by 0-15% (improved IAQ), but they increased peak exposure to the occupants, with some controls having much higher peaks than others. The temperature-based smart controls increased annual IAQ fan ventilation flow rates and fan energy use, with typical increases of roughly 40%. This could be problematic with higher energy use fan types (balanced, supply or CFIS), or in areas with polluted or humid outside air, where increased ventilation flows might worsen existing energy or IAQ problems.

Smart ventilation and baseline constant fan cases did not provide the same IAQ. To provide an apples-to-apples assessment of energy savings, we normalized the energy use in each case by the corresponding annual relative exposure. When normalized, weighted average energy savings increased. The best controls achieved weighted average site ventilation energy savings of 56 - 64% (591 - 676 kWh/year; 16 - 19% whole house HVAC savings), and TDV ventilation savings from 51 - 68% (2,180 - 3004 kWh/year; 9 - 12% whole house HVAC TDV savings).

Occupancy-based controls saved energy by reducing the whole house ventilation rate, but these controls were generally ineffective, with very low energy savings. Performance was improved somewhat through use of a 1-hour pre-occupancy flush out period, though savings were still marginal compared to temperature-based controls.

Auxiliary fan sensing increased site energy savings in all cases, from roughly 5 to 15%. This procedure increased the average non-normalized site ventilation savings for the best control types to a range between 50 and 58% (TDV ventilation savings between 48 and 67%).

Use of the smart ventilation controls was much more effective than increasing airtightness while using continuous fans sized to ASHRAE 62.2-2016, because the ventilation standard increases the required IAQ fan airflow, as infiltration is reduced. This limits the benefits of air sealing.

Current products available for $150 to $300 on the consumer market have the core hardware capabilities to act as smart ventilation controls (fans or wall controllers with integrated temperature and humidity sensors), but very few of the currently available products actually ensure compliance with the ASHRAE ventilation standard, and none use the time-varying ventilation approach from Appendix C of ASHRAE 62.2 to facilitate time-shifting of ventilation flows over more than a 24-hour period. More work is required in order to allow builders and designers to take credit for smart ventilation control strategies in demonstrating compliance with California' Title 24 Building Energy Code. Also, field demonstrations of the energy and IAQ performance of smart ventilation controls are needed in new California homes, before these technologies can be adopted at scale. An adapted version of the varQ control algorithm is being field tested in 12 - 16 dwellings as part of the U.S. DOE Building America program in the years 2020-2022.

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Appendices

Lock-Out (Lockout) Control Description

The lockout TSVC controls the ventilation fan based on the relatively predictable diurnal variation in outside dry bulb temperature, experienced across climate zones, based on patterns of solar irradiation. Using pre-calculated estimates, this smart controller turns the ventilation fan off during the hottest or coldest hours of the day (depending on season). The ventilation airflow is increased during all other hours of the day to ensure equivalence with a continuous fan (see Table 8). The lockout period (coldest vs. hottest hours) is selected each day based on the CEC definition of heating and cooling seasons.

Time Period	***Fan ON***
Lockout	OFF
Non-Lockout	ON

Table 8 Lockout TSVC control strategy.

To calculate the best hours to turn the ventilation fan off, we used all 16 CBECC weather files for the representative California locations. We used the following method. For each month of the year (1:12), an average outside temperature was calculated for each hour of the day (0:23), resulting in 288 values (12*24). This was done for each of 16 climate zones. We then sorted the hourly average temperatures for each month from lowest and highest, and we categorized the lowest and highest hours for every month and climate zone. The hours that occurred most frequently in the low and high categories were selected for the lockouts in Table 1.

Time Period	***Coldest Hours***	***Hottest Hours***
4-Hour	03:00 – 07:00	13:00 – 17:00
6-Hour	02:00 – 08:00	12:00 – 18:00
8-Hour	00:00 – 08:00	11:00 – 19:00

Table 9 Coldest and hottest 4-, 6- and 8-hour periods in each day. Used in TSVC lockout strategy.

Figure 86 shows the relative exposure, relative dose and outside temperature for an example temperature lockout strategy in a Arcata, CA (CZ1) two-story prototype home at 1 ACH_{50}. The lockout period is highlighted in pink. As expected, the relative exposure climbs quickly during the lockout period, up to peak around 1.8. Then the over-sized ventilation fan operates continuously during all other hours, bringing the relative dose to roughly 0.97, which reflects the integrated exposure over the prior 24-hours.

The exact size of the ventilation fan was pre-calculated for each case such that if operated continuously, the daily average relative exposure would be less than 0.97. This pre-calculation requires information about the house size, estimated infiltration (e.g., Q_{inf} from 62.2) and baseline fan airflow. Pre-calculation was performed for all CEC climate zones and prototypes that we assessed, the required fan size multipliers (relative to the baseline 62.2 IAQ fan airflow) are provided in Table 10.

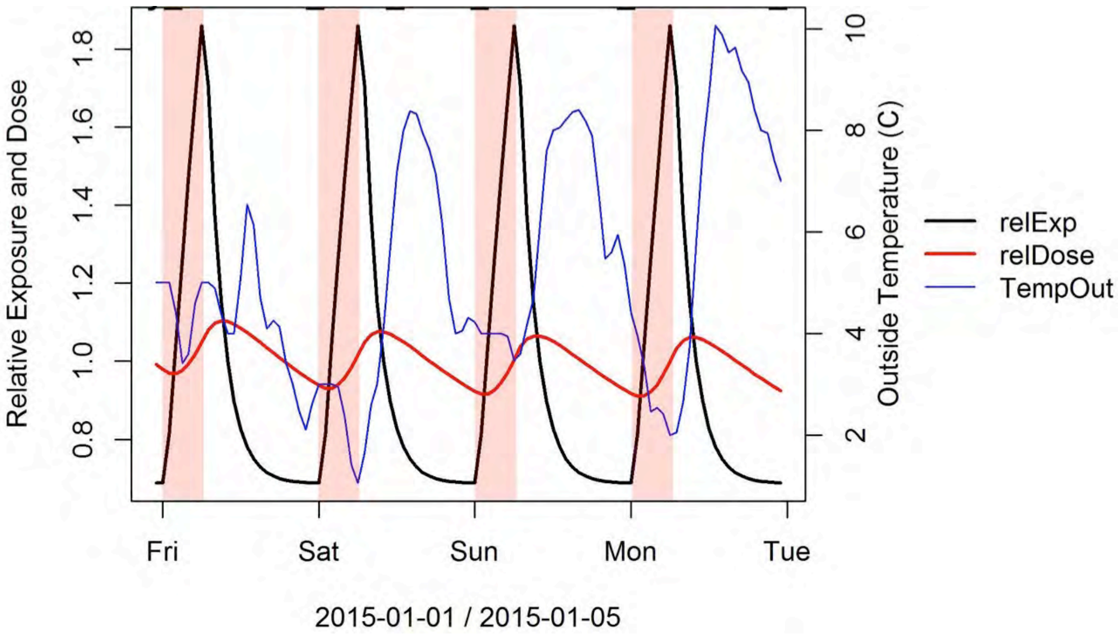


Figure 86 Illustration of the lockout control in 2-story, 1 ACH_{50} home in CZ1. Six-hour lockout period highlighted in pink.

CZ	***Prototype***	***Airtightness (ACH_{50})***	***Lockout Period (hours)***		
			4	***6***	***8***
1	1story	1	1.35	1.65	2.2
1	1story	3	1.3	1.5	1.8
1	1story	5	1.35	1.5	1.75
1	2story	1	1.35	1.6	2.1
1	2story	3	1.3	1.5	1.75
1	2story	5	1.55	1.7	1.9
3	1story	1	1.35	1.65	2.2
3	1story	3	1.3	1.5	1.8
3	1story	5	1.35	1.5	1.75
3	2story	1	1.35	1.6	2.1
3	2story	3	1.3	1.5	1.75
3	2story	5	1.5	1.65	1.85
10	1story	1	1.35	1.65	2.25
10	1story	3	1.3	1.55	1.9
10	1story	5	1.3	1.5	1.75
10	2story	1	1.35	1.65	2.1
10	2story	3	1.3	1.5	1.8
10	2story	5	1.35	1.5	1.75
16	1story	1	1.35	1.65	2.25
16	1story	3	1.3	1.5	1.9
16	1story	5	1.3	1.5	1.75
16	2story	1	1.35	1.65	2.1
16	2story	3	1.3	1.5	1.75
16	2story	5	1.4	1.55	1.75

Table 10 Table of fan size multipliers for use with 4-, 6- and 8-hour lockout controls.

Running Median (MedRe) Control Description

This smart control targets custom high and low relative exposure values based on comparing the current outside temperature (T_i) to its running median value ($T_{rollmedian}$). When in heating season and it is currently colder than the running median, the ventilation is reduced (target RE_{high}), otherwise it is increased (target RE_{low}). Vice versa in the cooling season. The relative exposure values should be equidistant from 1.0. For example, 0.5 and 1.5, or 0.4 and 1.6. The maximum appropriate values can be calculated using the smart fan-oversizing fraction ($F_{oversize}$) using Equations 9 and 10. The control conditions are outlined in Table 11. As a reminder, there is no direct control based on daily integrated exposure (i.e., relative dose) in this strategy, the controller simply targets either the high and low exposure targets. The running median will provide the temperature at which we expect an equal number of hours at each exposure target. This should allow the controller to maintain average relative exposure very close to one.

The value in this approach would be the controller's ability to shift ventilation between time periods, depending on the length of the running median period. The lockout control approach described in Section 0 allows shifting of ventilation between hours of the day. The running median approach allows shifting within hours of the day, as well as between days, weeks or months that are overall warmer or cooler. A running median period of 7-days allows shifting between days. A 30-day running median period allows shifting of ventilation between weeks. Finally, using the annual median as the control point allows shifting of ventilation between months/seasons. We expect greater energy savings with longer running median periods, but this may come at the cost of failing to maintain relative exposure below one on an annual basis.

Season	***High Relative Exposure Target Condition***
Heating	$T_i < T_{rollmedian}$
Cooling	$T_i > T_{rollmedian}$

Table 11 Control for running median TSVC.

$$\boldsymbol{RE_{high} = 1 + \left[1 - \frac{1}{F_{oversize}}\right]} \qquad (9)$$

$$\boldsymbol{RE_{low} = \frac{1}{F_{oversize}}} \qquad (10)$$

We assessed this running median approach by analyzing weather data for all 16 CEC climate zones using rolling median periods of 3-, 7-, 14- and 30-days (all right-adjusted, such that no "future" data was included in the median calculation). For each location, we calculated the running median outside temperature and compared this with the real-time dry bulb temperature. During the heating, if the real-time value was less than the running median, then we assigned a relExp target of 1.5 (under-venting due to cold weather), and if the real-time temperature was above the running median, then we targeted 0.5 (over-venting due to warm weather). The opposite relationships were used during the cooling season. We then calculated the annual average exposure using these assignments. The annual mean relative exposures for each climate zone and running median time period are listed in Table 12. The average across climate zones is at the bottom of the table. Notably, these values are simple estimates and will not match exactly those from our real-time simulations. This is because it takes time for the real-time relExp to travel between the low and high target values (i.e., the change from 1.5 to 0.5 is not instantaneous), and it increases and decreases at different rates depending on the direction.

As the rolling median period grew longer, this approach lost the ability to provide estimated annual relative exposures below one. We believe this occurred, because the longer time periods are not sufficiently representative of the temperatures that will occur in the future, so the median is no longer a reliable control parameter. The prior three days is a better predictor of the following three days, than the prior month is a predictor of the next month. The 7-day period was the longest rolling period with acceptable expected performance across all CA climates. The 14-day had marginal performance in many locations, though it is close enough that we believe it is worth testing with full simulations. The 30-day period was higher still. We have simulated only the 30-day running median period, as we expect it to have the greatest energy savings.

Climate Zone	***Annual Average Relative Exposure Estimate Running Median Control***			
	3-day	***7-day***	***14-day***	***30-day***
1	0.948	0.949	0.947	0.900
2	0.987	0.990	0.999	1.014
3	0.975	0.974	0.994	1.016
4	0.990	0.994	0.999	1.016
5	0.977	0.979	0.989	1.002
6	0.997	0.998	1.003	1.020
7	1.002	0.998	1.024	1.054
8	1.003	0.999	1.026	1.038
9	0.986	0.992	1.025	1.045
10	0.998	1.001	1.018	1.033
11	0.977	0.980	0.991	1.016
12	0.987	0.988	0.997	1.022
13	0.982	0.991	0.999	1.030
14	0.985	0.980	0.992	1.013
15	0.984	0.977	1.016	1.037
16	0.987	0.996	1.020	1.050
Average	*0.985*	*0.987*	*1.002*	*1.019*

Table 12 Annual average relative exposure values for each CEC Climate Zone based on simple relative exposure targets.

Seasonal Control (Season) Control Description

Another TSVC approach is to control to different average relative exposure targets depending on the season. Based on our past work, reducing the ventilation rate during the heating season (and increasing it during cooling season) has a net-energy benefit. So, for a seasonal controller, we target higher average exposure during heating season (reduced ventilation rate) and lower exposure during cooling season (higher ventilation rates). The ASHRAE ventilation standard requires the annual average relative exposure to be less than one to be compliant. So, high and low exposure targets can be calculated for any climate zone using a weighted average approach that should provide an annual average very close to one.

We begin by selecting a heating season mean relative exposure target ($RE_{mean,heating}$). Equation 11 is then used to calculate a corresponding cooling season mean exposure target ($RE_{mean,cooling}$) that maintains the annual average exposure less than the annual exposure target (RE_{annual}, typically 1 or 0.97). We used an RE_{annual} value of 0.97 in calculating our control parameters in our simulations. The cooling exposure target depends on the fraction of annual hours spent in the heating season (f_{heat}). If the required cooling season target is less than $1/F_{oversize}$, then annual equivalence is impossible. In Table 14, we provide pre-calculated f_{heat} values for each climate zone and the associated mean cooling season RE targets for each climate zone based on heating season targets from 1 to 1.5 (we used an annual exposure target of 0.97 to derive these cooling targets). As heating season mean increases, the cooling mean must go down. When the $RE_{mean,cooling}$ target is less than $1/F_{oversize}$, the controller will not have annual exposure less than one. To aid in compliance for the Seasonal controls, the fans were additionally oversized, with $F_{oversize}$ set to equal $1.2 / RE_{mean,cooling}$. For all climate zones except CZ10, we only simulated the highest $RE_{mean,heating}$ value where the corresponding $C_{mean,cooling}$ value was greater than 0.5 (roughly an $F_{oversize}$ of 2). For example, in CZ3 the highest $RE_{mean,heating}$ value we simulated was 1.2, because 1.3 required an $RE_{mean,cooling}$ of 0.383. For CZ10, we simulated all cases with $RE_{mean,heating}$ 1.2 to 1.5.

$$\boldsymbol{RE_{mean,cooling}} = \frac{[(\boldsymbol{RE_{annual}} - \boldsymbol{RE_{mean,heating}} \times \boldsymbol{f_{heat}}]}{(\mathbf{1} - \boldsymbol{f_{heat}})} \quad \textbf{(11)}$$

RE_{annual} = annual relative exposure target (e.g., 1 or 0.97 or as desired)

$RE_{mean,cooling}$ = mean relative exposure target during all cooling season hours

$RE_{mean,heating}$ = mean relative exposure target during all heating season hours

f_{heat} = fraction of annual hours that are heating season

Season	***Fan ON Condition***
Heating Season	relExp > $RE_{mean,cooling}$
Cooling Season	relExp > $RE_{mean,heating}$

Table 13 Control states for the Seasonal TSVC.

CZ	**Heating Season Fraction (f_{heat})**	**Cooling Season Mean RE Targets for Each Heating Season Target**					
		1	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
1	1	NA	NA	NA	NA	NA	NA
2	0.592	0.926	0.781	0.636	0.491	0.346	0.201
3	0.640	0.917	0.739	0.561	0.383	0.205	0.027
4	0.525	0.937	0.826	0.715	0.605	0.494	0.383
5	0.813	0.840	0.406	-0.028	-0.462	-0.895	-1.329
6	0.476	0.943	0.852	0.761	0.670	0.580	0.489
7	0.415	0.949	0.878	0.807	0.736	0.665	0.594
8	0.376	0.952	0.892	0.831	0.771	0.711	0.651
9	0.400	0.950	0.883	0.817	0.750	0.684	0.617
10	0.435	0.947	0.870	0.793	0.716	0.639	0.562
11	0.521	0.937	0.829	0.720	0.612	0.503	0.394
12	0.515	0.938	0.832	0.726	0.620	0.514	0.408
13	0.485	0.942	0.848	0.754	0.660	0.566	0.472
14	0.516	0.938	0.832	0.725	0.619	0.512	0.406
15	0.208	0.962	0.936	0.910	0.883	0.857	0.831
16	0.650	0.914	0.728	0.542	0.357	0.171	-0.015

Table 14 Cooling season mean RE targets for each CZ, varying heating season targets, annual exposure target of 0.97.

Cut-Off Temperature Control (CutOff) Control Description

Past work on temperature controlled smart ventilation suggested that a simple cut-off temperature was an effective approach to reducing ventilation load through smart control (Less et al., 2014). In this work, we developed a more complicated cut-off approach that ensures annual relative exposure less than one using a weighted average approach and parametric optimization (as in the Seasonal controller).

Heating and cooling season exposure targets (H_{mean} and C_{mean}) are calculated using the same weighted average method described for the seasonal controller. Then low and high exposure targets are developed that are the same in both seasons. The low RE target is always dependent on the fan over-sizing ($1/F_{oversize}$). The high exposure target (RE_{max}) and the cut-off temperatures for each season are determined by parametric optimization coded in R. For each climate zone, we assessed relative exposure and annual ventilation load for heating season mean exposure targets varying from 1 to 2 by increments of 0.1. For each heating season mean value, we tested high exposure targets (identical for heating and cooling) from 1 to 3 by increments of 0.1, and we assessed heating and cooling cutoff temperatures spanning the entire range of seasonal outdoor temperatures by 0.5°C increments. Annually, we selected the parameters that minimized the ventilation energy use, while maintaining estimated annual exposure below 0.97. Ventilation energy use was estimated using a simplified Q*rho*cp*dT approach, with airflow estimated as Q_{tot}/RE_{target}. Ventilation load was translated to site energy assuming a 95% efficient gas heater and an air conditioner with EER of 12.8. Free heating or free cooling were not allowed to offset ventilation load. No fan energy or air handler energy estimates were included.

Depending on the season, the controller selects either the high or the low exposure target, based on the current temperature (T_i) and the cut-off temperature (T_{cutoff}). The control logic is summarized in Table 15.

Season	***RE_{high}***	***RE_{low} (1/$F_{oversize}$)***
Heating	$T_i < T_{cutoff}$	$T_i > T_{cutoff}$
Cooling	$T_i > T_{cutoff}$	$T_i < T_{cutoff}$

Table 15 Control states for the temperature cut-off control.

An example optimization output is pictured in Figure 87 for CZ10 (Riverside) assuming a fan oversizing of 2. We show estimated ventilation energy use (y-axis) compared with maximum exposure values (x-axis) for a variety of heating season mean values (different colored lines). We see that for this climate zone, the energy use is minimized when the heating season mean is 1.5 and the high exposure target is 1.8. Estimated savings in this scenario are 36% of the ventilation load. We ran this optimization routine for every climate zone in California using a fan multiplier of 2, and the control parameters are listed in Table 16 (See Table 17 for optimized parameters with fan multiplier of 3). The controller only requires four parameters—$T_{cutoff,heating}$, $T_{cutoff,cooling}$, RE_{max} and $F_{oversize}$.

The optimization tended to select cutoff temperatures where the house airflow would be reduced for the maximum number of hours. This suggests that small reductions in ventilation rate over greater numbers of hours are more effective than greater reductions in ventilation rate over fewer hours. In general, the high exposure targets were only a few tenths greater than the heating season average exposure targets, meaning that this approach will limit peak exposure quite well.

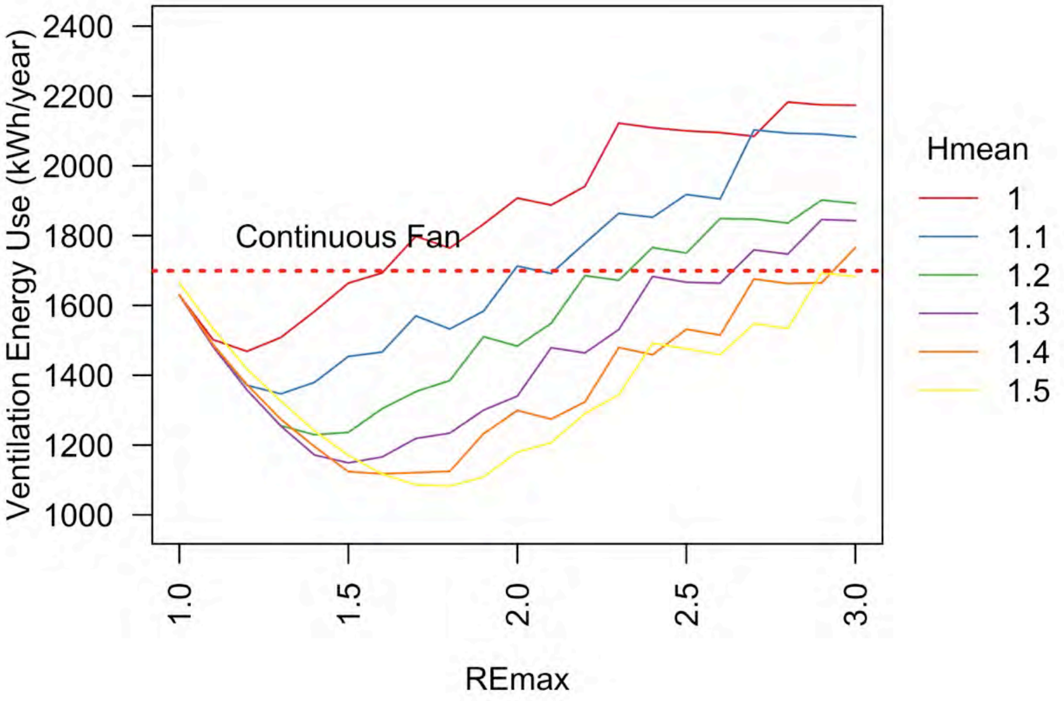


Figure 87 Example of parametric optimization results for CZ10, using the Cutoff control. Optimum is H_{mean} of 1.5, RE_{max} of 1.8 with estimated site energy savings of 36% (assuming $F_{oversize}$ of 2).

CZ	H_{mean}	C_{mean}	RE_{max}	$T_{cutoff,heat}$	$T_{cutoff,cool}$	*Estimated Site Energy Savings (%)*
1	1	NA	1	31.5	NA	4
2	1.2	0.64	1.3	16.7	26.5	24
3	1.2	0.56	1.3	15.6	22.5	20
4	1.3	0.60	1.4	17	26.9	29
5	1	0.84	1.1	17.1	14.1	10
6	1.4	0.58	1.6	16.9	24.5	36
7	1.6	0.52	1.7	17.5	24.9	42
8	1.7	0.53	1.9	17.9	30.9	46
9	1.6	0.55	1.8	17.4	32.5	41
10	1.5	0.56	1.8	16.5	34.1	36
11	1.4	0.50	1.5	17.4	41.7	26
12	1.4	0.51	1.5	16.9	36.9	30
13	1.4	0.57	1.5	16.4	36.1	27
14	1.4	0.51	1.6	15.5	39	28
15	1.3	0.88	1.5	18	30	31
16	1.2	0.54	1.3	13	26.8	21

Table 16 Optimized cutoff control parameters with $F_{oversize}$ = 2.

CZ	H_{mean}	C_{mean}	RE_{max}	$T_{cutoff,heat}$	$T_{cutoff,cool}$	***Estimated Site Energy Savings (%)***
1	1	NA	1	31.5	NA	4
2	1.4	0.35	1.5	18.2	35.5	32
3	1.3	0.38	1.4	16.6	23.5	26
4	1.5	0.38	1.6	18	30.4	37
5	1.1	0.41	1.2	18.1	22.1	18
6	1.6	0.40	1.7	18.9	25.5	43
7	1.8	0.38	1.9	18	23.9	48
8	1.9	0.41	2.1	18.9	28.9	52
9	1.8	0.42	2	18.4	32	45
10	1.6	0.48	1.8	18.5	32.1	39
11	1.4	0.50	1.5	17.9	33.7	28
12	1.5	0.41	1.6	17.9	33.9	33
13	1.5	0.47	1.6	17.4	34.6	29
14	1.4	0.51	1.5	18.5	33.5	29
15	1.4	0.86	1.6	19	29	34
16	1.3	0.36	1.4	14	28.3	25

Table 17 Optimized cutoff control parameters with $F_{oversize}$ = 3.

Optimized Variable Airflow (VarQ) Control Description

We also tested continuously variable airflow TSVC controllers that scale the target ventilation airflow or relative exposure based on the current inside-outside temperature difference. These include the VarQ and VarRe control types, described here and in 0. These proportional controllers shift ventilation away from periods of large indoor-outdoor temperature difference to mild or even beneficial time periods. A variable airflow controller can use either a variable airflow fan or it can schedule a fixed-speed fan to cycle in order to achieve varying average flows over some short period (e.g., 20 minutes). Both proportional controllers use the f-scale calculation shown in Equation 12, which compares the current temperature difference (T_i – T_{therm}) against the Seasonal maximum temperature difference (T_{max} – T_{therm}). The value is bounded between 0 and 1, and it is multiplied by either a ventilation airflow or a peak relative exposure target.

$$f_{scale} = 0 \le \left[1 - \frac{(T_i - T_{therm})}{(T_{max} - T_{therm})}\right] \le 1 \tag{12}$$

T_i = current outdoor temperature, °C

T_{therm} = thermostat setting, °C

T_{max} = seasonal maximum temperature (hottest or coldest, by season), °C

T_{max} is a seasonal value representing the coldest expected temperature during the heating season and the warmest expected temperature during the cooling season (see Table 18 for these values for each CEC climate zone, calculated from CBECC-Res weather files). The f-scale factor is calculated once each time-step. An illustration of the f-scale value is plotted for heating (black line) and cooling (red line) seasons in Figure 88. This is illustrative only and does not reflect temperatures from a CEC climate zone.

Climate Zone	***Annual Minimum Temperature (°F)*** ***T_{max} - Heating***	***Annual Maximum Temperatures (°F)*** ***T_{max} - Cooling***
1	29	81
2	27	103
3	31	91
4	15	99
5	29	87
6	25	102
7	41	90
8	34	105
9	34	107
10	29	109
11	28	113
12	28	109
13	30	108
14	20	106
15	36	115
16	17	90

Table 18 T_{max}, annual minimum and maximum outdoor temperatures for each CEC climate zone.

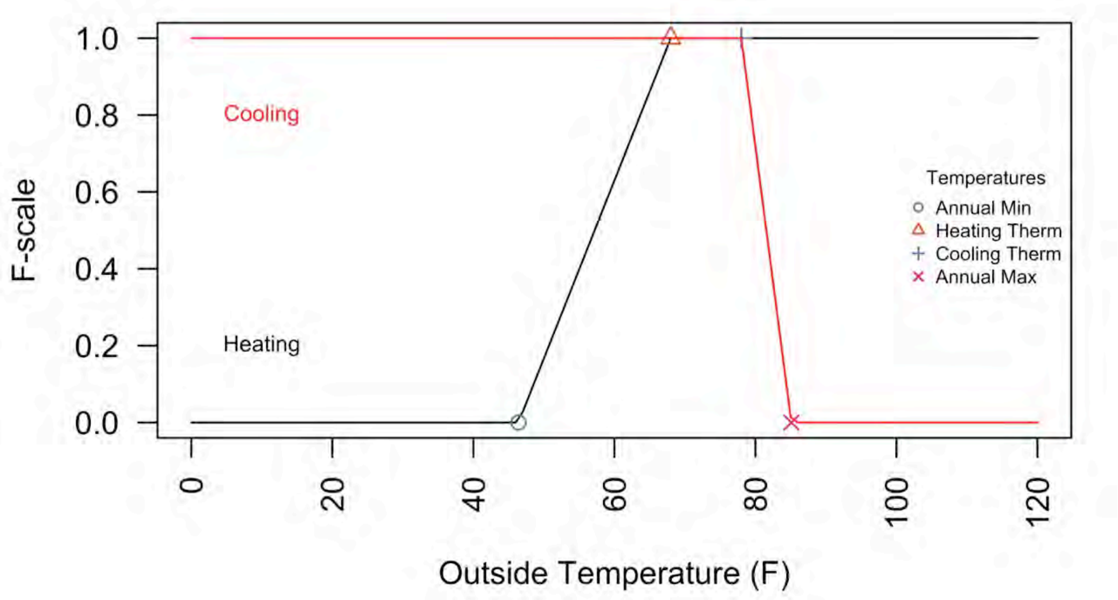


Figure 88 F-scale factors for proportional temperature control in heating (black) and cooling (red) seasons.

The VarQ TSVC uses this f-scale factor and multiplies it by the smart ventilation fan maximum airflow as in Equation 13. This scales the target fan airflow between 0 (off) and the maximum, which is the two-times the baseline continuous ventilation fan airflow. We illustrate the resulting airflows across a range of outside temperatures in Figure 7. The heating season airflow (black line) is set to 0 when outside temperature is below the T_{max} value (roughly 45°F here), it scales fan airflow linearly up to the maximum airflow when outside air is the same as the thermostat setting (65°F), and the fan airflow remains at maximum at all temperatures warmer than the thermostat setting (free heating). The opposite happens in cooling season (see the red line), again taking advantage of free cooling whenever possible.

$$Q_i = Q_{fan} \times f_{scale} \tag{13}$$

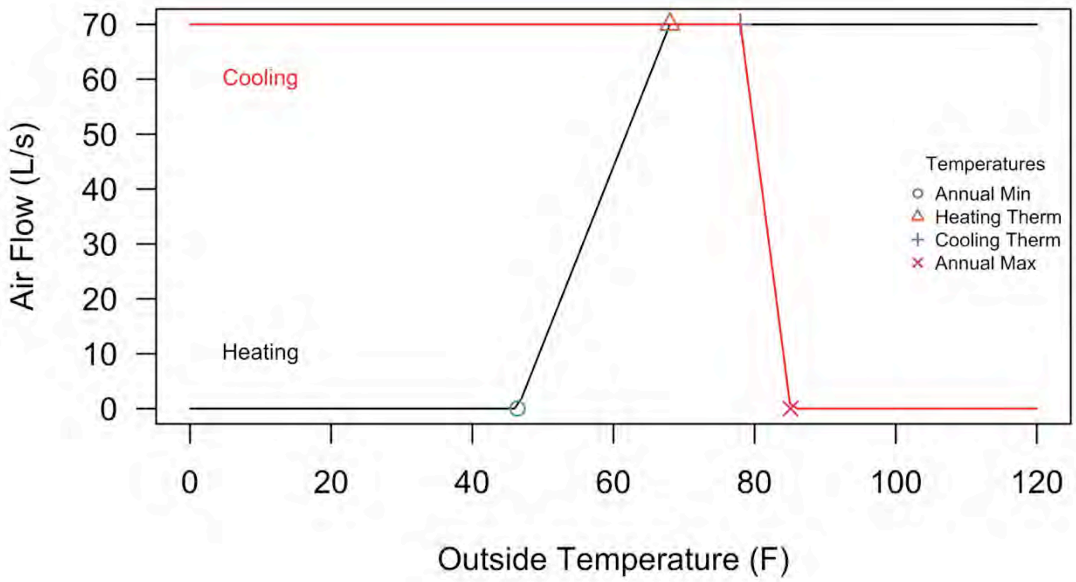


Figure 89 Example airflows for a 70 L/s smart ventilation fan in heating (black) and cooling (red) seasons, generated using F-scale factor across range of outside temperatures.

For a given distribution of outside temperatures in a given climate, there is no guarantee that using the seasonal hottest and coldest temperatures for T_{max} will give an annual relative exposure less than or equal to 1. Using CEC weather data, we pre-calculated the annual relative exposure that this strategy would provide for each case, using prototype house data and estimates of infiltration (Q_{inf}) and fan airflows. In nearly all CEC climate zones, this resulted in an annual estimated exposure substantially below one. So, this approach would over-ventilate most homes and was not optimized from an energy perspective.

We determined that the VarQ control did not necessarily need to scale down to the seasonal maximum or minimum temperatures, rather the $T_{max,heating}$ value could be increased above the annual minimum temperature, and the $T_{max,cooling}$ value could be decreased below the annual maximum temperature (see Equations 14 and 15). Ventilation energy is reduced the more these values are increased/decreased above/below the annual max/min temperatures, subject to the requirement that exposure must be estimated to be less than 0.97. In essence, the sloped lines in Figure 89 would become more vertical, further reducing ventilation airflow during hot/cold periods. We refer to the increase/decrease as T_{offset}.

T_{offset} was determined numerically by parametric optimization coded in R. We simplified this optimization problem by forcing T_{offset} to be the same in heating and cooling seasons. Optimization of the seasons independently from one another could offer marginally improved control performance. Optimization targeted the largest T_{offset} value that still satisfied the relative exposure requirement (annual RE < 0.97). As T_{offset} increases, so do energy savings and annual exposure. For each case, we calculated the appropriate $T_{max,heating}$ and $T_{max,cooling}$ values. The optimal control parameters used in our simulations are provided in Table 19. The T_{offset} values varied substantially by climate zone, but were reasonably consistent across house parameters (i.e., airtightness and size). While we did not do this in our simulations, one could select single representative $T_{max,heating}$ or $T_{max,cooling}$ values for each climate zone, so as to simplify this control specification. For example, in CZ3, we could reasonably say that $T_{max,heating}$ is 42°F for all cases, while $T_{max,cooling}$ is 79°F.

In order to perform these estimates on a generic home, a designer would need the weather data file, house size/volume information, baseline 62.2 fan airflow, fan size multiplier and infiltration estimates.

$$\boldsymbol{T_{max,heating} = T_{min,annual} + T_{offset}} \tag{14}$$

$$\boldsymbol{T_{max,cooling} = T_{max,annual} - T_{offset}} \tag{15}$$

Prototype	***Airtightness (ACH_{50})***	***CZ***	***$T_{max,heating}$ (°F)***	***$T_{max,cooling}$ (°F)***
1-story	1	1	31.58	77.6
1-story	3	1	31.58	77.6
1-story	5	1	30.58	78.6
2-story	1	1	31.58	77.6
2-story	3	1	31.58	77.6
2-story	5	1	21.58	87.6
1-story	1	3	41.56	80.22
1-story	3	3	42.56	79.22
1-story	5	3	43.56	78.22
2-story	1	3	41.56	80.22
2-story	3	3	43.56	78.22
2-story	5	3	41.56	80.22
1-story	1	10	43.76	94.4
1-story	3	10	44.76	93.4
1-story	5	10	46.76	91.4
2-story	1	10	43.76	94.4
2-story	3	10	45.76	92.4

2-story	5	10	47.76	90.4
1-story	1	16	19.24	87.96
1-story	3	16	20.24	86.96
1-story	5	16	21.24	85.96
2-story	1	16	19.24	87.96
2-story	3	16	20.24	86.96
2-story	5	16	21.24	85.96

Table 19 Parametrically optimized $T_{max,heating}$ and $T_{max,cooling}$ values for each case and climate zone, maintain annual relative exposure <=0.97. VarQ.

Optimized Variable Relative Exposure (VarRe) Control Description

The same f-scale outside temperature approach detailed above can also be used with a variable relative exposure controller. The concepts are the same, but rather than targeting a certain airflow, a relative exposure value is targeted by the controller. The controller turns the ventilation fan on only when the real-time exposure exceeds the target exposure (see Table 20). It is notable, that this controller does not actively control daily integrated exposure (i.e., relative dose) to below one, rather the controller simply tries to maintain the target at each time-step. This means the targets need to be pre-calculated such that they will average less than one over the year.

Condition	***Fan Status***
$RE_i > RE_{target}$	ON
$RE_i <= RE_{target}$	OFF

Table 20 Control strategy for VarRe using the RE_{target} calculated at each time step.

Equation 16 shows how the relative exposure target (RE_{target}) is calculated at each time step, using f-scale, fan size multiplier and a maximum exposure target. $F_{oversize}$ is the fan size multiplier for the smart fan relative to the size of the 62.2-2016 fan (1.5 is 50% larger, 2.0 is 100% larger, etc.). This roughly fixes the minimum relative exposure value that can be targeted by a fan that is operated continuously ($1/F_{oversize}$). The RE_{max} value is the peak relative exposure allowed (ASHRAE 62.2-2016 allows a peak up to 5).

In the VarQ controller, the $T_{max,heating}$ and $T_{max,cooling}$ values were varied to optimize performance, but in the VarRe controller we used the annual T_{max} values (Table 18) and instead varied the maximum relative exposure targets to optimize energy performance. For each climate zone, we determined unique RE_{max} values independently for heating and cooling seasons, which minimized ventilation load while maintaining estimated exposure below 0.97. These RE_{max} values were estimated using parametric optimization implemented in R. The optimum was selected as the combination of heating and cooling season RE_{max} values that minimized the net-ventilation load (Q*rho*cp*dT), while having an annual mean relative exposure less than 0.97. Unlike in the VarQ optimization, here we independently treated the $RE_{max,heating}$ and $RE_{max,cooling}$ values, varying each value between 1 and 5, by increments of 0.1. Optimized VarRe control parameters are provided for each CEC climate zone in Table 21 based on the assumption of a fan size multiplier of two (smaller or larger fans would require different optimized control parameters). The results are independent of house type/size, airtightness, etc., which makes estimation of the control parameters less burdensome on the user.

$$\boldsymbol{RE_{target}} = \left[\boldsymbol{RE_{max}} - \left[\boldsymbol{RE_{max}} - \frac{\mathbf{1}}{\boldsymbol{F_{oversize}}}\right] \times \boldsymbol{f_{scale}}\right] \quad \textbf{(16)}$$

CZ	Optimized RE_{max} Values	
	Heating	**Cooling**
1	1.5	1.5
2	2.5	1.75
3	2.5	5
4	3.75	1.75
5	2.25	5
6	4.5	5
7	4	5
8	4.75	1.5
9	4	1
10	3.75	1.5
11	2.5	1.25
12	2.75	1
13	2.5	1.25
14	2.75	1
15	4.5	1.75
16	2	2

Table 21 Optimized RE_{max} values for heating and cooling season for each CEC Climate zone, assuming an IAQ fan with double the 62.2 airflow requirement.

An example VarRe control is plotted across a range of outside temperatures in Figure 90, showing the relative exposure target at each outside temperature. The RE_{max} values are different in heating (4.0) and cooling seasons (2.0), and you can see how the RE targets scale linearly between the thermostat setting and the annual minimum temperature in heating (or maximum temperature in cooling season). As with the VarQ control, in heating when outside air is above the thermostat setting, ventilation is increased to its maximum to get free heating (RE target of 0.5), vice versa in cooling season. The VarRe control is distinct from the VarQ in that it never fully tells the ventilation fan to shut off, rather a high exposure is targeted, such that ventilation airflow is reduced. We expect more variability in airflow and higher peak exposure for the VarQ control.

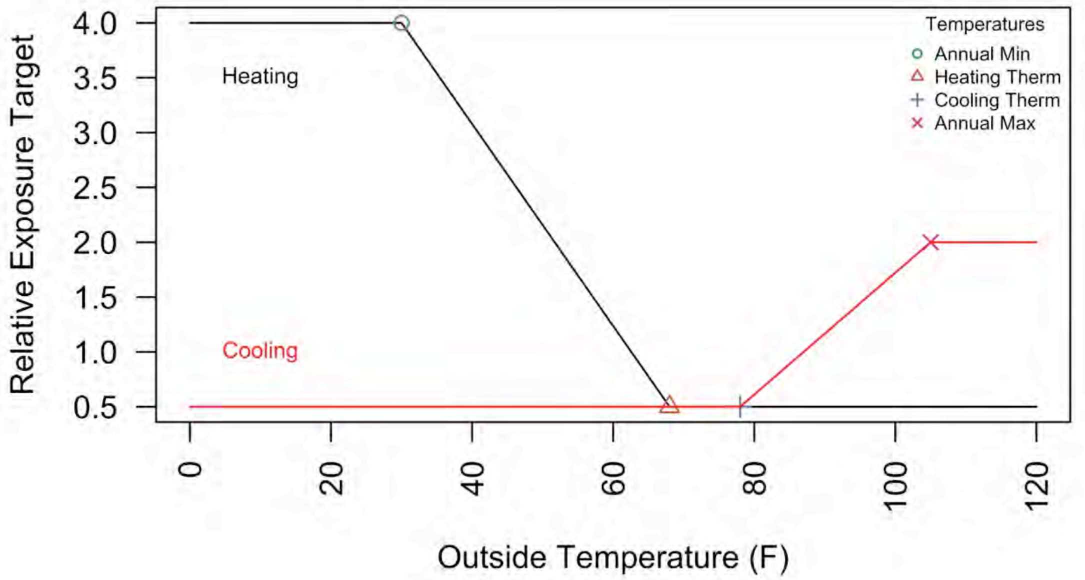


Figure 90 Relative exposure targets that vary continuously with outside temperature, using an *RE_{max}* values optimized independently for heating and cooling seasons.

Occupancy Controls (Occ) Control Description

The Occupancy SVC is a real-time IAQ control that responds to the occupancy of the home and shuts off (or reduces to low speed) the ventilation fan during unoccupied periods. In this work, we assess the performance of three versions of an Occupancy SVC: (1) fan OFF during unoccupied periods, (2) fan on low speed during unoccupied periods, and (3) a version that flushes the house at a high ventilation rate one hour before occupancy. A control description for the first fan-off control is provided in Table 22, representing the basic Occupancy SVC. We focus on a common 1st shift occupancy pattern with a 9-hour weekday absence period and otherwise continuous occupancy. The operation of the control is described in the paragraphs below.

During the unoccupied period, the relative exposure is continually calculated and it is controlled to a maximum value of 5, as required by ASHRAE 62.2-2016. This maximum relative exposure is based on the acute to chronic concentration ratios for pollutants of concern. More details are available in M. H. Sherman, Logue, & Singer (2011) and Max H. Sherman et al. (2012). The IAQ fan can be turned off during unoccupied time periods, because the occupants are not exposed to the contaminants in the space. This is acceptable, as long as the controller accounts for the increased exposure the occupants receive when returning home after the ventilation system had been off.

During unoccupied periods, the relative dose is no longer calculated, and rather is fixed at its last occupied value. When occupants return home, relative dose is calculated again and quickly rises above one in response to the high relative exposure. The IAQ controller must increase the ventilation rate to bring relative exposure and relative dose below one. We refer to this as the ‘recovery period’. The duration of the recovery period is dependent on the IAQ fan size and the peak relative exposure reached during the unoccupied period.

An illustration of the Occupancy SVC is provided in Figure 9. The day begins with the IAQ fan turning on and off to cycle the relative exposure (*relExp*, red line) above and below 1. Exposure increases when the fan is off and decreases when the fan is turned on. Light grey highlighted periods show IAQ fan on periods, and the aqua region shows the unoccupied mid-day period. The relative dose (*relDose*, blue line) tracks the running average of the relative exposure and is fixed at almost exactly one. The unoccupied period is marked by relative exposure increasing to a peak around 2.7 when the occupants return home. The relative dose increases slightly when occupants return home, and it is reduced back below one during the recovery period. The IAQ fan is off during the entire unoccupied period, and then it is on continuously until the recovery period ends when both relative exposure and relative dose are less than one (approximately 23:00). This same pattern is repeated each day of the week with an occupant absence.

Condition	***Fan ON Condition***
Occupied	relExp > 1 OR relDose > 1
Unoccupied	relExp > 5

Table 22 Occupancy control strategy, fan off during unoccupied times.

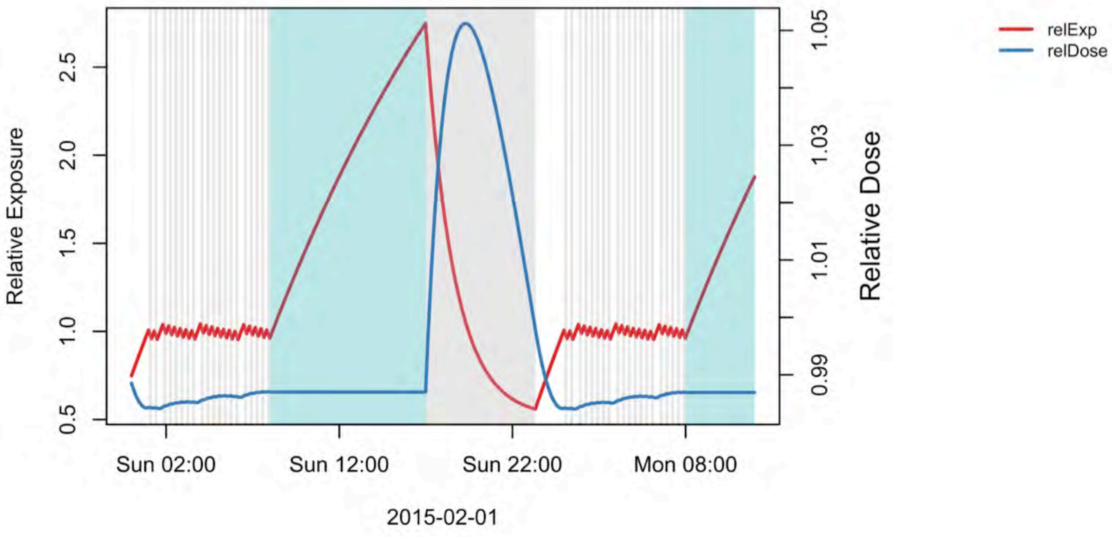


Figure 91 Illustration of Occupancy control operation with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey, unoccupied period in aqua.

This occupancy SVC is distinguished from many other demand-controlled devices, which have historically used either relative humidity or CO_2 as indicators (Emmerich & Persily, 2001; Fisk & De Almeida, 1998; Raatschen, 1990). This approach assumes that occupancy is directly detected by any variety of methods, which could include IR motion sensors, smart phone network detection, smart meter analytics, simple timer-based scheduling, etc. Unlike the temperature-based controls described in the prior section, the occupancy controller is intended to save energy by reducing the average ventilation rate of the home, while maintaining exposure less than one.

We will simulate one occupancy pattern, with 9-hour weekday absences from 8am to 5pm, representing a typical 1st shift workweek. Occupancy is continuous on weekends. While not simulated in this work, the model is also set-up to assess shorter and longer absence periods of 4- and 12-hours. The number of occupants at any given time will be unspecified and is unnecessary for this control strategy.

Low Fan Airflow While Unoccupied

As noted above, the ventilation fan will be treated in two different ways during the unoccupied period. First, the IAQ fan will be turned off during unoccupied times, subject to a relative exposure limit of 5 (see control description in Table 22). Second, the IAQ fan will be operated at a lower airflow that is some fraction of the ASHRAE 62.2 fan airflow (see control description in Table 23). Mortensen, Walker, & Sherman (2011) showed that for a variety of unoccupied periods, emission assumptions and constant fan airflows, the peak effectiveness of an occupancy controlled system occurred when the ventilation rate during unoccupied times was between 0.13 and 0.4 of the constant air volume system. Their results suggest that a value of roughly 0.35 will be appropriate for the cases we are simulating (i.e., fixed pollutant emission during both occupied and unoccupied hours, roughly 8-12 hour absence periods). As such, we will use this 0.35 as our target in these cases. We implement this by multiplying the continuous fan airflow by 0.35 during unoccupied time periods. This approach should reduce the peak exposure experienced everyday by the occupants, and it will hopefully reduce the average ventilation rate required to maintain exposure below one, thus saving energy.

Condition	***Fan ON Condition***
Occupied	relExp > 1 OR relDose > 1
Unoccupied	$Q_{fan} = 0.35 \times Q_{62.2}$

Table 23 Occupancy control strategy, fan at 35% of ASHRAE 62.2 continuous Q_{fan} airflow during unoccupied times.

A secondary, but still important effect, is the outdoor conditions during the unoccupied period. For example, the 1st shift occupancy pattern includes only daytime absences. During heating, this mid-day period is often the mildest time of day, which limits the value of reducing the ventilation rate, because temperature differences are small. During cooling, reducing the ventilation rate during the day is valuable, particularly in the mid- to late-afternoon. Consistent with this, Less & Walker (2017) found that hot climates had higher energy savings in the 1st shift compared with a 3rd shift occupancy pattern. Whereas this pattern was reversed in all of the heating dominated locations, where the 3rd shift had much higher energy savings. In general, an occupancy controller with a 1st shift schedule will operate opposite of a temperature-based controller. A temperature-based controller will over-vent during the day, when occupants are not present, and it will reduce the ventilation rate at night when occupants are home. These interactions will be addressed in our multi-parameter control cases described in Section 0.

Pre-occupancy flush out

We will also test versions of the occupancy controller where the controller can predict when occupants will return home. In these example cases, the controller begins the over-ventilation recovery period before occupants return home. We have reproduced a figure from Less & Walker (2017) demonstrating typical relative exposure patterns in an occupancy controller with no pre-venting, 1- and 2-hour pre-occupancy flush outs in Figure 10. This shows how the flush outs drastically reduce peak exposure to the occupants and lessen the over-ventilation period. For example, in the 9-hour absence pattern, the occupants return home at 17:00, and this controller would turn the fan on continuously starting at 15:00 for a 2-hour flush out. This approach should reduce occupant peak exposure, lessen the recovery period and save energy. Less & Walker found that 1- and 2-hour flush outs had very similar energy performance, so we only test a 1-hour flush out in this work.

Less & Walker (2017) demonstrated that a pre-occupancy flush out paired with a RIVEC occupancy controller substantially increased energy performance of the controller, roughly doubling median energy savings for a 1st shift occupancy controller. They found similar savings when using a 1- or 2-hour flush out period. The reason the flush out was so effective was that it drastically reduced the peak relative exposure experienced by the occupants, as well as drastically reducing the over-ventilation requirements. This reduced the overall total air exchange required to maintain equivalence with the continuous fan. They reported that for a control with no recovery period, 60% of the over-ventilation requirement was due to controlling relDose to one, even after relExp was already below one. As noted earlier, greater reductions in air exchange lead to greater energy savings. Less & Walker found that just turning the fan off for 9-hours and not controlling exposure, reduced the air exchange rate by 38%. Using no pre-occupancy flush out reduced this to only a 12% reduction (26% was need to recover and maintain equivalence). In comparison, the 1- and 2-hour pre-occupancy flush outs had 22 and 28% reductions in AER.

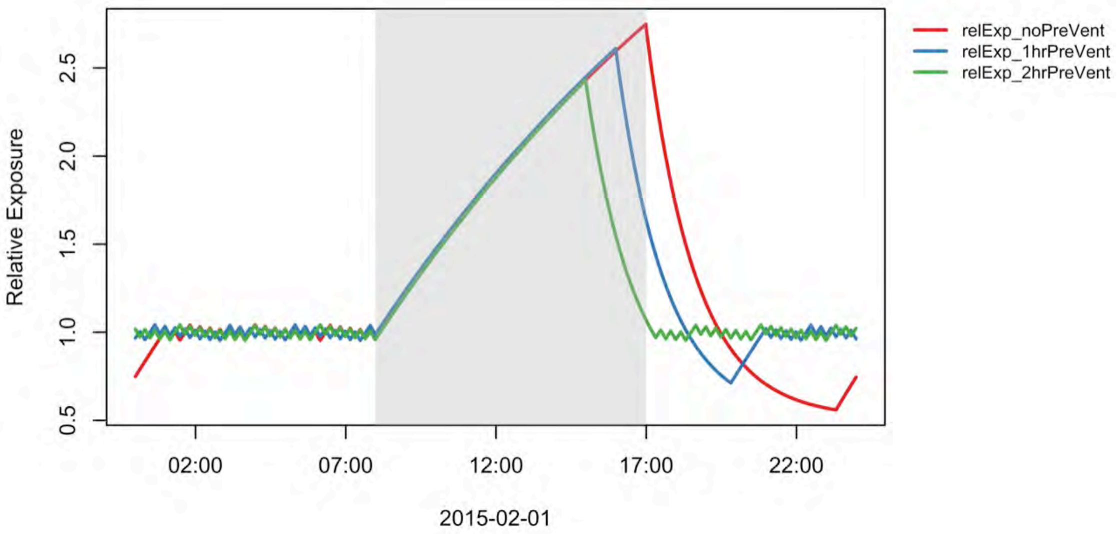


Figure 92 Relative exposure with no, one- and two-hour pre-occupancy flush out periods. Unoccupied period highlighted in light grey. Reproduced from Less & Walker (2017).

The risk with the pre-occupancy flush out strategy is that it may be more difficult for a controller to predict when occupants will return home than it is to sense that they have returned home. The prediction requires a predictable pattern, whereas the simple approach with no flushing period requires only an accurate sensor (the low airflow during unoccupied times might also be more flexible in response to variable occupancy patterns). In addition, this only works for typical workweek schedules, with predictable home and away periods. Luckily, Less & Walker (2017) showed that a one-hour flush out was roughly equivalent in energy performance as the two-hour flush out, which gives the controller flexibility. A simple approach to predicting when occupants will return would be a running average of the prior five work day return times or the like.

The system could also work on a schedule that is manually entered by the occupants that reflects their typical home and away patterns. Alternatively, a system could be used that is integrated with an occupant's cell phone that informs the controller when the occupants are within a certain radius of their home or some such approach.

An optimized pre-occupancy flush out would bring the relative exposure value to exactly one the minute occupants returned home. The two-hour pre-occupancy flush out happened to achieve this almost exactly in the test homes. In reality, this would vary with fan over-sizing, house size, natural infiltration, unoccupied time period, etc., and it would be nearly impossible to predict given variability in occupancy patterns. But the results reported by Less & walker (2017) suggest that this optimization might have little value, since 1-hour was nearly as good as 2-hour flush out. So, product designers do not need to worry about perfect prediction of occupancy patterns, rather being within an hour is sufficient.

Auxiliary Fan Controls

A smart control strategy developed in the earliest versions of the RIVEC smart ventilation controller was to sense and detect operation of other exhaust devices in the home, including bathroom, kitchen and laundry fans, as well as a vented clothes dryer. The Auxiliary Fan SVC is a real-time RIVEC control that senses the operation of these other exhaust devices. These airflows are included in the estimate of the real-time ventilation (Q_i) and in calculation of relative exposure and dose as described in Section 0 (see Table 24 for control description). Essentially, these additional airflows are added to the ventilation rate used in calculating relative exposure and dose, so the central fan's operation can be traded off on a one-to-one basis with auxiliary fans. Total auxiliary fan operation was 160 minutes per day in each simulation, but the fan sizes varied between kitchen, bathroom and dryer fans. Roughly speaking, this allows the RIVEC fan to be turned off for approximately 160 minutes each day. This is distinct from controls that time-shift ventilation (i.e., temperature-based controls), because they have to increase the average ventilation rate in order to maintain exposure less than one, whereas this control reduces the average ventilation rate. The benefits of this type of control scale directly with the amount of auxiliary fan use and airflow. Secondary impacts depend on the time of day and outside temperature during auxiliary fan use.

Control Variable	***Fan ON Conditions***
Relative Exposure	>1
Relative Dose	>1

Table 24 Control details for Auxiliary Fan SVC.

Detailed Description of the EMS Programs and Actuators

For each of the unique simulation scenarios the EMS control logic is contained in two different files. One file contains programs common to all scenarios (`EMS_FMU_NoLeakage_WithFan_AllPath.imf`), and one file (`CONTROLS_[`*`control name`*`].imf`) containing programs used only for the specific smart control and supporting objects used by that control. Table 25 lists all programs and the order they are called in. Table 26 lists the main EMS actuators used to implement smart ventilation control strategies and to capture the electrical energy use of the fans.

Table 25 EnergyPlus EMS Programs and call order

EnergyPlus EMS Programs	Function	Call sequence
Infiltation_Mixing	This is the main program used to collate the mass flow rates reported for each flow element in CONTAM, and to calculate the resulting mass and airflow in the attic and house zones.	1
CheckControlInputs	Sets and verifies the control specific parameters	2
CalculateControlDecision	Calculates the whole house flow rate (*WHFlow*) for each of the simulated control strategies, BaseFan, Occ, Cutoff, lockout, VarQ, VarRe and MedRe. For all controls, except VarQ, ControlDecision turns the main IAQ fan either on or off, based on the current and target relative exposure (and in some cases relative dose). VarQ calculates a continuously variable airflow value, rather than simply providing an on-off signal.	3
CalculateFanPowerUse	Calculates electrical power use by the IAQ fan based on the fan airflow, which is controlled by the ControlDecision smart controls. .Power use varies based on the scaled maximum power use (FanPowerRef), and the control flow ratio (FanRatio) that varies between 0-1 based on the fan control, such that: $WholeHouseFanPower=FanRatio*FanPowerRef$ Where FanRatio is equal to the whole house flow rate (*WHFlow*) divided by the fan size (FanSize): $FanRatio= WHFlow / FanSize$ Where the FanSize is taken directly from the scenario definition file	4

	(labeled FSM, in Table 33 below) and WHFlow is calculated in the CalculateControlDecision program. The FanPowerRef is the sum of the FanSize and the reference fan power (Fanpower), which is again a scenario input variable (IAQfanPower). *FanPowerRef = Fanpower*Fansize*	
CalculateAirFlow	Estimates the whole house flow rates used by the smart controller, including infiltration, the IAQ fan, and when required by the control strategy, the auxiliary mechanical flows. Estimation is done as follows: 1. Estimate natural infiltration (Qinf), based on either the time-varying AIM-2 model or using the fixed annual effective infiltration rate from ASHRAE 62.2-2016 2. If required, calculate any auxiliary fan airflows (AuxFans) including exhaust flows from the dryer, kitchen, and bathroom fans. 3. Specifically for the VarQ strategy, if the scenario specifies that the control takes the operation of the auxiliary fans into account when calculating the WHFlow, then adjust the WHFlow by the AuxFans flow rate accordingly. 4. Calculate the combined whole house airflow estimate (see Section 0) using different approaches for balanced verses unbalanced IAQ fans, using these equations based on ASHRAE 62.2 2016 Normative Appendix C, Section C2.3 Combination of Infiltration and Mechanical Ventilation. Equations C8-C9. For balanced IAQ fans and unbalanced auxiliary airflows: *TotalQ_m3s=Qinf*(Qinf/(Qinf+ AuxFans))+ WHFlow + AuxFans* For unbalanced IAQ and auxiliary airflows:: *TotalQ_m3s =Qinf*(Qinf/(Qinf+WHFlow+AuxFans))+ WHFlow + AuxFans,*	5
CalculateExposureDose	Calculate the current "controller" relative exposure and dose based on the total ventilation airflow estimated in the AirFlow procedure	6

	described above	
CalculateRealExposureDose	Calculates the "real" exposure/dose, based on the total ventilation airflow predicted using the co-simulation model, representing the actual ventilation in the model.	7
HVAC_Supervision	Temperature setpoint dead-band control , implements an effective lag in the operation of the heating and cooling system. For the heating operation, when the temperature of the zone is falling the heating system does not activate until it falls below an offset (set to 1degree C) below the set point. Heating is then turned off after the zone temperature rises more than the offset above the setpoint temperature. The actual thermostat uses a constant setpoint of 23 degrees C for both cooling and heating. The operation of the HVAC is then overridden by actuator control of the system availability, calculated based on the actual desired setpoint temperature and dead-band. The system is available for operation when the temperature of the zone is within the dead-band. This mimics the behavior of a residential HVAC system that would typically operate at full capacity and cycle depending on the thermal response of the space.	8

Table 26 EnergyPlus EMS Actuators

EnergyPlus EMS Actuators	Function
SupplyFanAvailability	Sets the HVAC fan availability schedule, used by the HVAC_Supervision program to control operation of the supply fan modeled in EnergyPlus. This allows the energy use of the supply air fan to be captured using the realistic fan performance curves defined in EnergyPlus for HVAC equipment.
Cooling_Availability & Heating_Availability	As above used for temperature setpoint deadband control in the HVAC_Supervision program defined below. Sets the availability schedule for the Coil:Cooling:DX and Coil:Heating:Gas objects respectively.
WholeHouseFanPowerOverride	Controls an EnergyPlus electrical equipment object used to track the whole house fan power use (WHFanPower). Power use is based proportionally to the fan flow rate, such that: WHFanPower= FanRatio*FanPowerRef Where FanRatio = *WHFlow* /FanSize FanPowerRef *WHFlow* whole house flow rate, and FanSize is the fan scaling factor read from the scenario definition file.
Living Infiltration_1 and UAtcInfiltration	Actuates the *Air Exchange Flow Rate* of the ZoneInfiltration:EffectiveLeakageArea objects used to set the total outdoor air infiltration for the living and attic zones. We confirmed that the rate set is a mass flow rate in units of kg/s.
LivingZoneToAHZoneMixing and AHZoneToLivingZoneMixing	Actuates the *Air Exchange Flow Rate (kg/s)* of two ZoneMixing objects, that represent the flow from the attic to the living zone, and from living zone to attic.
ExhuastFlow	Represents the total exhaust fan flow (IAQ fan, bathroom and kitchen). Sets a schedule value that is communicated to CONTAM via the FMI.
BalanceFlow	For scenarios with an air tightness of 1 ACH_{50}, the ExhuastFlow rate is balanced by an equivalent supply flow

	which is also sent to the CONTAM model,

Infiltration Models Used in Smart Controls—Qinf and AIM-2

Consistent with the ASHRAE 62.2-2016 standard, natural infiltration is treated in one of two ways for our real-time relative exposure and relative dose calculations. Each smart control is tested with both methods of accounting for infiltration.

First, a fixed annual effective infiltration rate can be used, referred to as Q_{inf} and calculated as in Equation 7. These values are calculated according to house geometry, leakage area and location (wsf factors). This is the infiltration rate that would give the same annual relative exposure as the predicted time-varying infiltration rate, which is dependent on indoor and outdoor temperatures, as well as wind speed, direction and a host of other parameters. This effective infiltration value tends to under-predict infiltration rates when temperature differences are large or when it is windy, and it over-predicts infiltration when conditions are calm and with small temperature differences. The derivation of the current wsf factors is described in detail by Turner, Sherman, & Walker (2012).

The second approach to treating infiltration in demonstrating ASHRAE 62.2-2016 compliance is to use the AIM-2 infiltration model from the ASHRAE Handbook of Fundamentals, which provides real-time estimates of infiltration rates based on outdoor temperature and wind conditions. The 62.2 standard refers to this as the *Smaller Time Step Method* (Section C2.2.2). The model has been validated through field measurements (I. S. Walker & Wilson, 1998). The model inputs include house leakage area, shelter factors, wind speed modifiers, wind and stack coefficients.

The value of using AIM-2 in temperature-based smart ventilation controls is that it allows the controller to account for the fact that higher ventilation rates are in-fact occurring during times with greater temperature differences or wind. By accounting for this, the controller will reduce IAQ fan airflow rates, which should save energy. The controller will also know when natural infiltration rates are low, and it will compensate with higher IAQ fan airflows, but with less energy impact.

In order for a smart controller to apply the AIM-2 model, it would need reliable, real-time outdoor temperature and wind data. This is not always possible, and smart controllers can be effective without this data. So, for each of the most promising control strategies we test, we will assess their performance using Q_{inf} and using AIM-2 infiltration methods.

At each time-step (5-minutes in EnergyPlus), a natural infiltration estimate is calculated as the combined wind and stack airflows. Wind airflow (Q_W) is estimated using Equation 17. Stack airflow (Q_S) is calculated using Equation 18. The combined total airflow (Q_{AIM-2}) is estimated using Equation 19. The coefficients used in the model are selected based on house characteristics, including number of stories, foundation type, presence of a flue, etc. We used model coefficients assuming slab-on grade foundation and no flue present as outlined in Table 27.

$$Q_w = c \times C_w(sGU_{met})^{2n} \quad (17)$$

$$Q_s = c \times C_s(|T_{in} - T_{out}|)^n \quad (18)$$

$$Q_{AIM-2,i} = \sqrt{{Q_w}^2 + {Q_s}^2} \quad (19)$$

$Q_{AIM-2,i}$ = total house infiltration at time step I predicted by AIM-2 model, L/s

Q_w = wind-induced infiltration airflow, L/s

Q_s = stack-induced infiltration airflow, L/s

c = house leakage coefficient, $m^3/s\text{-}Pa^n$

C_w = wind coefficient

s = shelter factor

G = wind speed multiplier

U_{met} = meteorological site wind speed, m/s

n = pressure exponent

Model Coefficient	***1-story***	***2-story***
Wind Speed Multiplier (G)	0.48	0.59
Shelter Factor (s)	0.5	0.5
Wind Coefficient (C_w)	0.156	0.170
Stack Coefficient (C_s)	0.054	0.078
Pressure Exponent	0.65	0.65

Table 27 AIM-2 model coefficients used in SVACH simulations.

CONTAM Envelope Leakage Distribution, Wind Pressure Coefficients and Shelter Factors

Envelope Leakage Distribution

The leakage distribution refers to the orientation, height, size and locations of the leaks in a building envelope. The distribution of leaks, primarily by height, but also by orientation, can have substantial impacts on infiltration estimates. In addition to changing infiltration airflows, leakage distributions also affect how unbalanced fan airflow combines with natural infiltration to predict whole house airflow. The leakage distributions are described in detail for the 1- and 2-story prototypes in Table 28 and Table 29, respectively, including the height and size of each leak in the CONTAM models. In CONTAM, all leaks had discharge coefficients of 1.0 (a factor already accounted for in use of effective leakage area). The CONTAM envelope leakage flow elements are pictured in Figure 93. For the attic space, ceiling leakage was included, as were three cracks for each orientation representing unintentional attic leakage, as well as builder-installed venting to satisfy building code.

Floor height and wall leaks are evenly distributed on each of the cardinal faces of the homes, which is represented by the % values in the "Leakage Fraction, Total" vs. "Leakage Fraction, per Face" columns (the latter is simply the former value divided by 4). Five individual leaks are modeled on each of four walls, with heights evenly distributed along the total height of the walls (varies by number of stories). Overall, the 1-story homes have 25% floor height leakage, 25% wall leakage and 50% ceiling leakage (into the separately modeled attic zone), which is consistent with the default assumption of 50% ceiling leakage specified in the Title 24 2016 Alternative Calculation Method (ACM). The leakage areas in the 2-story homes have 16% floor height leakage, 52% wall leakage and 32% ceiling leakage. These values were selected to give leakage per unit wall/ceiling area roughly similar to those in the 1-story home, as well as similar leakage per linear foot of slab perimeter.

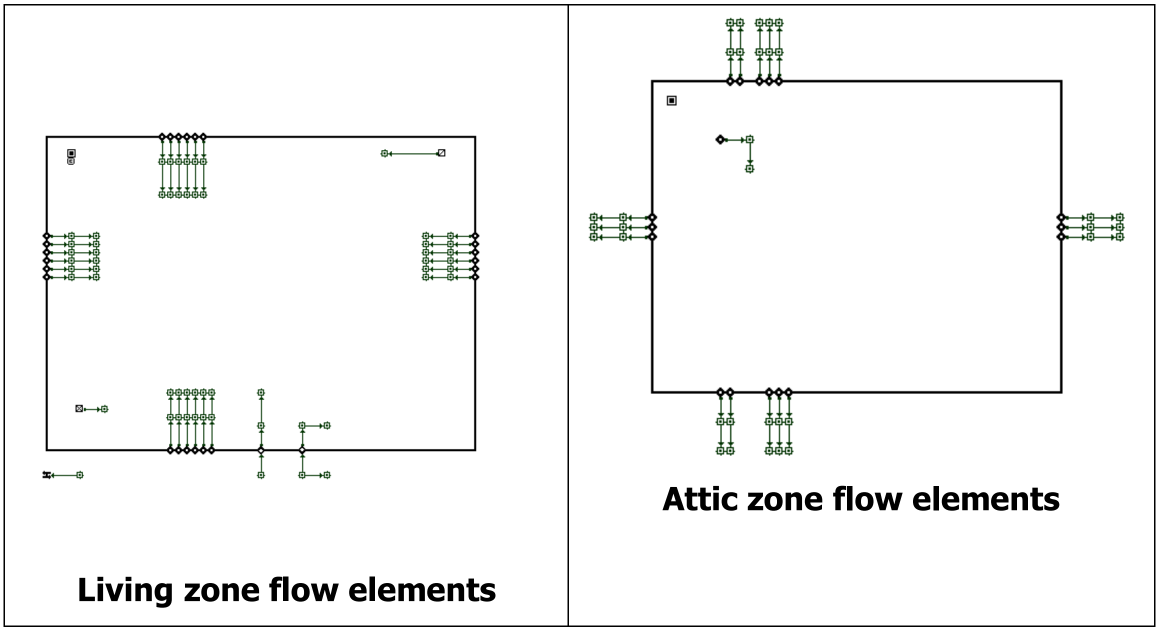


Figure 93 Location of flow elements on building envelope in CONTAM.

Leak Type	***Leak Height From Floor (m)***	***Leakage Fraction, Total***	***Leakage Fraction, per Face***	***Leakage Areas Per Leak (cm^2)***		
				1 ACH_{50}	***3 ACH_{50}***	***5 ACH_{50}***
Floor	0.0	25%	6.3%	6.64	19.91	33.18
Wall_1	0.3	5%	1.3%	1.33	3.98	6.64
Wall_2	0.8	5%	1.3%	1.33	3.98	6.64
Wall_3	1.4	5%	1.3%	1.33	3.98	6.64
Wall_4	1.9	5%	1.3%	1.33	3.98	6.64
Wall_5	2.5	5%	1.3%	1.33	3.98	6.64
Ceiling	2.7	50%	50.0%	53.09	159.28	265.47
Total		***100%***	***100%***	***106.19***	***318.56***	***530.94***

Table 28 1-story prototype house leakage distribution.

Leak Type	***Leak Height From Floor (m)***	***Leakage Fraction, Total***	***Leakage Fraction, per Face***	***Leakage Areas Per Leak (cm^2)***		
				1 ACH_{50}	***3 ACH_{50}***	***5 ACH_{50}***
Floor	0.0	16%	4.0%	5.79	17.36	28.93
Wall_1	0.6	10%	2.6%	3.76	11.28	18.81
Wall_2	1.7	10%	2.6%	3.76	11.28	18.81
Wall_3	2.9	10%	2.6%	3.76	11.28	18.81
Wall_4	4.1	10%	2.6%	3.76	11.28	18.81
Wall_5	5.2	10%	2.6%	3.76	11.28	18.81
Ceiling	5.8	32%	32.0%	46.30	138.89	231.48
Total		***100%***	***100%***	***144.67***	***434.02***	***723.37***

Table 29 2-story prototype house leakage distribution.

We customized the 2-story prototype's leakage area distribution, because the fixed 50% ceiling leakage assumption of Title 24 does not stand up to scrutiny when comparing the results for 1- and 2-story homes. For a 5 ACH_{50} home, the 1-story prototype (2100 ft^2) has total leakage area of 530 cm^2, or 265 cm^2 in the ceiling. The same 2-story prototype (2700 ft^2) has 722 cm^2 total leakage area, which would imply 361 cm^2 in the ceiling. This would create almost 100 cm^2 more leakage area in the ceiling, while the ceiling area in the 2-story home is roughly half that in the 1-story. Thus this fixed approach puts a lot more leakage area in a lot less ceiling area, effectively doubling the leakage area per unit ceiling area. We cannot think of a credible reason that 2-story homes would have double the leakage area per unit ceiling area. We hypothesize that the measurements by Proctor et al. represent an average distribution including both 1- and 2-story homes in the ECO study. Unfortunately, the average distribution may substantially misrepresent both home types—underestimating ceiling leakage fraction in 1-story homes and over-estimating it in 2-story.

The number of flow elements in the CONTAM model was chosen based on the trade-off between simulation accuracy and model complexity. We wanted to represent flow variation with orientation to adequately capture wind-driven ventilation, as well as by height in order to estimate vertical stack-driven forces due to temperature difference and height. The distribution of the cracks was based on expert understanding of typical distribution of attic leaks in California homes.

In addition to the infiltration flow elements, we also added two flow elements on the south wall to represent the whole house fan. For the balanced fan models, both flow elements are used to provide flow in opposite directions. In the unbalanced model a single flow element is used to represent an exhaust fan. No ducts were modeled in CONTAM, as they were considered to be in conditioned space, and therefore as having no effect on house air exchange with outside. The flow rate of the whole house fan is set by the smart ventilation controller.

Wind Pressure Coefficients and Shelter Factors

Envelope leaks are exposed to different pressures depending on their orientation and the direction of the wind. As such, CONTAM allows the user to apply either built-in or customized wind pressure coefficients, which vary by orientation. But CONTAM does not allow for use of shelter factors, which account for the effects of other nearby buildings on the wind pressures exerted on a building. Specifically, an isolated building experiences very different wind pressures than a home located in a row of other homes (as in the common block configuration in the U.S.). The exception in COINTAM is a global wind speed modifier coefficient, which does not vary by wind direction, and therefore was not suitable for use in these building models.

We applied custom wind pressure coefficients and shelter factors for floor and wall leaks based on their orientation as detailed in Table 30. The wind pressure coefficients and shelter factors are the same as those used in the validated REGCAP heat, moisture and mass simulation model (I.S. Walker, Forest, & Wilson, 2005).

	Combined Wind Pressure and Shelter Coefficients – HOUSE			
Incident Wind Angle	***North (0°)***	***South (180°)***	***East (90°)***	***West (270°)***
30	0.531	-0.219	0.005	-0.527
60	0.261	-0.066	0.085	-0.247
90	-0.104	-0.084	0.035	-0.115
120	-0.055	0.256	0.069	-0.226
150	-0.200	0.531	0.004	-0.527
180	-0.300	0.600	-0.637	-0.650
210	-0.219	0.531	-0.527	0.005
240	-0.066	0.261	-0.247	0.085
270	-0.084	-0.104	-0.115	0.035
300	0.256	-0.055	-0.226	0.069
330	0.531	-0.200	-0.527	0.004
360	0.600	-0.300	-0.650	-0.637

Table 30 House custom combined wind pressure and shelter coefficients, by incident wind angle and surface orientation.

Attic leakage elements also had custom wind pressure coefficients, matching those used in the validated attic model implemented in the REGCAP simulation. The attic leaks do not have any sheltering and are reproduced in Table 31.

	Combined Wind Pressure and Shelter Coefficients – ATTIC			
Incident Wind Angle	***North (0°)***	***South (180°)***	***East (90°)***	***West (270°)***
30	-0.350	-0.277	-0.156	-0.250
60	-0.250	-0.060	-0.059	-0.284
90	-0.104	-0.085	-0.023	-0.154
120	-0.051	-0.245	-0.048	-0.259
150	-0.253	-0.350	-0.133	-0.250
180	-0.400	-0.400	-0.196	-0.200
210	-0.277	-0.350	-0.250	-0.156
240	-0.060	-0.250	-0.284	-0.059
270	-0.085	-0.104	-0.154	-0.023
300	-0.245	-0.051	-0.259	-0.048
330	-0.350	-0.253	-0.250	-0.133
360	-0.400	-0.400	-0.200	-0.196

Table 31 Attic custom wind pressure coefficients, by incident wind angle and surface orientation.

EnergyPlus / CONTAM Co-Simulation Approach

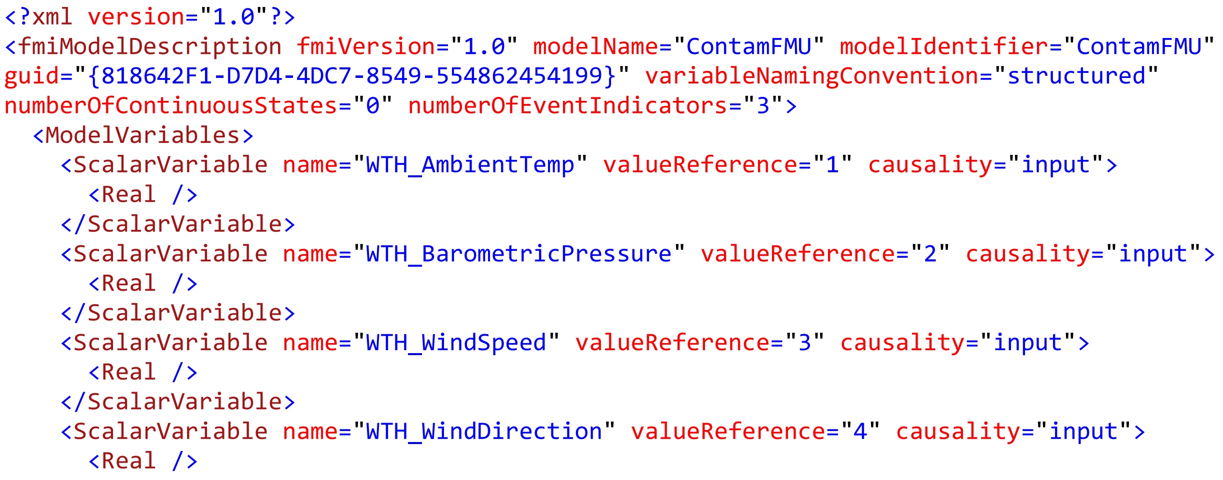
Co-simulation setup

The co-simulation uses EnergyPlus as the master that communicates with a Functional Mockup Unit implementation of Contam. The FMU contains the Contam project model, a variable verification file (.vef) and a model description dictionary (.xml) and the Contam implementation (ContamFMU.dll). As introduced in the section titled Implementation of the EnergyPlus and CONTAM Co-simulation, the *Contam 3D Export* tool from NIST is used to generate these files, and generate corresponding EnergyPlus EMS objects, as an .idf code snippet.

Setting up the co-simulation can be summarized in 3 steps. Firstly, the export tool may generate more data exchange elements than required, so step one is to remove unwanted variables from the .vef, .xml, and idf files. Step 2 is to check that all of the required variables are present in the files. Step 3 is to include the .idf snippet into the building model .idf and write the EMS scripts that will set and read values from the EMS *ExternalInterface* objects.

Variable Declaration and Determining

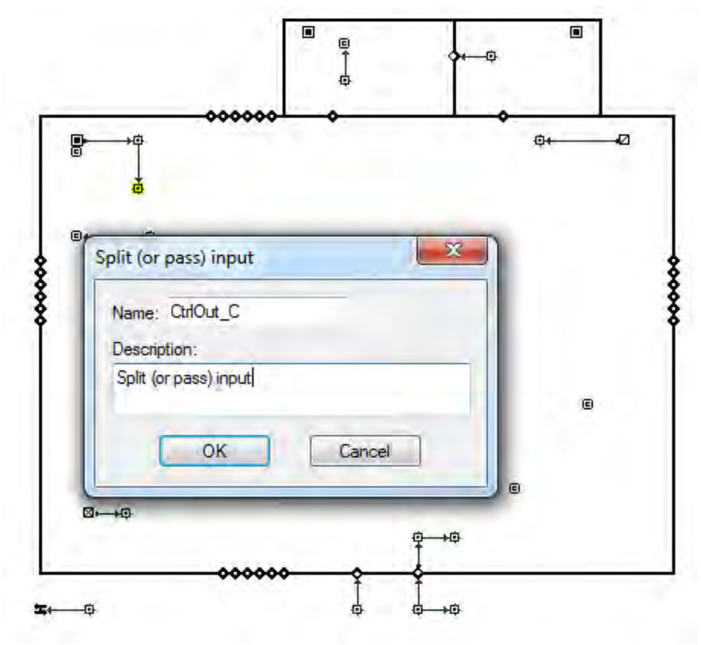
The “modelDescription.xml” summarizes the parameter exchanging between EnergyPlus and CONTAM; Figure 94 shows an example snippet of the XML file.



```
<?xml version="1.0"?>
<fmiModelDescription fmiVersion="1.0" modelName="ContamFMU" modelIdentifier="ContamFMU"
guid="{818642F1-D7D4-4DC7-8549-554862454199}" variableNamingConvention="structured"
numberOfContinuousStates="0" numberOfEventIndicators="3">
  <ModelVariables>
    <ScalarVariable name="WTH_AmbientTemp" valueReference="1" causality="input">
      <Real />
    </ScalarVariable>
    <ScalarVariable name="WTH_BarometricPressure" valueReference="2" causality="input">
      <Real />
    </ScalarVariable>
    <ScalarVariable name="WTH_WindSpeed" valueReference="3" causality="input">
      <Real />
    </ScalarVariable>
    <ScalarVariable name="WTH_WindDirection" valueReference="4" causality="input">
      <Real />
```

Figure 94 FMU model description dictionary XML file

Data variables are sent from EnergyPlus to CONTAM, and from CONTAM to EnergyPlus, summarized in Table 32. There are a few predefined variables that are generated by the export tool that relate to the transfer of environmental data from EnergyPlus to Contam variable ID’s 1-4. Summary variables, such as “MIX_2_attic_to_1_livingzone”, do not need additional specification. The remaining variables must be defined in the Contam model. Contam “control variables” are treated as inputs from EnergyPlus. Contam “reporting variables” are treated as data to be transferred to EnergyPlus. Figure 95 shows an example of adding a Split (or pass) input variable.



Name: CtrlOut_C

Description: Split (or pass) input

Figure 95 Control variable defined in CONTAM

The nomenclature for these variables, and for the variables described in the contam.vef file, can be found in the CONTAM user manual (Dols, Emmerich, & Polidoro, 2016), Section 6.2 ENERGYPLUS INPUT FILES.

Table 32 Variable exchanging dictionary summary

Default variables (from EnergyPlus to Contam)		
ID	Variable name	Description
1	WTH_AmbientTemp	Outdoor Dry-Bulb Air temperature, C
2	WTH_BarometricPressure	Outdoor atmospheric pressure, pa
3	WTH_WindSpeed	Wind speed, m/s
4	WTH_WindDirection	Wind direction
Control variables (from EnergyPlus to Contam)		
ID	Variable name	Description
5	TAIR_1_attic	Attic temp, C
6	TAIR_1_livingzone	Living zone dry-bulb air temperature, C
7	CTRL_I_CtrlIn_01	Air cleaning sink ratio
8	CTRL_I_CtrlIn_02	Outdoor air fraction
9	CTRL_I_CtrlIn_03	Total exhaust flow rate, m3/s
10	AHS_supply_1_livingzone	Supply air mass flow rate, kg/s
11	AHS_return_1_livingzone	return air mass flow rate, kg/s
12	PCTOA_SingleZoneAHU	OA fraction, %
13	TAIR_SingleZoneAHU(Rec)	Supply air duct temp,C
14	TAIR_SingleZoneAHU(Sup)	Return air duct temp,C
Reporting variables (from Contam to EnergyPlus)		
ID	Variable name	Description
15	MIX_2_attic_to_1_livingzone	Mass flow from Attic to living zone (air mixing), kg/s
16	MIX_1_livingzone_to_2_attic	Mass flow from living zone to attic (air mixing), m3/s
17	INFIL_1_livingzone	living zone infiltration from outside, m3/s
18	INFIL_2_attic	Attic infiltration from outside, m3/s
19	CTRL_O_CtrlOut_C	Living zone CO2 concentration
20	CTRL_O_CtrlOut_exhaust	Total exhaust mass flow rate, kg/s
21	CTRL_O_CtrlOut_mixing	Net Zone mixing from Attic to living zone, kg/s
22-	CTRL_O_CtrlOut_NW/WW/EW/SW_1/2/3/4/5	Air flow rate through envelop cracks, kg/s

The control variables are used to transfer data from EnergyPlus to CONTAM through the FMU, and are limited to values between 0 – 1, so we need to scale the value and match the units. Reporting variables, such as CTRL_O_CtrlOut_exhuast, can be floating point numbers.

The contam.vef variable exchange file is "used by the ContamFMU.dll to coordinate data exchange information at the beginning of a co-simulation run. This file will contain a list of variables that are to be exchanged during co-simulation." Figure 96 gives an example of a variable verification file used in this project. The first line is the total number of exchange variables, followed by the default and control inputs denoted by the string "I", and finally the reported outputs denoted "O". The second string, such as: "WTH_AmbientTemp" is the variable name, which must match the "modelDescription.xml" file. The three letter identifier, (wws, wvd etc) describes the type of data being transferred and is needed by CONTAM so that it knows which type of Contam data the variable connects to. The final string is the variable name as it appears in Contam. A more detailed description of these is found in the Contam user manual. (Dols, Emmerich, & Polidoro, 2016).

```
VariableExchangeFile 1.0 fmi 3
61
I WTH_AmbientTemp wat
I WTH_BarometricPressure wbp
I WTH_WindSpeed wws
I WTH_WindDirection wwd
I TAIR_2_attic zti  2 attic
I TAIR_1_livingzone zti  1 livingzone
I CTRL_I_CtrlIn_02 cti CtrlIn_02
I CTRL_I_CtrlIn_07 cti CtrlIn_07
I CTRL_I_CtrlIn_03 cti CtrlIn_03
I AHS_supply_1_livingzone ahs 1 livingzone 1
I AHS_return_1_livingzone ahr 1 livingzone 1
I PCTOA_SingleZoneAHU poa SingleZoneAHU
I TAIR_1_SingleZoneAHU(Rec) zti 1 SingleZoneAHU(Rec)
I TAIR_1_SingleZoneAHU(Sup) zti 1 SingleZoneAHU(Sup)
O MIX_1_livingzone_2_attic mix 1 livingzone 2 attic
O INFIL_2_attic inf 2 attic
O MIX_2_attic_1_livingzone mix 2 attic 1 livingzone
O INFIL_1_livingzone inf 1 livingzone
O CTRL_O_CtrlOut_mixing cto CtrlOut_mixing
```

Figure 96 Variable verification file

Variable Matching

All variables defined in the must be present in the the .vef, .xml, must also have a corresponding EMS interface object associated with it in the model .idf file. The variables transferred from EnergyPlus need an ***ExternalInterface:FunctionalMockupUnitImport:From:Variable*** object , and all the variables transferred into EnergyPlus require a ***ExternalInterface:FunctionalMockupUnitImport:To:Variable*** object. Furthermore, the variables transferred from EnergyPlus are also required to be specified in "Output:Variable". The variables from EnergyPlus can either be a variable calculated in core EnergyPlus programs or defined in EMS. Variables defined in EMS are needed to be defined as global variables.

Confirming Moist-Air Conditions and Mass Flow Rates Between EnergyPlus and CONTAM

For the co-simulation results to be meaningful, it is essential that the two tools represent the same thermodynamic conditions, and that the infiltration rates calculated in CONTAM are faithfully replicated in EnergyPlus. This is complicated by the fact that the current version of the contamFMU does not specify the humidity of the air. This presents a problem when trying to harmonize our two models. When CONTAM is used as a standalone application (not using co-simulation), its moisture and mass balance model considers the humidity of the indoor and outdoor air in its calculation, with the outdoor humidity coming from a weather file. When using co-simulation however, the weather data, outdoor temperature, wind speed and direction, come from EnergyPlus's weather file via the FMI. CONTAM's moisture balance calculation then assumes dry air for its calculations, resulting in different assumptions of air density in the two tools. This presents an issue if the method described by Dols et al (Dols & Polidoro, 2015) is employed. Dols et al. pass the air change rate from CONTAM to EnergyPlus as a volumetric air change rate that is calculated by CONTAM using the dry air density. When we initially implemented the off-the-shelf contamFMU, we found mass imbalances between the two tools, which led to a reported loss of mass. This discrepancy was deemed unacceptable and so we abandoned the approach of having CONTAM calculate the zone infiltration, and instead used an EnergyPlus EMS program to calculate the total zone infiltration. In this approach, the mass flow rate of every flow path in the CONTAM model was sent to EnergyPlus, and net-ventilation airflows were calculated for the main zone and attic using a calculation in EMS code. This customization ensured that mass was maintained and balanced between CONTAM and EnergyPlus.

The equation used in EMS code for this calculation is:

$$\boldsymbol{\dot{V}_{oa}} = \frac{\Sigma \boldsymbol{\dot{m}_{inf}} + \Sigma \boldsymbol{\dot{m}_{mix}}}{\boldsymbol{\rho_{zn}}} \qquad \textbf{(20)}$$

where $\dot{V}_{oa}$ is the volumetric flow rate for fresh air coming into the zone, $\sum \dot{m}_{inf}$ is the sum of the infiltration mass flow rates into the zone through all the cracks, $\sum \dot{m}_{mix}$ is the sum of the zone mixing mass flow rates into the zone from the Attic, and ρ_{zn} is the zone air density (as a function of house zone temperature, humidity and atmospheric pressure).

The mass flows into the conditioned house zone were converted to a volumetric ventilation airflow using EnergyPlus's moist air density. This volumetric airflow was then used to specify the volumetric air change rate in EnergyPlus using a *DesignInfiltration* object. EnergyPlus reports this air change rate as a mass flow rate, which was confirmed to be the same as the mass flow rate returned from CONTAM.

Detailed Scenario File Description

Table 33 describes all of the input parameters in the scenario input file, and their uses.

Table 33 Scenario definition file

Parameter	Example	Description/purpose
ID	85	Numerical id allocated sequentially
KeyTerm	1story_1ACH50_CZ10	Unique prototype identifier, including all combinations of the 24 prototype homes (3 airtightness levels, 4 climate zones and 2 prototype home geometries)
Prototype	1story	Selects EnergyPlus building model geometry for 1- or 2-story
cz	X10	Selects CEC climate zone (1, 3, 10 or 16)
czID	10	ID for climate zone
ACH50	1	Building envelope air tightness (ACH50)
AIM_C	0.011135023	Envelope leakage coefficient, AIM-2 model . Parameter c used in controller infiltration calculation using AIM-2 method
AIM_Cs	0.054	Stack coefficient, AIM-2 model. Parameter cs in controller infiltration calculation using AIM-2 method
AIM_Cw	0.156	Wind coefficient, AIM-2 model. Parameter cw in controller infiltration calculation using AIM-2 method
AIM_G	0.48	Wind speed multiplier, AiM-2 model. Parameter G in controller infiltration calculation using AIM-2 method
AIM_s	0.5	Shelter factor, AIM-2 model (see 0). Parameter s in controller infiltration calculation using AIM-2 method
Cmean	NA	Cooling season mean relative exposure target. Not used directly in simulations, but provides meta-information about the case.
ControlType	Occ	Control type for different control strategies
CoolingAHUfanPower_w	320	Cooling system air handler fan power consumption, watts
CoolingAirflow_m3.s	0.38	Cooling system air handler airflow rate (designed value), m3/s
EER	12.8	Cooling system EER (converted to COP)
ELA_m2	0.010618807	Effective leakage area, used in Contam model
FSM	2	Fan speed multiplier, used to increase airflow of baseline IAQ fan

Fan.Type	HRV	Specifies if the “Balanced” vs. “Exhaust”
Flush1	0	Occupancy control pre-occupancy flush out, hour 1
Flush2	0	Occupancy control pre-occupancy flush out, hour 2
Flush3	0	Occupancy control pre-occupancy flush out, hour 3
Flush4	0	Occupancy control pre-occupancy flush out, hour 4
HeatingAHUfanPower_w	161.3	Heating system fan rated power, watts
HeatingAirflow_m3.s	0.19	heating system air flow rate (designed value), m3/s
HeatingCapacity_J.s	7033.705684	Heating system capacity, J/s
Heating_AFUE	0.92	Heating system efficiency, Annual Fuel Utilization Efficiency
Hmean	NA	Heating season mean relative exposure target. Not used directly in simulations, but provides meta-information about the case.
IAQfanAirflow_m3.s	0.039911762	Continuous IAQ fan air flow from baseline case for each KeyTerm, m3/s. The Fan Size Multiplier is used to translate this into an over-sized fan for the smart control cases.
IAQfanPower_w	17.40551938	Continuous IAQ fan power from baseline case for each KeyTerm, watts
Infiltration	Qinf	Controller infiltration estimation method (AIM-2 or Qinf)
Qinf	0.003352683	Annual effective infiltration estimate from ASHRAE 62.2-2016,m3/s.
REMaxCooling	NA	High relative exposure target, used in VarRe, Cutoff and MedRe controllers.
REMaxHeating	NA	Low relative exposure target, used in VarRe, Cutoff and MedRe controllers.
REmax	NA	High relative exposure target used during heating season to reduce ventilation, used in Seasonal controller
REmin	NA	Low relative exposure target used during cooling season to increase ventilation, used in Seasonal controller.
SixtyTwoTwoFan	0.039911762	Continuous IAQ fan air flow from baseline case for each KeyTerm, m3/s. The Fan Size Multiplier is used to translate this into an over-sized fan for the smart control cases. Identical to IAQfanAirflow_m3s.

Strategy	NineHour	Occupancy schedule for "Occupancy" control
TCutoffCooling	78.8	Cooling cut off temperature for "Cut off" control, F
TCutoffHeating	57.4	Heating cut off temperature for "Cut off" control, F
Type		Not used
UnoccFlow	0.35	For Occupancy SVC, this is the fractional airflow relative to the baseline continuous IAQ fan airflow.
duration	9	Duration of unoccupied period.
proto	1	Not used
TmaxCoolingInF	NA	Cooling season maximum temperature used to proportionally scale control targets for the VarRe and VarQ controllers, F. For VarQ, this is the maximum cooling season temperature, and for VarRe this is some optimized value that is less than the maximum value.
TmaxHeatingInF	NA	Heating season minimum temperature used to proportionally scale control targets for the VarRe and VarQ controllers, F. For VarQ, this is the minimum heating season temperature, and for VarRe this is some optimized value that is greater than the minimum value.

Weighted Average Method

In addition to reporting results across the house and simulation parameters described above, we also perform a weighted average assessment, which is targeted towards representing smart ventilation control performance in new homes built in California. As such, the weighted average method gives strong emphasis to the types of homes that are built in the state and where they are built. Namely, this means strong weighting for cases with more air leakage in climates 3 and 10 (Oakland and Riverside).

Each case is weighted according to the expected distribution of the parameter in new homes throughout the state. The weighted average parameters used in our analysis included climate zone (see Table 36 and Table 37), envelope airtightness (Table 34) and house prototype (Table 35). Each factor is briefly discussed below. This is an imperfect approach to characterizing the entire new California single-family building stock, but it does give us a way to generalize and summarize our results. For example, this method gives greater weight to results from the mild climate zones in Southern and Central California where most new home development occurs in the state, and it reduces the effect in sparsely populated zones, like CZ1 (Arcata) or 16 (Blue Canyon). The average result under these weights for each fan sizing method was calculated using Equation 21.

$$\overline{x} = \frac{\sum_{i=1}^{n}(x_i * w_{prototype,i} * w_{cz,i} * w_{ACH50,i})}{\sum_{i=1}^{n} w_{prototype,i} * w_{cz,i} * w_{ACH50,i}} \tag{21}$$

x = Variable in question (e.g., relative exposure, ventilation energy use)

$w_{prototype}$ = house prototype weight

w_{CZ} = climate zone weight

w_{ACH50} = airtightness weight

The airtightness weights (Table 34) are designed to roughly estimate current airtightness in new California homes, with most new construction achieving roughly 5 ACH_{50}, and diminishing numbers of new homes achieving 3 ACH_{50} and very low numbers with greater airtightness of 1 ACH_{50}.

	Envelope Airtightness (ACH_{50})		
	5	***3***	***1***
Estimated Weights	0.63	0.30	0.07

Table 34 Envelope airtightness weighting factors

Prototype weights (Table 35) match those provided in the description of the single-family Title 24 prototype buildings that are used for analysis supporting development of the Title 24 energy code (Nittler & Wilcox, 2006).

	1-story, 2,100 ft^2	***2-story, 2,700 ft^2***
Weighting Factor	0.45	0.55

Table 35 Prototype weighting factors

Climate zone weights (Table 36 and Table 37) are based on the fraction of total projected new housing starts in 2017 in each CEC climate zone, using data provided to the 2016 CASE teams by the CEC Demand Analysis office. We have reproduced exactly the estimates provided by Rasin & Farahmand (2015) in Table 14 of the Residential High Performance Walls CASE report. Yet, we simulated only climate zones 1, 3, 10 and 16, and we attribute projected housing starts in non-simulated climate zones based on geography and overall heating/cooling degree days (see Table 36 for our assignment of non-simulated climates to those we simulated, for example, the CZ4 and CZ5 weights were added to the CZ3 weighting). The combined weights for zones 1, 3, 10 and 16 are provided in Table 37. The vast majority of weight (96%) is applied to the CZ3 and 10 results.

CZ	***City***	***2017 New Single-Family Homes***	***2017 New Homes Fraction***	***Rough HDD$_{65}$ Range***	***Rough CDD$_{80}$ Range***	***CZ Weight Assignment***
1	Arcata	695	0.006	3800-4500	0-50	1
2	Santa Rosa	2602	0.024	2600-4200	200-900	3
3	Oakland	5217	0.048	2500-3800	10-500	3
4	San Jose-Reid	5992	0.055	2300-2900	200-1000	3
5	Santa Maria	1164	0.011	2300-3000	200-900	3
6	Torrance	4142	0.038	700-1900	500-1200	10
7	San Diego-Lindbergh	6527	0.060	1300-2000	500-1100	10
8	Fullerton	7110	0.066	1300-1800	700-1300	10
9	Burbank-Glendale	8259	0.076	1100-1700	1300-1600	10
10	Riverside	16620	0.154	1600-1900	1400-1900	10
11	Red Bluff	5970	0.055	2500-4300	600-1900	3
12	Sacramento	19465	0.180	2400-2800	900-1600	10
13	Fresno	13912	0.129	2000-2700	1000-2200	10
14	Palmdale	3338	0.031	1900-2700	2000-4200	10
15	Palm Spring-Intl	3885	0.036	1000-1300	4000-6600	10
16	Blue Canyon	3135	0.029	4300-6000	200-1000	16

Table 36 New construction estimates for single-family homes in 2017 and weighting assignments for un-simulated climate zones.

	1 (Arcata)	***3 (Oakland)***	***10 (Riverside)***	***16 (Blue Canyon)***
Total Weight Factor	0.0064	0.1939	0.7707	0.0290

Table 37 Climate zone weighting factors.

Normalization Method

Due to both smart control and baseline cases having controller relative exposure not exactly equal to 1.0 (as initially discussed in Section 0), normalization was performed as follows.

We created a set of cases for each combination of climate zone and house prototype (two prototypes, four climates) that had no air exchange either through fans or natural infiltration. Energy consumption in these cases was deemed the "envelope-only" energy use. This envelope energy use was subtracted from the HVAC energy use for each standard case to estimate the total energy consumption added to the home by outside air exchange (including both mechanical and natural airflows). This ventilation energy was then multiplied by the annual mean real exposure for the case, in order to estimate the ventilation energy use that would have occurred if the real exposure was exactly 1.0. For example, if a case was slightly over-ventilated relative to the target airflow (e.g., mean exposure of 0.98), the ventilation energy use in that case was multiplied by 0.98 to approximate the slightly lower ventilation energy use that would have occurred if exposure were equal to 1.0. This normalized ventilation energy was then added back onto the envelope-only energy use for each case, and these adjusted HVAC energy use values were used to estimate energy savings of smart controls relative to baseline continuous IAQ fan cases.

We also tested an alternative normalization approach that parametrically varied the smart control parameters in order to get controller exposure to equal 1.0, and the two normalization methods had very good agreement in predicted total HVAC energy use. So, in this work, we present the results of the simpler method described in the prior paragraph.

Demand Response and Peak Demand

California faces unique grid reliability issues due to its high saturation of renewable energy sources (e.g., solar, wind and hydro), as well as issues with servicing the peak electricity demand on the hottest days of the year. Accordingly, the utilities offer time-of-use rate plans, in accordance with CPUC requirements. Some also issue peak day alerts for 9-15 days per year, typically the hottest days, when customers are encouraged to shed electrical demand using a very high price signal, roughly $0.85 per kWh. These efforts are termed Demand Response, and the goal is to get utility customers to voluntarily reduce their energy demand at certain times of day and on certain days of the year.

Smart ventilation controllers can contribute to demand response peak demand savings, largely by reducing the ventilation portion of the cooling load during the hottest times of day. In fact, many of the smart ventilation controls that we tested in this work automatically perform peak shedding, due to their outdoor temperature controls, which will reduce the ventilation rate during hot (or cold) periods. In addition to this, some of the controls might offer additional peak period benefits through pre-cooling with increased ventilation rates at night, effectively acting like economizers. That being said, none of the controls assessed in this work are specifically “demand response” or “peak demand” controllers. Such a controller would do nothing but turn the IAQ fan completely off during the peak period(s). Some of the smart controls do something very similar to this, but in general, they are reducing the IAQ fan airflow during hot outdoor conditions, rather than fully turning it off.

We assess peak period performance by assessing the HVAC power consumption that is shed during the peak hours on the hottest days of the year in the smart control cases relative to the baseline cases. The peak period is assumed to be between 2 and 6pm (per PG&E rate plans) on the hottest 10-days of the year—a total of 40-hours of the year. We select different sets of 10-days for each CEC climate zone weather file. We first calculate the average temperature between 2 and 6 pm for each day of the year. We then select the 10 warmest days on average as our “peak” days. Finally, we estimate total HVAC energy consumption during these peak periods, including the compressor, furnace, air handler, IAQ fan and auxiliary fan power consumptions. For demand response estimates, we estimate the reduction in average wattage during the 4-hour peak period, as well as percent reduction in the entire HVAC load during the peak period.

Time Dependent Valuation (TDV) Energy

In addition to the peak analysis described in 0, we also calculate energy performance using time dependent valuation energy, as is required to demonstrate compliance with the Title 24 building energy code. TDV changes the value of energy depending on when it is used, with higher penalties for consumption during periods that stress the grid and increase consumer and grid operation costs. TDV factors are provided for every hour of the year for electricity and gas, and they vary by CEC climate zone. We use the TDV factors that ship with the CBECC-Res residential Title 24 compliance software for the 2019 code cycle. We combine these with the hourly energy consumption estimates from EnergyPlus for the cooling, heating, air handler and ventilation fan equipment. We generally report TDV savings in a percentage format, but we use kilowatt-hours when reporting absolute energy use. We convert TDV from Btus to kWh by dividing by 3,412. It is critical to note that the smart controls that were designed through parametric optimization (e.g., VarQ, VarRe, CutOff) were not optimized using TDV energy, but rather simple site energy savings. The same optimization could be performed based on TDV consumption, and surely the ideal control parameters would change and we expect TDV savings would increase accordingly.

Mechanical IAQ Fan Sizing

Baseline Fan Sizing

All baseline ventilation fans are sized according to the current calculation method in ASHRAE 62.2-2016. This means a target ventilation rate (Q_{tot}) is calculated based on home floor area and number of occupants/bedrooms as in Equation 22. An effective annual average infiltration airflow (Q_{inf}) is then estimated using the results of a blower door pressurization test as in Equation 23. Finally, a mechanical fan airflow (Q_{fan}) is calculated using the target airflow and estimated infiltration per Equation 24. The total ventilation rate requirement for the single story home is 93 cfm and 119 cfm for the two story home.

$$\boldsymbol{Q_{tot} = 0.15A_{floor} + 3.5(N_{br} + 1)} \tag{22}$$

Q_{tot} = Total required ventilation rate, L/s

A_{floor} = floor area of residence, m^2

N_{br} = number of bedrooms (not less than one)

$$\boldsymbol{Q_{inf} = \frac{NL(wsf)A_{floor}}{1.44}} \tag{23}$$

Q_{inf} = Effective annual infiltration rate, L/s

NL = normalized leakage, derived from blower door testing

wsf = weather and shielding factor from Normative Appendix B 62.2-2016, varies by climate zone

A_{floor} = floor area of residence, m^2

$$\boldsymbol{Q_{fan} = Q_{tot} - \emptyset(Q_{inf} \times A_{ext})} \tag{24}$$

Q_{fan} = required mechanical ventilation rate, L/s

Q_{tot} = Total required ventilation rate, L/s

Q_{inf} = Effective annual infiltration rate, L/s

A_{ext} = 1 for single-family detached homes

ϕ = 1 for balanced ventilation systems and otherwise: Q_{inf}/Q_{tot}

Baseline Exposure and Superposition in ASHRAE 62.2

Our results showed the baseline continuous fan cases were under-ventilated relative to the targets established in ASHRAE 62.2-2016, yet the fans were sized using the standard. We found that relative exposure was greater than one in these cases, because of a bias in the methods used to combine unbalanced mechanical and natural infiltration airflows—referred to as superposition. This bias impacts fan sizing calculations and house airflow estimates when calculating relative exposure. The bias is problematic when designing and assessing smart controls, because the standard requires them to achieve exposure less than 1.0, while the baselines do not meet that same criteria. This acts as an energy disadvantage for the smart controlled fan. The energy penalty of increasing airflow can be similar in magnitude to the anticipated smart ventilation savings for some controllers (see Less and Walker (2017)). Balanced ventilation fans are not subject to the superposition equations in 62.2-2016, so do not suffer from this bias in fan sizing or house airflow estimation.

ASHRAE Standard 62.2-2016 sizes an IAQ fan using a target airflow (Q_{tot}) and an estimation of infiltration (Q_{inf}) that is based on a blower door test. Superposition equations were introduced in ASHRAE 62.2-2016 in order to account for the different ways in which balanced and unbalanced fans combine with natural infiltration. The old formulation used in the standard (i.e., simple addition of fan and infiltration airflows) ensured, almost by definition, that unbalanced IAQ fans did not achieve the target ventilation rate (Q_{tot}). Estimation of a number of new superposition models was presented by Hurel, Sherman, & Walker (2016). Each model could be formulated to either predict house airflow or to size a ventilation fan based on a target airflow. The most simple and accurate models were incorporated into ASHRAE 62.2-2016 for fan sizing calculations (by Addendum S), and for estimation of total house airflow when using relative exposure to demonstrate compliance (as is done with smart controls). But two discrete and different models were used for these two applications, and they are not an identity forwards and backwards. The result is that if you size a fan based on a target airflow and an infiltration estimate, and you then combine that resulting fan airflow with the same infiltration estimate, you do not get the target airflow back out of the systems of equations. Rather you always get an estimated airflow less than the target airflow.

Both superposition models incorporated by the standard calculate a phi sub-additivity coefficient, which is used to adjust the infiltration estimate when using unbalanced ventilation fans.

The “backward” formulation is used in fan sizing:

$$\emptyset_{backward} = \frac{Q_{inf}}{Q_{tot}} \tag{25}$$

$$Q_{fan} = Q_{tot} - \emptyset_{backward} \times Q_{inf} \tag{26}$$

The “forward” formulation is used in estimating total airflow:

$$\emptyset_{forward} = \frac{Q_{inf}}{Q_{inf}+Q_{fan}} \tag{27}$$

$$Q_{house} = Q_{fan} + \emptyset_{forward} \times Q_{inf} \tag{28}$$

For nearly any example set of values, Q_{house} (the result of forward estimation) is not equal to Q_{tot} (the target value used in fan sizing). For example, a target airflow of 50 L/s (Q_{tot}) and infiltration of 20 L/s (Q_{inf}) gives a fan size of 42 L/s (Qfan = 50 – 20 x (20 / 50)). But in the reverse formulation, Q_{house} is 48.5 L/s (42 + 20 x (20 / (20 + 42)). This will lead to a relative exposure of 50/48.5 = 1.03.

This imbalance in fan sizing and airflow estimation depends on the ratio of the infiltration (Q_{inf}) to the target airflow (Q_{tot}). We show resulting relative exposures (target airflow Q_{tot} divided by predicted house airflow Q_{pred}) for continuous unbalanced fans across a range of Q_{inf}/Q_{tot} ratios in Figure 97 below. The peak effect occurs when infiltration is 80% of the total airflow, with a relative exposure just below 1.1. There is nearly no effect when the infiltration is much smaller than the target airflow.

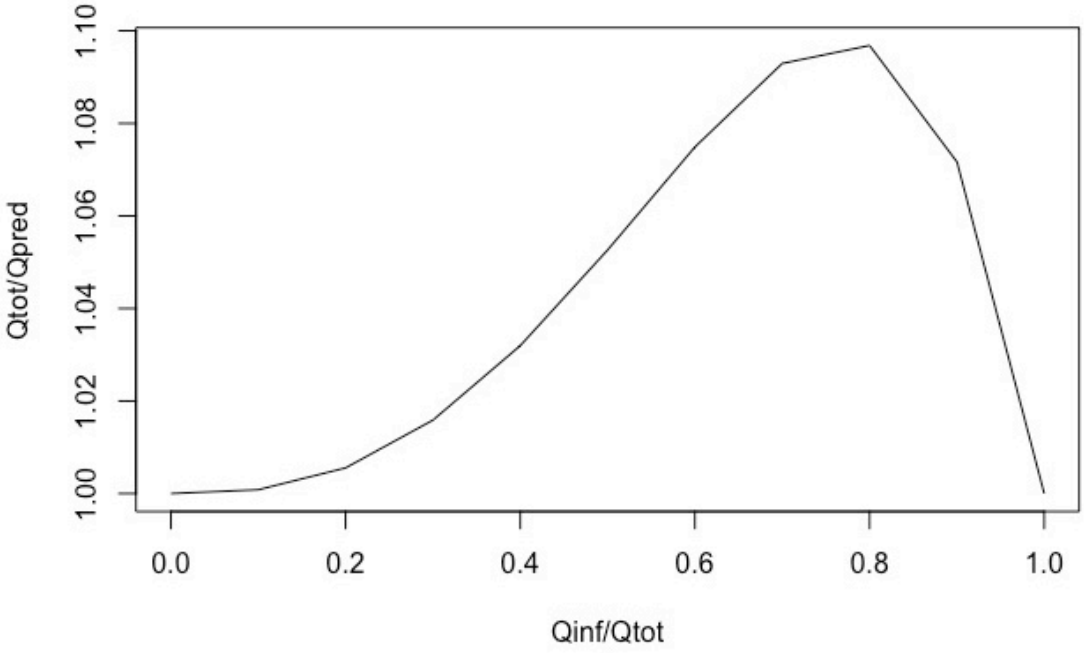


Figure 97 Illustration of bias in the ASHRAE 62.2-2016 unbalanced fan sizing calculation.

Smart Control Fan Sizing

To maintain equivalence with homes ventilated to the target airflow calculated using ASHARE 62.2-2016, smart controlled fans that time-shift ventilation rates must be over-sized. Most SVC fans are double the flow of the corresponding baseline cases. Where fans are not doubled, the Fan Size Multiplier (FSM) is noted in the control description. This multiplier is sometimes also used directly in the control development and setting of control parameters. For example, the smallest exposure value that a fan can achieve is well approximated by 1/FSM. If the FSM is 2 (double the baseline), then the steady state concentration at full fan flow would be half that in the baseline case. A triple over-sized fan could reach a minimum exposure of 1/3, etc. The lower the exposure is able to go, the more under-ventilation the controller can use to strategically save energy. For example, the target high and low exposure values used in the running median control are FSM and 1/FSM, respectively.

This approach works very well in a very airtight home, where the fan airflow is nearly equal to the whole house airflow. But in the leakier homes, the ventilation fan is only a fraction of the target ventilation rate, so doubling the fan airflow fails to double the whole house airflow. In effect, fan airflow doubles, infiltration is unchanged, and the resulting whole house flow is slightly less than doubled, and exposure is greater than the 1/FSM target (e.g., 0.5). So, the minimum exposure target used in some control types may in fact not be reachable, which skews the exposure higher than desired. This issue worsens as the natural infiltration rate (Qinf) predicted using ASHRAE 62.2-2016 equations increases relative to the target ventilation rate (Qtot). Many of the SVC are designed to achieve an annual exposure of 0.97 (instead of 1.0) to account for just such imperfections in control structure, definitions and operation.

We expect that the sizing of the smart controlled fan will have substantial impacts on performance, with effects varying strongly by the type of control strategy and eve fan type. Less & Walker (2017) showed that when using occupancy controls, increasing the size of a balanced IAQ fan had very little impact on energy performance, though the annual average exposure went down marginally as fan size increased. They also found that using an unbalanced fan with a controller that cycles the fan on and off led to increases in annual air exchange and associated ventilation energy. This was the result of superposition effects in the combining of unbalanced airflows with natural infiltration. To summarize, unbalanced fan airflows are sub-additive with natural infiltration (see Equation 24), and the amount of additional airflow provided by a fan changes with the ratio of the fan airflow to the infiltration airflow. As the fan airflow gets larger relative to the infiltration airflow, the fan contributes more to total house airflow—it gets more credit. As the fan gets smaller relative infiltration, it gets less credit. When a larger fan cycles on and off to provide the same relative exposure as a continuous fan with lower airflow, the unavoidable result is that the average air exchange increases for the cycling fan (as does ventilation energy use). This occurs for unbalanced smart controlled fans, but would also apply to any unbalanced ventilation system operated on a timer or otherwise cycled to maintain an average airflow.

For smart controls that do not change their target exposure values or overall control approach with fan size, we expect nearly no effect for balanced fans, and moderate negative effects for unbalanced fans as their over-sizing increases. But other smart control strategies, such as some of the temperature-based controls, change their target relative exposure values based on fan sizing. In these cases, larger smart controlled fans should increase energy savings, because they allow more time shifting of ventilation than smaller fans do.

Sensitivity Analysis

Airtightness

We estimated the median ventilation site and TDV energy savings for each control type across airtightness levels (see site energy in Figure 98 and TDV in Figure 99). Most new homes in the state are currently being built in the 4-5 ACH_{50} range, and we expect that as new homes become zero energy with the 2019 code cycle, homes at the 3 ACH_{50} level will increase to some extent. Homes at 1 ACH_{50} are rare and will remain so, so we consider this the least relevant data segment.

The controls respond differently to airtightness, with some having fairly consistent responses across airtightness levels (e.g., Seasonal control for site energy, or VarRe control for TDV), while most others vary. The 5 ACH_{50} performed the best for many control types when considering site energy percent savings, but this benefit disappeared for TDV assessments, where the leakiest homes were either similar to or worse than the most airtight cases (for top-performing VarRe, VarQ and Cutoff controls). VarQ site energy performance at the 5ACH$_{50}$ leakage level does not perform as well as other controls. Most notably, the VarRe control performs similarly to VarQ in 3 ACH$_{50}$ cases but substantially outperforms it in the leakiest homes, giving it the clear advantage on average. For TDV savings, the VarQ is much better than VarRe in all air leakage levels, but especially for the 3 ACH$_{50}$ cases.

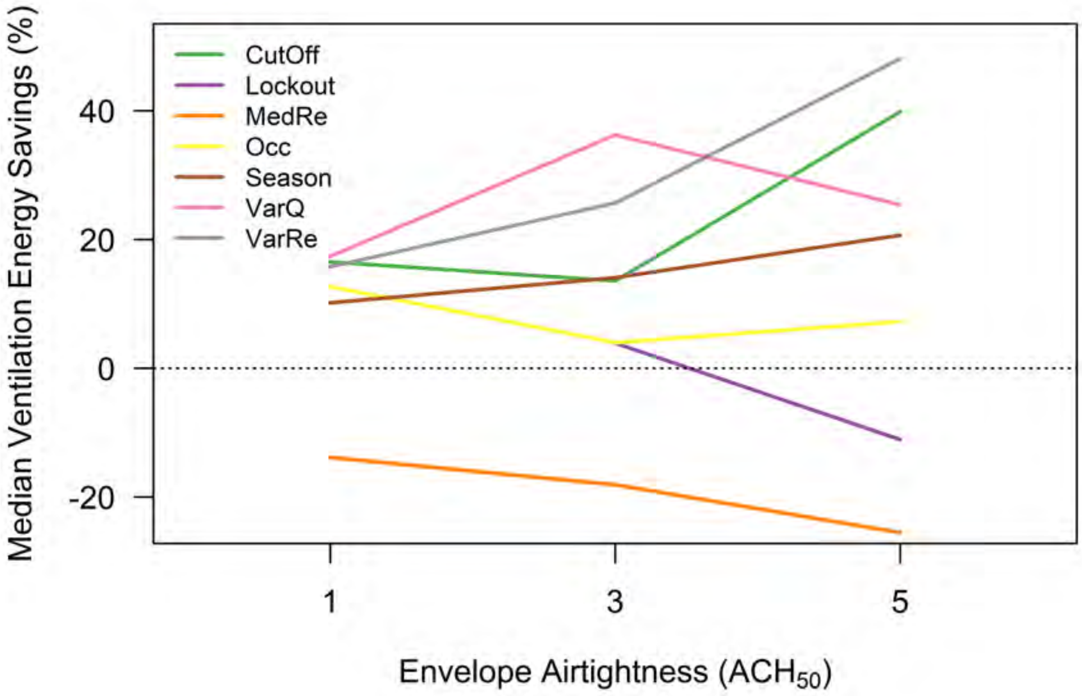


Figure 98 Median ventilation energy savings aggregated by airtightness and control type.

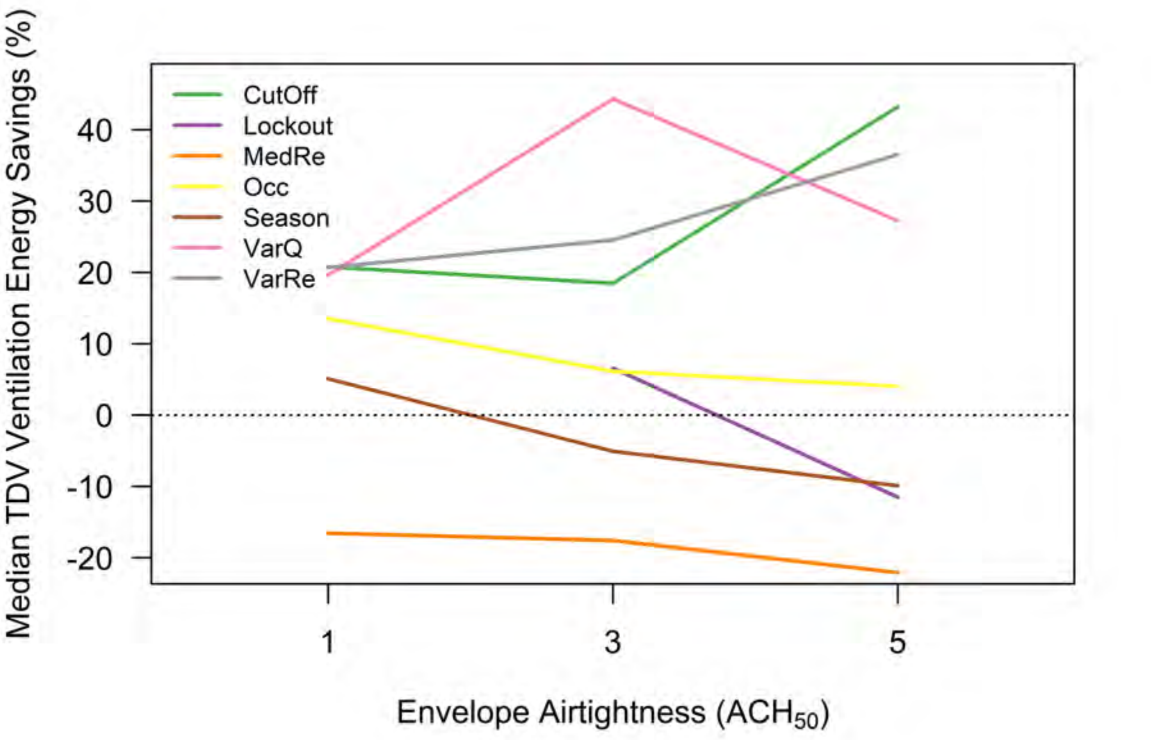


Figure 99 Median TDV ventilation energy savings aggregated by airtightness and control type.

Climate Zone

The SVC also varied a lot by climate zone, with CZ10 (Riverside) having the highest percent site energy ventilation savings for nearly all control types. CZ3 and 16 were generally similar in performance, while CZ1 had by far the lowest average savings across all control types. This relationship shifts when using TDV energy, with CZ3 (Oakland) generally having the greatest ventilation TDV energy savings across some control types (CutOff and VarRe), while others still had maximum savings in CZ10 (VarQ, Lockout and MedRe). Median TDV ventilation energy savings for VarQ were by far the greatest of all controls in CZ10 (median savings >60%), where most new home development occurs in the state. The next best control in terms of TDV savings had 20% lower median ventilation savings. The other CZ with large amounts of development is CZ3, and VarQ performs similarly in that location to the Cutoff and VarRe controllers.

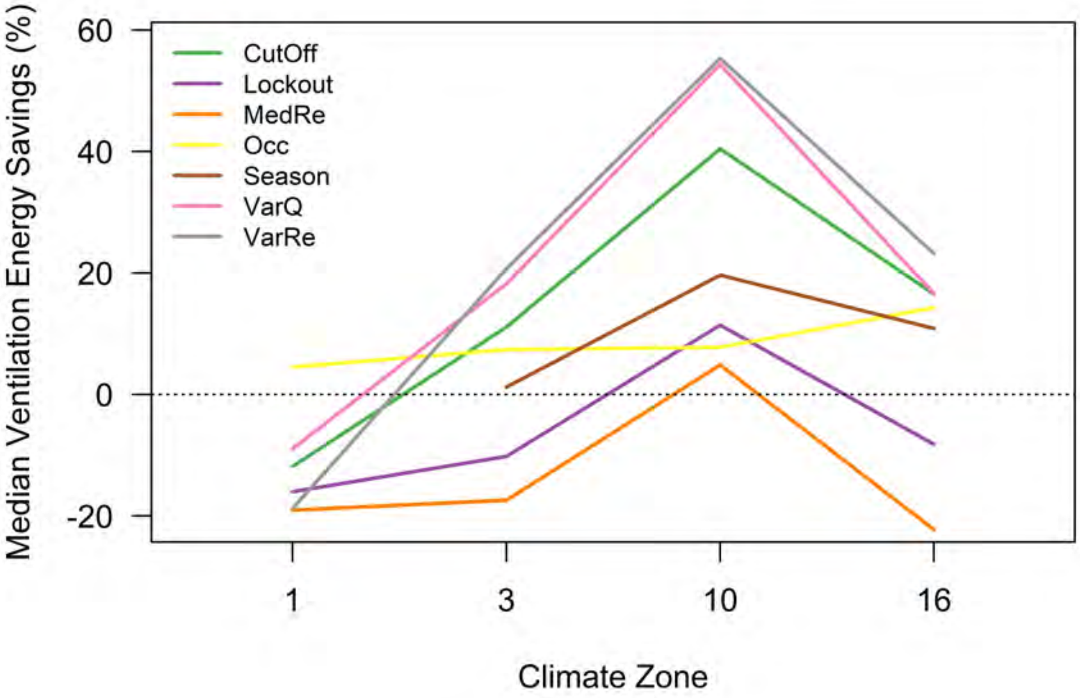


Figure 100 Median ventilation energy savings aggregated by climate zone and control type.

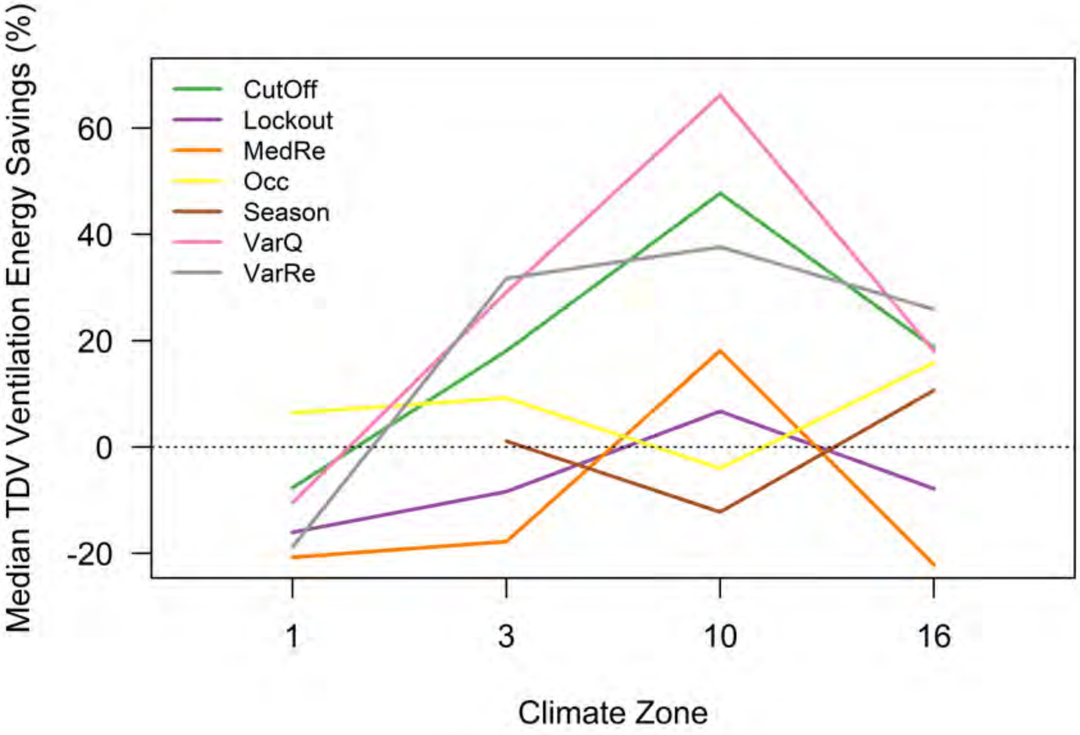


Figure 101 Median TDV ventilation energy savings aggregated by climate zone and control type. Prototype House

Prototype

Smart control performance also varied by the prototype house—2-story large (2,700 ft^2) vs. 1-story medium homes (2,100 ft^2). We show the median site ventilation savings for each control type and prototype home in Figure 102 (TDV savings in Figure 103). Both the VarQ and Lockout controllers have substantially greater median ventilation savings in the 1-story medium homes, which is true for both site and TDV energy. For site energy, all other controls have marginally improved performance in the 2-story large homes. The VarRe controller has reasonably stable ventilation savings for both prototypes in site and TDV energy, but its savings in the 1-story homes is more than 20% lower than the VarQ controller.

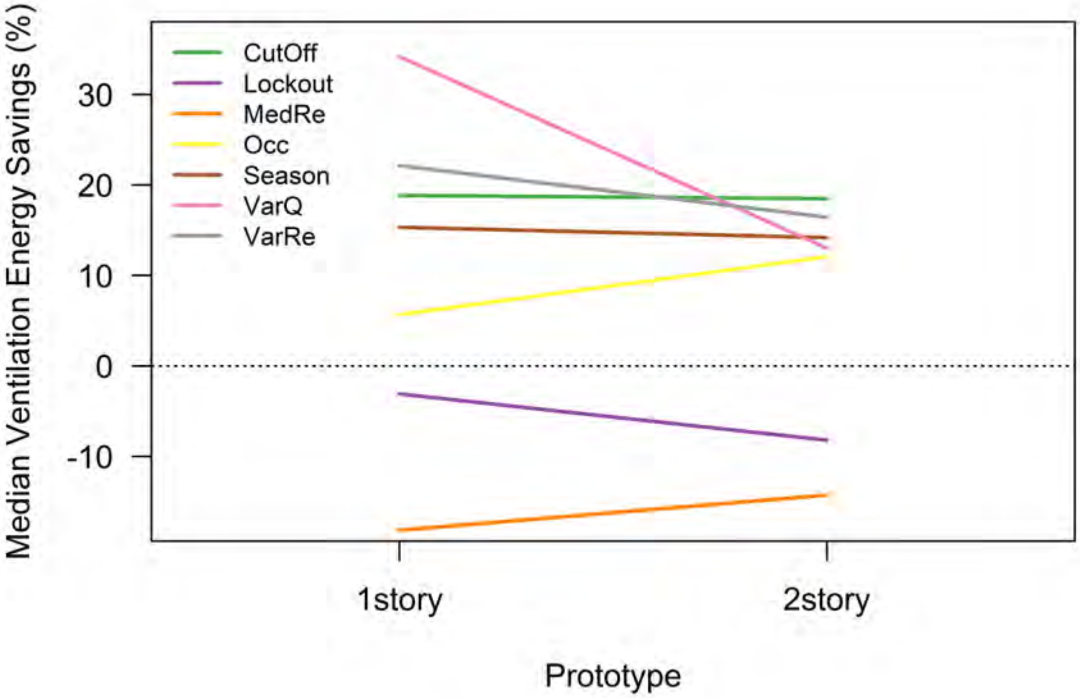


Figure 102 Median ventilation energy savings for each combination of control type and prototype.

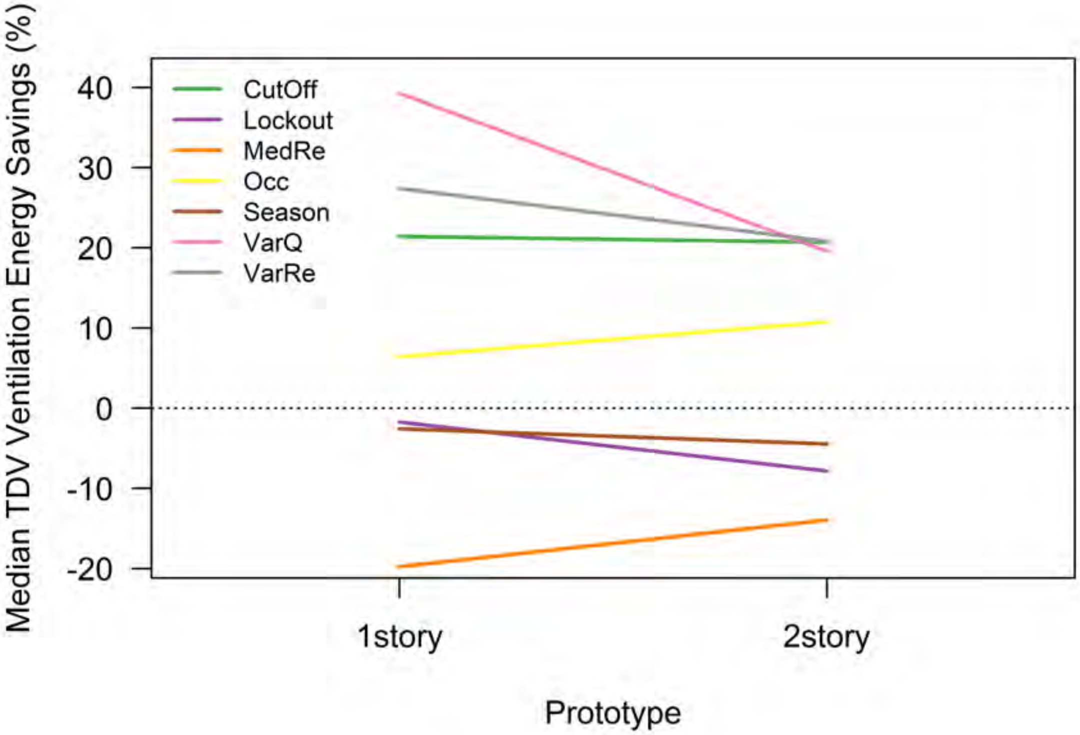


Figure 103 Median TDV ventilation energy savings for each combination of control type and prototype.

Currently Available Ventilation Controllers

The table below represents a market search for ventilation control technologies that are currently available and include some amount of controls based on sensing of temperature, humidity or other inputs. It does not include simple timer-based controls or controls that meet ventilation standards, but do not offer sensor integration with the controls.

Manufacturer	***Product/Model #***	***Cost***	***RH Sensor***		***Temperature Sensor***		***Main Link***	***"Smart" Control Functions and Description***
			In	***Out***	***In***	***Out***		
Field Controls	Fresh Air Ventilation Control	$100	x			x	https://www.fieldcontrols.com/fresh-air-ventilation-control?page_id=92	Control up to 4 appliances, including dampers, ERV/HRV, HVAC central blower and various exhaust fans. Climate modes: Normal, Hot, Cold or Disabled. They have relations of indoor RH and outside temperature at which they either eliminate all venting, restrict to 25% of target, or vent fully. Optionally monitoring bath and laundry exhaust, etc. using pressure or current sensors, which credits against airflow requirement! 30-minute ventiing decision. Hot Climate: off <25F, during heating but limited to 25% of target 25-32F, during heating only 32-40F, normal venting from 40-90F (with indoor RH limits), 25% 90-100F, off >100F. Cold Climate: off <0F, during heating but limited to 25% of target 0-25F, during heating only 25-50F, normal venting from 50-90F (with indoor RH limits), 25% 90-100F, off >100F. "Normal" Climate: off <17F, during heating but limited to 25% of target 17-25F, during heating only 25-40F, normal venting from 40-90F (with indoor RH limits), 25% 90-100F, off >100F.
Honeywell	TrueIAQ	$55	x	x	x	x	https://customer.honeywell.com/en-US/pages/product.aspx?cat=HonECC+Catalog	Controls humidifier, dehumidifier, whole house and local exhaust fans. ASHRAE 62.2 fan controls. Day/night timer-based ventilation. Manually enter # of bedrooms and floor area (or cfm for 62.2). Vent Shut Offs: 0=Auto vent regardless of outdoor conditions 1=Off at 75°F dew point or 99°F air temp 2=Low speed at 65°F dew point or 85°F air temp. Off at 75°F dew point or 99°F air temp Note: If option 1 or 2 is selected, then ASHRAE 62.2

							&pid=DG115EZIAQ/U	Standard will not be met.
Honeywell	Vision Pro IAQ	$280	x		x	x	https://forwardthinking.honeywell.com/products/thermostats/visionpro/visionpro_iaq.html	Controls humidifier, dehumidifier, whole house and local exhaust fans. ASHRAE 62.2 fan controls. Day/night timer-based ventilation. Manually enter # of bedrooms and floor area (or cfm for 62.2). There is an indicator on the thermostat saying it "P" or "F" 62.2. Ventilation control 0 No ventilation 1 Ventilation always allowed 2 Ventilation not allowed during sleep period 3 Vent all with lockouts 4 Vent off sleep with lockouts. Select high, low or both ventilation lockouts for temperature. 90 to 110 by 5F. -20 to 0F by 5F. Also, high indoor humidity control can increase ventilatino in heating mode.
Aprilaire	8126A Ventilation System	$165	x		x	x	https://www.aprilaire.com/whole-house-products/ventilation/model-8126a	CFIS only. 62.2-2010 target airflows. High and low temperature cutoffs. Humidity control with high indoor RH limit and corresponding behavior based on outdoor temp. Default is to turn venting off <0F, allow with heating operation between 0 and 20F, otherwise on but with humidity limits. Turns off >100F. Between 50 and 100F, humidity dependent with 55% indoor RH cutoff (so no ventilation "drying" is allowed). 90F high limit for "warm" climate setting. They've got good outdoor temp vs. indoor RH figures showing control operation.
Broan/Venmar	Altitude/Platinum Controller	$180			x	x	https://www.venmar.ca/224-accessories-air-exchangers-accessories-altitude-wall-	CFIS only. Low temp cutoff -40 to 32F. High temp cutoff 33 to 104F.

							control.html	
Broan/Venmar	X-Touch/Gold-Touch	$120	x			x	https://www.venmar.ca/508-accessories-x-touch-wall-control-40455.html	CFIS. Indoor RH controller increases AER when exceeding limits, manual tells user to turn this dehumidistat feature off during cooling season. One of five CFIS speeds is selected by the controller depending on combination of indoor RH and outdoor temperature.
AirKing	QuFresh	$260 (includes fan)		x		x	http://www.airkinglimited.com/page/qfam-fresh-air-machine.html	Supply Fan, 40-120 cfm. Energy Saving Mode, allows user to configure upper and lower limits for temp and rh
Build Equinox	CERV2	Unknown	x	x	x	x	http://www.buildequinox.com/cerv2/	Integrated CO2 and VOC measurement and ventilation control. Integrates on-board heat pump rather than traditional ERV heat exchanger, to provide boost heating/cooling in recirc mode. MERV13 standard filtration. Can recirc and condition, ventilate and condition, just ventilate, or turn off. Seems like there are CO2 and VOC thresholds set by user, which the system then controls to. This limit-based approach can be combined with scheduled or continuous ventilation, as well.
Broan/Venmar	FIN-180P	Unknown		x		x	http://www.broan.com/Fresh-Air-Systems/Su	Supply fan, 25-180 cfm. Continuous option, otherwise 5 comfort settings based on climate zone. A sophisticated algorithm selects the best time of the day for ventilation and takes advantage of air handler usage. MERV8 or MERV 13 filter. High and low cutoffs for outside temperature and dew point, vary by climate zone

							pply-Fan/Fresh-In%E2%84%A2-Supply-Fan/FIN-180P#resources	(covering CZ1-4). Low end 40F cutoff with 23F Dewpoint upper limit between 85 and 90F, dewpoints of 73-75F. There are separate temperature settings if a heating/cooling call exists, it looks like they preferentially ventilate during heating/cooling calls.
Ultra-Aire	DEH 3000/3000R	Unknown	x	x		x	https://www.ultra-aire.com/deh-30003000r/#health5c24-870a	Designed to integrate with the Ultra-Aire line of whole house ventilating dehumidifiers and allows homeowners to precisely monitor and control moisture levels, manage fresh air ventilation (with optional damper), and activate air filtration. Can lock dehumidifier in with or out when cooling calls occur. There is only a high temperature cutoff, no low temp option.
AirCycler	TempGaurd	Unknown				x	https://www.aircycler.com/pages/tempguard	Cold off temperature, 35F +/- 5F. Hot off temperature, 95F +/- 5F.

Table 38 Descriptions of currently available ventilation technologies that enable control based on temperature, humidity or other inputs. Note: none of these are designed to maintain equivalent exposure, as required by the ASHRAE 62.2-2016 ventilation standard.

APPENDIX C:
Multi-Zone Smart Ventilation Controls

Introduction

Overview of Single-Zone Work

LBNL has developed, documented and simulated a variety of single-zone smart ventilation controls methods, based on outdoor temperature, occupancy and auxiliary fan sensing, for a suite of homes built to the 2016 California Title 24 Prescriptive standards. The controls comply with the ASHRAE 62.2-2016 ventilation standard, including its equivalent exposure method for demonstrating compliance of smart ventilation-controlled systems (Appendix C in ASHRAE 62.2-2016).

Broadly, smart controls attempt to shift ventilation rates and times to save energy, improve indoor air quality (IAQ), and/or reduce operating costs, while ensuring that annual-average occupant exposure to indoor contaminants is equal to or less than would be expected for a constant ventilation rate using a fan sized to 62.2-2016 guidelines (i.e., relative exposure ≤ 1.0).

We used EnergyPlus to simulate the control strategies in the single-zone simulations, and to predict energy use. A CONTAM co-simulation predicted the dwelling airflows.

We simulated two prototype dwellings, each aligned with the CEC single-family prototypes —a 1-story 2,100 ft^2 home and a 2-story 2,700 ft^2 home. Envelope airtightness was chosen as 1, 3, or 5 ACH$_{50}$. Climate zones considered were CEC climates CZ1 (Arcata), CZ3 (Oakland), CZ10 (Riverside), and CZ16 (Blue Canyon). These reflect the variety of heating and cooling demands throughout the state. We modeled large-capacity fans for smart control cases, which generally allowed for double the airflow compared to the base case continuous fan prescribed by 62.2-2016.

As mentioned above, the continuous fan scenarios were taken as the baseline for energy and IAQ predictions, in order to compare to the smart control cases. In the analysis, predicted results from each climate zone were aggregated by weighting the outcomes by the projected new housing starts in that climate zone, in order to estimate state-wide impacts for new construction.

Broadly, the simulation results show that controller performance and benefits varied

- Smart controls were generally ineffective in CZ1 (Arcata), due to area's lack of a cooling season and its low diurnal temperature swing.
- Controls that shifted ventilation rates seasonally, rather than over the course of the day or month, were the most effective. These controls maintained lower overall ventilation rates during the heating season, and increased ventilation rates during the cooling season. The best controls also reduced ventilation during hot hours and increased ventilation during mild periods in the heating season.
- Although occupancy-based controls tended to reduce energy use by decreasing the net whole house ventilation rate, these controls were generally ineffective, because the overall energy savings were very low or marginal. Their performance improved somewhat when the control used a 1-hour pre-occupancy flush out period, but the savings were still marginal when compared to saving from temperature-based controls.
- Auxiliary fan sensing increased energy savings in all controllers, from roughly 5 to 15%, with smaller increases in the highest performing control cases. In other words, accounting for the operation of other exhaust devices in the home, such as bathroom or kitchen fans, improves energy use.
- Smart ventilation controls were more effective than increasing airtightness and operating continuous fans, because the ventilation standard increases the required IAQ fan airflow as infiltration is reduced. This practice limits the energy benefits of air sealing.
- The most successful smart controls used parameters pre-calculated by an optimization routine. These reduced the weighted average site ventilation energy use by 41 - 51%. Time-dependent valuation (TDV) weighted average ventilation energy reductions were higher, at 36 - 61%. Peak demand from 2-6pm on the hottest days of the year was reduced through the use of the smart controls, with peak load reductions up to 300 watts. We believe that specific peak controls could achieve even greater reductions in demand.
- The vast majority of site energy savings were for heating end-uses (>90% of total savings), while TDV energy savings were split more evenly between heating and cooling.
- Smart controls reduced the average occupant pollutant exposure by 0-10% (improved IAQ). However, they commonly increased peak exposures, with some controls allowing much higher peaks than others.
- Whole house ventilation rates increased on average by roughly 40% for the best control types. This increases fan energy use and could increase indoor levels of outdoor contaminants in some cases.

IAQ and exposure are not identical across all cases, so we also normalized energy savings by relative exposure in order to approximate energy use for equivalent IAQ. After this normalization, weighted average site ventilation savings for the best outdoor temperature-based control types tended to be 56 - 64% compared to the baseline (TDV ventilation savings between 51 - 68%).

More work is required in order to allow builders and designers to take credit for smart ventilation control strategies in demonstrating compliance with California's Title 24 Building Energy Code. The simplest approach may be to modify CBECC-Res so that it can support user-input variable ventilation rates, which could be pre-calculated by manufacturers or design teams for specific control types.

Introduction to Multi-Zone Smart Ventilation Control

In homes that use a central air handler to distribute heating and cooling through ductwork, the home is effectively well-mixed during system operation. This is the most common heating and cooling configuration in new California homes. Typical airflows through the central AHU are 5-6 house air changes per hour in recirculation, which dominates most inter-zonal and outdoor airflow rates. Other mixing mechanisms include natural infiltration and buoyancy-driven flows (Sherman & Walker, 2010). As a result, during system operation, contaminant concentrations are nearly uniform throughout the home. This means the house can be realistically treated as a single zone from a ventilation and IAQ perspective. Our single-zone work, summarized in the prior section, follows this assumption (as do U.S. ventilation standards).

Nevertheless, many homes in the U.S. are not well-mixed, instead exhibiting zonal ventilation and IAQ behavior. These homes either do not use a central AHU to distribute heating and cooling, or they use smaller equipment that operates less frequently than was previously common in residences. For example:

- Some new and existing homes in colder climates use hydronic boiler systems built upon either traditional radiators or in-floor tubing. These homes have no mechanical mixing of interior zones (outside of cooling operation, if provided).
- Mini-split heat pumps are gaining popularity in high-performance homes in the U.S., largely due to their high efficiency, variable output, low capacity (for highly insulated homes), quiet operation, and elimination of ducting (which saves cost, time, space, and diagnostic testing). These systems provide multiple indoor head units that condition individual zones. While they do move air, they do not force inter-zonal mixing.
- Many multifamily residences use point-source heaters, such as gas-fired wall or floor furnaces, which do not contribute significantly to inter-zonal mixing.
- Many new high-performance homes with ducted AHU systems have much less runtime (due to improved envelopes) and lower airflows than were common in older generations of homes. This could particularly be the case in mild climates, like California. They also have lower natural infiltration rates and less mixing due to internal flows induced by natural ventilation. This means they may not be as well-mixed internally, and they may act as zonal homes for many hours of the year.

- In a subset of new, advanced homes, zonally-distributed ventilation systems are already common, with supply outlets and exhaust inlets located strategically throughout the home. The common approach in these advanced homes (e.g., Passive House or the like) is to exhaust air from "wet" rooms—like the kitchen, bathrooms and laundry—and to supply ventilation air to all other locations.

Given these trends, zoned ventilation and IAQ may be a reality in new homes of the future, as well as in certain types of existing homes. This presents an opportunity to reduce ventilation energy use, while providing equivalent health and IAQ for occupants. For example, if zones are reasonably well isolated from one another, then a ventilation system could be controlled to only ventilate occupied zones (just as a single-zone home can have its ventilation rates reduced when occupants leave the house). Such a system should further reduce ventilation rates during occupied periods, because it will only serve the occupied zones.

Many countries formulate their ventilation requirements in residences around room-by-room airflow requirements. For example, Canada's CAN/CSA-F326-M91 (2010) standard (CAN/CSA, 2010) requires supply of 10 L/s in master bedrooms and 5 L/s to all other room types, including other bedrooms, living room, dining room, family room, recreation room, kitchen, bathrooms and laundry. It also allows exhaust flows from kitchens, bathrooms and laundry rooms at a continuous rate of 30 L/s in kitchens and in bathrooms (10 L/s each). If both outdoor air supply and exhaust flow rates are measured, the total minimum ventilation capacity for the dwelling is taken as the larger of the two values. Total rates of flow can be determined by summing the flow rates through each component of an outdoor air supply or exhaust system.

As noted above, homes that are zoned from a ventilation and IAQ perspective, whether explicitly or effectively, are becoming a reality in the US. At the same time, the ventilation equipment currently installed in very efficient new homes distributes ventilation airflows zonally (since this is considered essential in very airtight dwellings). Like the Canadian example above, codes and standards in other countries already specify their dwelling mechanical ventilation requirements in terms of airflows to specified zones, recognizing the need and value of this approach. A smart controlled zonal ventilation system may be able to take advantage of the unique characteristics of zoned dwellings, and zonal occupancy patterns in those dwellings, to drastically reduce the energy use associated with ventilation and good IAQ.

Methods

EnergyPlus/CONTAM Simulation Framework

Each scenario (i.e., each combination of home prototype, airtightness, climate zone, controller, and so on) was simulated using EnergyPlus (v9.1.0). EnergyPlus delegated its airflow predictions to CONTAM (v3.3) at each time step, via its Functional Mockup Unit (FMU) interface. CONTAM also predicted the transport of all species except moisture. The CONTAM model development process and inputs are detailed in Appendix Supplementary Appendix: Creating CONTAM models for SVACH multi-zone study.

These simulations were run by a framework that managed the input data, provided runtime support for the simulation tools, and saved and analyzed the output. The simulation framework comprises a selection of individual tools, each targeted at specific tasks. This section broadly describes these tools and how they interact.

A version control system was used to develop the tools, and to make them available for follow-on work. This source code repository also stores: (1) static input files, such as weather and outdoor contaminant files; (2) EnergyPlus input files that define the prototypes; (3) EnergyPlus Runtime Language (Erl) code that defines the controllers; and (4) detailed documentation on setting up and running the framework.

Input Preparation

The software repository contains scripts (i.e., high-level code) and documentation that prepare inputs for the multi-zone simulations. These include:

- Scripts for generating schedules. The schedules define time-dependent inputs such as occupant locations; door opening positions; and heat and pollutant generation due to showering, cooking, and background activity.
- Scripts for generating scenario files. Each scenario selects a particular combination of building prototype, building leakage, building control scheme, climate zone, and so on. Thus defining a scenario for EnergyPlus requires choosing the corresponding input files and input parameters. A scenario file stores the choices for one or more scenarios.
- Scripts for converting files of outdoor concentrations to CONTAM format.
- Scripts for calculating CONTAM inputs such as wind pressure profiles, contaminant properties, leakage areas, and zone volumes.
- Documentation on creating the CONTAM models.
- Tables of final leakage parameters. Each CONTAM model gets tuned, by hand, to one or more desired leakage levels. These tables store the final input parameters, for use when populating the CONTAM FMUs.
- Documentation on creating a CONTAM FMU from a CONTAM input file. The FMU contains the input file, plus configuration information and library code that allow EnergyPlus to interact with CONTAM.

- Scripts for modifying an existing CONTAM FMU, in order to produce multiple FMUs that differ by leakage level and simulation times (to support testing). These scripts also generate FMU control files, which contain the EnergyPlus input configurations needed to run a particular FMU.

Runtime Support

The repository contains scripts that run the scenarios generated during the preparation step. These include:

- A script for verifying inputs. The repository does not store input files generated by scripts (such as the scenario files), or files that contain large blobs of binary data (such as the FMUs). To ensure that a simulation uses the most recent versions of these files, a script checks these files against the expected summary checksum.
- A script for generating EnergyPlus input (IDF) files. The script reads a scenario file, verifies inputs, and assembles one IDF file for each scenario. The resulting IDF file contains the schedules, parameters, and Erl control code specified by the scenario. In addition, embedded comments list the weather and outdoor concentration files to use at runtime (which vary by climate zone).
- A script for running EnergyPlus simulations. The script brings together the IDF file, FMU, and specified runtime inputs, then runs the simulation and saves selected output files for later inspection. It also isolates the EnergyPlus runs, to enable parallel execution.

Post Processing

The repository contains scripts that post-process the simulation results. This includes creating figures, extracting summary data from the detailed (timestep-level) output, and aggregating the summary data across simulations.

Prototype Dwellings

We developed the model input parameters for three prototype dwellings—1-story single-family, 2-story single-family, and a multi-family apartment unit. All home prototypes were designed to match, as well as possible, the prescriptive requirements contained in the Title 24 2016. Where possible, we also included any new requirements for envelope insulation performance in the 2019 code documents. These are described in further detail in the Methods sections of Appendix B: Single-Zone Smart Ventilation Controls.

The apartment prototype dwelling is treated uniquely, in that all but one of its exterior surfaces are treated as adiabatic and without any leakage to outside or adjacent apartment units. The assumption is that adjacent units are identically conditioned, so heat transfer across the party-wall/floor surfaces is zero, and that the apartment is perfectly compartmentalized (i.e., isolated) from the adjacent units. These assumptions fundamentally affect the thermal, ventilation and IAQ performance of the apartment unit prototype. For example, when exhaust flows are specified in each zone of the apartment unit, some of those zones have no leakage paths to outside, so the make-up air for the exhaust flows must come from other zones that do have leakage paths to outside. In future work, we will explore the potential impacts of inter-unit leakage across walls, floor and ceiling for multi-family apartment units, and we will also explore a variety of configurations for hallway supply ventilation paired with apartment unit entrance door under-cuts.

The prototype dwellings were divided into at least four individual conditioned zones and one unconditioned attic zone (for single-family dwellings only) in each simulation tool, comprising:

- Kitchen (kit)
- Bathrooms (wet)
- Bedrooms (brm), all bedrooms in the single-family dwellings and the adult bedroom in the apt dwelling.
- Child's bedroom (brc), the children's bedroom only in apt prototype.
- Common (com)
- Family room (fam), the upstairs common area, only in the 2-story prototype.
- Attic (atc)

These zones were selected for a number of reasons. First, we separated zones that contain known point sources of contaminant emissions in homes, specifically the bathrooms (CO_2, water vapor and VOCs from personal care products) and the kitchen (cooking contaminants, including CO_2, NO_2, $PM_{2.5}$, and Acrolein). Simulating these as separate zones allowed us to coordinate the release of contaminants in those zones that experience episodic events, such as cooking and bathing. The zone concentrations can then reflect trends measured in occupied homes (e.g., peaks in cooking-related contaminants during cooking events in/near the kitchen, which then disperse to other zones).

Second, we separated the bedrooms from the other areas of the home, because many multi-zone controllers used an occupancy signal, and the bedroom is a common location where occupants spend relatively predictable and prolonged periods of time.

All remaining locations were lumped together as either "common" or "family" areas. These represent locations with no particular expected point-source pollutant emissions, and with no predictable continuous occupancy patterns.

The total conditioned floor area for each CEC prototype was apportioned to each of these zones using mean values estimated for new home construction in the U.S., based on builder surveys developed by the National Association of Home Builders (Emrath, 2013). The floor area fractions for each zone are listed in Table 1. Table 2 aggregates these areas together to align with the four (or five) zones in the models. For the multi-family apartment prototype, we adjusted the fractions slightly, by cutting in half the bathrooms/laundry zone (from 16% to 8% of total fractional floor area), and adding this floor area to the bedroom zone (from 28.8 to 36.8%). This was done to reflect typical bathroom sizes in a one-bathroom apartment with a very small laundry area with stacked washer/dryer units, as opposed to a laundry room as found in the SFD prototypes. Dimensioned floor plans are shown for each of these three prototype dwelling units in Figure 1 through Figure 4.

Table 1: Floor Area Distributions For Each Zone And Prototype.

Space Type	*Floor Area Fraction (%)*	*1-story Prototype (ft^2)*	*2-story Prototype (ft^2)*
Master Bedroom	12	252	324
Master Bathroom	6	126	162
Other Bedrooms	16.8	352.8	453.6
Other Bathrooms	6.3	132.3	170.1
Kitchen	11.6	243.6	313.2
Family Room	11.5	241.5	310.5
Living room	8.6	180.6	232.2
Dining Room	7.4	155.4	199.8
Foyer	3.4	71.4	91.8
Laundry	3.7	77.7	99.9
Other	12.7	266.7	342.9
TOTAL	**100**	**2100**	**2700**

Table 2: Aggregated Fractional Floor Area For Each Zone And Prototype.

Zone	*1-story Prototype, Floor Area Fraction (%)*	*1-story Prototype (ft^2)*	*2-story Prototype, Floor Area Fraction (%)*	*2-story Prototype (ft^2)*	*Apartment Floor Area Fraction (%)*	*Apartment Prototype (ft^2)*
Bedrooms	28.80%	604.8	28.80%	777.6	26.62%	231.6
brc	0.00%	0.0	0.00%	0.0	10.18%	88.6
Wet Rooms (Bath and Laundry)	16.00%	336.0	16.00%	432.0	8.00%	69.6
Other	43.60%	915.6	34.69%	936.7	43.60%	379.3
fam	0.00%	0.0	8.91%	240.5	0.00%	0.0
Kitchen	11.60%	243.6	11.60%	313.2	11.60%	100.9
TOTAL	**100.0%**	**2100**	**100.00%**	**2700**	**100.00%**	**870**

Figure 1: 1-story Single-family Detached Prototype Floor Plan, Includes Zoning And Dimensions. 2,100 ft^2.

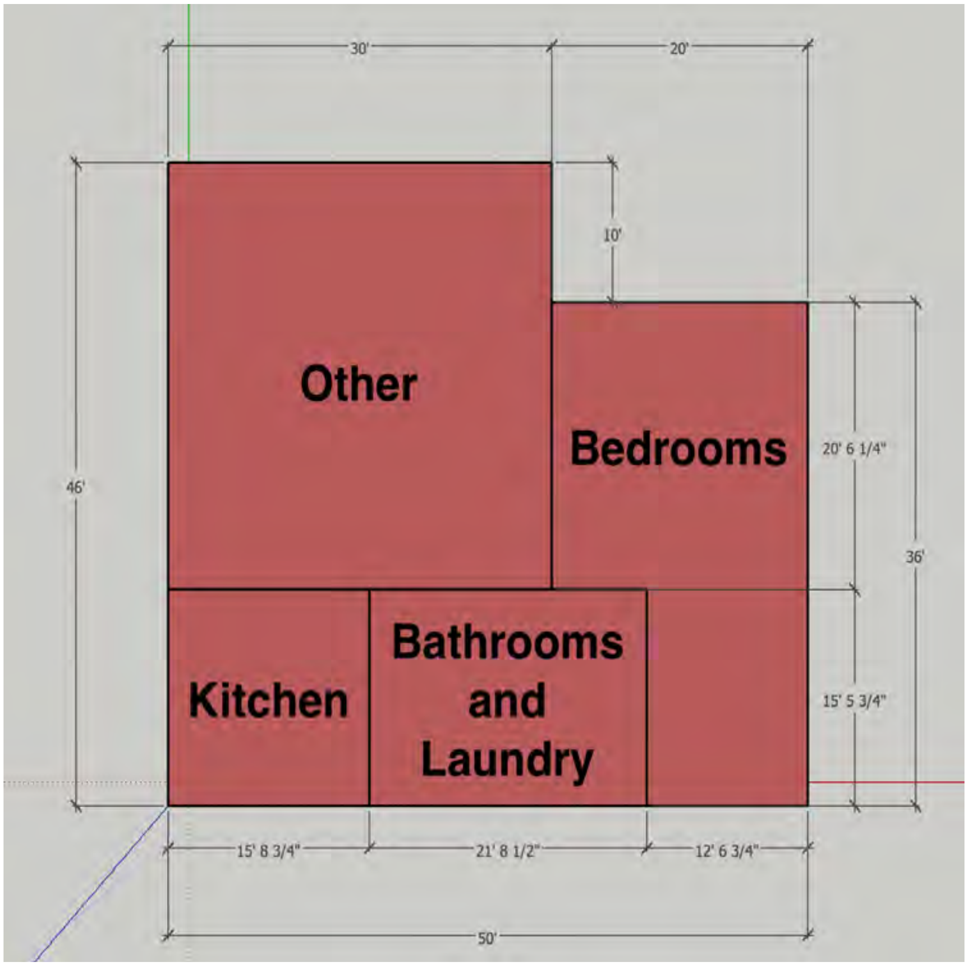


Figure 2: 2-story Single-family Detached Prototype Floor Plan, Level 1. Includes Zoning And Dimensions. 2,700 ft^2.

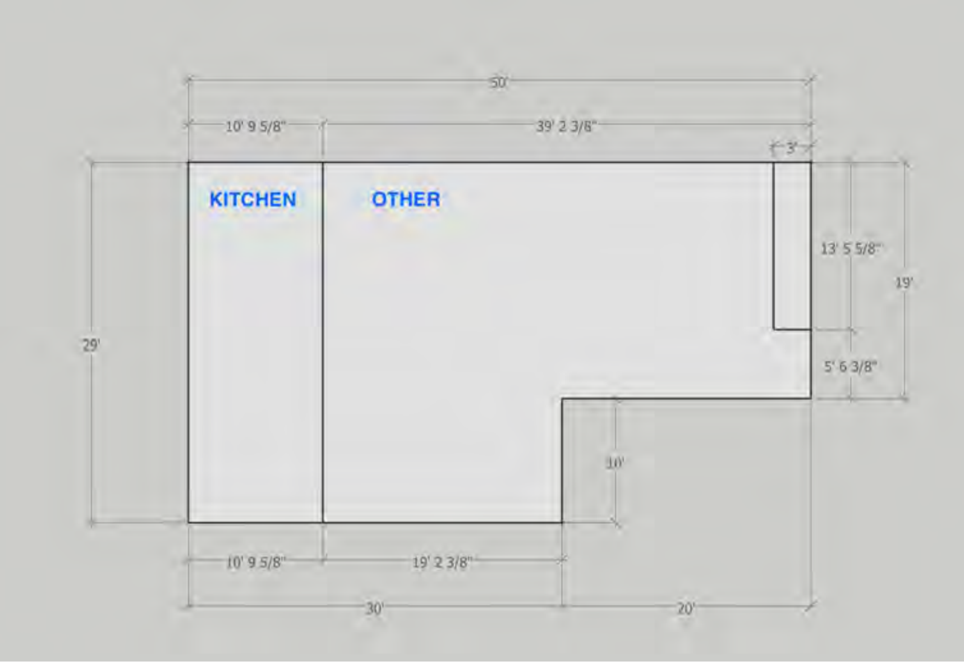
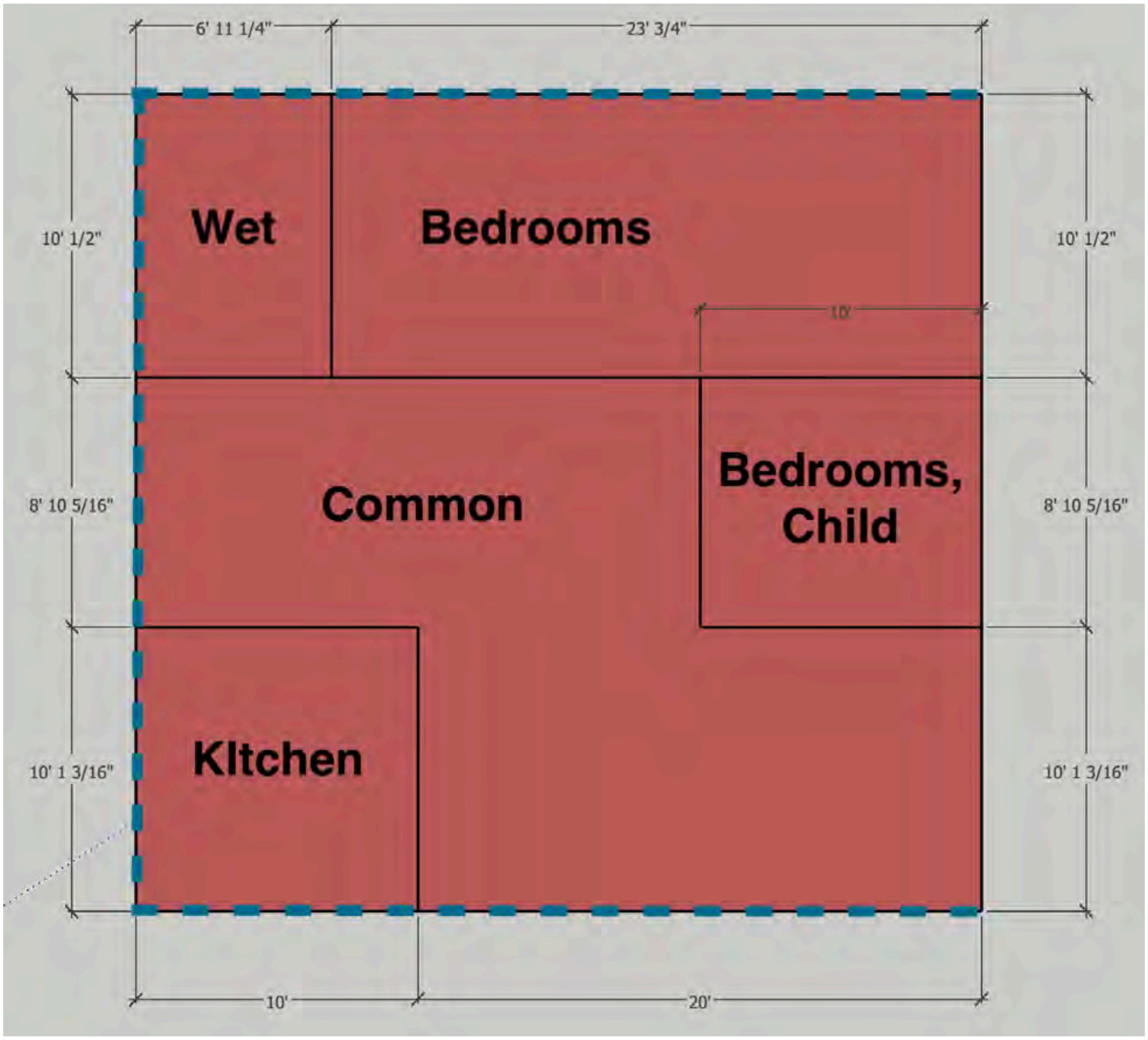


Figure 3: 2-story Single-family Detached Prototype Floor Plan, Level 2. Includes Zoning and Dimensions. 2,700 ft^2.

Figure 4 Multifamily Unit Prototype Floor Plan, Includes Zoning And Dimensions. 870 ft^2. Blue Dashed Lines Are Adiabatic, Sealed Surfaces.



Envelope Leakage and Leakage Distribution

As in the single-zone simulation phase, the dwelling envelope leakage rates were varied across expected ranges for current and future California dwellings. This produced dwellings with leakages of 0.6, 2, and 3 ACH_{50}. The envelope leakage for the multifamily prototype apartment unit was chosen as 3.5 ACH_{50}. Only a fraction of that leakage will be in envelope elements connected to "outside", such that the leakage area for the dwelling is more similar to the 0.6 ACH50 single-family cases.

The total leakage areas to outside (or the attic)—and their distribution between walls, floor and ceiling—was similar, but not identical, to those for the single-zone models used in phase one of SVACH. The envelope leakage in the zonal CONTAM airflow model was distributed based on the zone sizes, including fractional floor areas and exterior and interior wall lengths. See Appendix Supplementary Appendix: Creating CONTAM models for SVACH multi-zone study for more information.

Leakage paths included those between the conditioned zones and outside (or the attic), as well as inter-zonal leaks between adjacent conditioned zones (e.g., from bedrooms to wet rooms).

Leakage to outside (or the attic) included:

- Ceiling between the occupied zones and the unconditioned attic.
- Exterior Above Grade Walls, including leaks at the bottom plate.
- Note for the apartment, the leakage is in the exterior walls only.

Inter-zonal leaks included:

- Interior doors, as enumerated below. The door dimension will be 81.3 cm by 203.2 cm (32" by 80"). Each interior door will have a 2 cm height undercut leak (162.6 cm^2) that exists whether or not the door is open or closed.
- Partition walls separating zones horizontally. The adventitious (i.e., unintentional) leakage area rate is 2 cm^2 per 1 m^2 of the inter-zonal surface area. These unintentional leaks are distributed vertically from floor to ceiling, similarly to the leaks in the exterior above grade walls.
- Ceiling/floor interface between conditioned zones in the 2-story prototype. This ceiling/floor interface will have leakage areas sized at 2 cm^2 per 1 m^2 of the inter-zonal surface area.
- Stairwell will be included in the 2-story prototype home, connecting the lower and upper conditioned zones. Standard stairwell dimensions will be used of 91.4 cm by 410.5 cm (36" by 13′5-⅝"). Stairwell is modeled in CONTAM as a large opening in the floor of the second story (i.e., not using a stairwell model as would be appropriate for a commercial building)

All prototypes had the following interior doors between zones:

- Double-wide, non-operable door between Kitchen and Common

- One between Bedrooms and Common
- One between Bathrooms/Laundry and Common
- One between Bedrooms and Bath/Laundry

Kitchen-to-Other Zone Bi-Directional Mixing Fans will be placed in the CONTAM models as a means to model the mixing between the Kitchen and adjacent Common zones. In most new homes, the kitchen is contiguous with other spaces in the home, and while contaminants are emitted from cooking into the kitchen, there is reason to think those not removed directly by a vented range hood mix rapidly with adjacent volumes, rather than remaining localized in the kitchen. The mixing fans mimic this behavior by moving air to and from each of these zones, at rates determined to provide turnover mixing time of ten minutes. In the future, this will also allow us to estimate impacts if the kitchen were more physically separated, as in a traditional galley kitchen with a door that closes.

For the apartment, the leakage is in the exterior wall portions only and not in walls/floors/ceilings to adjacent apartments, i.e., we assume ideal compartmentalization. In future work, an additional apartment leakage site is a door undercut (or vent) to a common corridor for high-rise.

Vented attic leakage includes two types:

- Intentional builder-installed vent openings, sized at a ratio of 1 cm^2 for every 300 cm^2 of ceiling area. These vent openings are located at low and high locations along the sloped roof surfaces, roughly at soffit and ridge heights.
- Unintentional attic leakage that represents additional leaks not purposefully placed by the builder. These are sized as 0.3% of ceiling area. They are distributed at mostly at eave height, and at two locations vertically along the sloped roof surfaces.

Effective Moisture Penetration Depth Moisture Modeling

In order to model the buffering of moisture levels by indoor materials, we used the EnergyPlus Effective Moisture Penetration Depth (EMPD) model, which provides a 2-layer moisture sorption model for materials in each zone. We chose this model, versus a more common one-layer isotherm model, because recent research has shown that it provides better moisture predictions in occupied dwellings (J. Woods, Winkler, & Christensen, 2013; Jason Woods & Winkler, 2018; Jason Woods, Winkler, & Christensen, 2013).

To implement the EMPD model, we used an alternative heat balance algorithm in EnergyPlus (*MoisturePenetrationDepthConductionTransferFunction*). All materials that interact with the air moisture content were specified following the EnergyPlus example file "MoistureMaterials.idf". For example, the soft furnishings moisture settings were set to be identical to those for the Carpet material in the MoistureMaterials.idf file.

Materials that were specified to interact with the zone moisture balance include:

- Exterior walls
- Carpeted floors
- Ceilings
- Attic floor
- Roof deck
- Interior partition walls
- Soft furnishings
- Wood furnishings

Some materials and building surfaces were explicitly specified as part of the model geometry (e.g., exterior walls, interior partitions, floors, ceiling). The remaining surfaces (e.g., soft and hard furnishings, non-explicit interior partition walls) were estimated using typical surface area to volume ratios from the research literature (Manuja, 2018; Manuja et al., 2019), which were broken down for empty rooms and for fully furnished spaces. The values from Manuja et al. were used to estimate the total expected surface area in each conditioned zone as if it were empty (Table 3) and if it were fully furnished (Table 4). The estimated surface area for an empty room was deducted from the surface area estimates for fully furnished spaces, and the difference was taken to be the miscellaneous surfaces in each zone. This miscellaneous surfaces were treated as 66% hard wooden furniture and 33% soft furnishings.

The floor surface of each zone was assigned to be carpet, and the remaining empty room surface area estimate was assigned as painted sheetrock. The painted sheetrock was split between explicitly modeled surfaces, and non-explicit partitions, which were sized as the difference between the expected total sheetrock surface and the explicitly modeled surface areas in each zone.

Table 3: Empty Room Surface Areas for Each Prototype Zone, Using Multiplier Of 1.8 m^2/m^3 From Manuja et al. (2019).

Zone	1-story Prototype (m^2)	2-story Prototype (m^2)	Apartment (m^2)
Bedrooms	277.1	356.3	94.4
Bedroom, Child	0.0	0.0	36.1
Wet Rooms	154.0	197.9	28.4
Common	419.5	429.2	154.7
Family	0.0	110.2	0.0
Kitchen	111.6	143.5	41.2
TOTAL	**962.2**	**1237.1**	**354.8**

Table 4: Fully Furnished Room Surface Area for Each Prototype Zone, Using Multiplier of 3.2 From Manuja et al. (2019).

Zone	1-story Prototype (m^2)	2-story Prototype (m^2)	Apartment (m^2)
Bedrooms	492.7	633.4	167.9
Brc	0.0	0.0	64.2
Wet Rooms (Bath and Laundry)	273.7	351.9	50.5
Other	745.8	763.0	275.0
Fam	0.0	195.9	0.0
Kitchen	198.4	255.1	73.2
TOTAL	**1710.6**	**2199.3**	**630.7**

Climate Zones

As in the single-zone work, the climate zones were CZ1, 3, 10 and 16, in order to cover a range of climatic conditions. EnergyPlus weather files were developed that included the weather data contained in the CBECC-Res weather files used to demonstrate residential code compliance. This weather data will not be aligned in any specific way with outdoor contaminant levels, aside from water vapor, which varies in the weather files.

Space Conditioning Systems and Filtration

Two heat pump HVAC system types are simulated in this work—VRF mini-split heat pumps (VRF) and ducted air handling unit heat pumps (HPfau). We expect both types of HVAC to be relevant in the foreseeable future, and both are candidates for saving energy through zonal ventilation control. The HPfau represents the vast majority of current new home construction in the state, with a central air handler that distributes heating and cooling through a system of supply ducts to each zone, along with a single, centrally-located return duct. Notably, most new systems in the state use gas furances and not heat pump technology for space heating. The VRF system represents homes that do not have central forced air systems, and are instead served by distributed heating and cooling. Two all-electric system types were chosen as representative of future HVAC equipment in the state's homes, as the building stock becomes more electrified. Furthermore, using electric heat pumps in both cases allows more direct comparison of central forced air vs. distributed HVAC technologies. All HVAC systems were sized using the EnergyPlus auto-sizing feature, to ensure the equipment matches the loads presented in a given case. The elimination of gas furnaces from the prototype dwellings marks a substantial departure from the single-zone simulation work. Total HVAC site energy use is substantially reduced through use of heat pumps (leading to lower site energy savings), and TDV energy is also dramatically altered by use of electricity for heating.

System efficiencies (e.g., COP) were specified identically between these two system types, though the system models embedded in EnergyPlus result in different performance, as does the use of a ducted air handler in the HPfau systems. The gross heating COP was 3.4 for both system types, and the gross cooling COP's were 3.75 (a cooling COP of 3.95 was used in the single-zone work). While their efficiencies are intended to match one another, these system types differ in three important features: (1) thermostat location; (2) tendency for inter-zonal mixing; and (3) filtration.

Thermostat locations differ between HPfau and VRF systems. A single thermostat in the Common zone controls the HPfau system, and a call for heating or cooling in that location conditions all zones concurrently, regardless of their current needs. For example, a west-facing zone could over-heat due to solar gains through windows in the afternoon, without triggering the thermostat in the adjacent Common zone. In contrast, VRF systems have a thermostat in each occupied zone, and direct heating/cooling only to the zones that request it. This system type would deal with unbalanced loads throughout the dwelling more consistently, which presumably leads to less over- or under-conditioning.

Despite their differing locations, all thermal zones were controlled using the same thermostat schedule, as specified for demonstrating residential compliance with Title 24. We recognize that thermally zoned homes with zonal ventilation systems and occupancy sensors might very well benefit from controlling the zones to different temperatures, depending on their occupancy status. For example, a system could preferentially condition the bedrooms during sleeping hours, while allowing a deeper setback in the other zones. Nevertheless, we used fixed thermostat controls, to avoid confounding the observed impacts of the ventilation controls. However, we note this as a potential avenue for future investigations and deeper energy savings.

Thermostat and HVAC equipment behavior was modified in order to better reflect system cycling that occurs in actual residential HVAC systems. By default, EnergyPlus will continuously vary the heating or cooling delivered by the HVAC system in order to exactly meet the loads presented in a given time-step. This fixes the indoor temperature exactly at the thermostat setting. In order to induce system cycling and natural temperature fluctuations, we created a special control that forces the HVAC system to be completely off, until it falls below its thermostat dead band (0.55°C), at which point it operates at 100% capacity until it rises above its dead band temperature.

HPfau and VRF systems also differ in their tendency to induce **inter-zonal mixing airflows** between zones. An HPfau system has a central air handler, with supply outlets in each zone, and a single return inlet in the Common zone. When it operates, this system pressurizes the supply zones, and depressurizes the Common zone. The resulting pressure imbalance induces inter-zonal flows, typically from supply zones to the common return zone. They can also induce infiltration or exfiltration in the zones, as some of the pressure differences are relieved through envelope leakage paths rather than inter-zonal leakage paths. This is particularly true when interior doors are closed, such as during sleeping periods or when bathrooms are occupied. Closing the door to a pressurized zone will increase its exfiltration to outside, and the Common zone containing the return inlet will have increased infiltration. The VRF system, by contrast, does not induce any circulation or air flow throughout the zones in the dwelling. Nor does it induce pressure differencess between zones. For this system type, inter-zonal flows are driven only by temperature differences between zones, wind pressures, and auxiliary fans (e.g., for bathroom or kitchen ventilation). We expect that for VRF homes, zone mixing will be reduced, and pollutant concentrations will be less uniform throughout the dwelling. HPfau dwellings should be more mixed and have more uniform pollutant concentrations, though this will depend on HVAC system runtime and system flow rates, both of which might be quite small in low-load, high-performance new dwellings in California climates.

Filtration differs between HPfau and VRF systems, since, as required by the 2019 Title 24, the HPfau systems and outdoor air supplies will be equipped with MERV 13 particle filtration that removes particles whenever the system operates. The recirculating flows through the VRF mini-split heat pump head units are treated as having no removal efficiency for PM2.5 due to their limited ability to accommodate MERV 13 filters.

The HVAC systems were created in EnergyPlus using the HVAC Template object. The templates were copied (and then edited) from the EnergyPlus v9.1 Input Output Reference. The Variable Refrigerant Flow Mini-Split Heat Pump system used three templates: the VRF System template, the VRF Zone template, and the Thermostat Template. The Heat Pump with Forced Air unit used the Heat Pump System Template, the Unitary Zone Template, and the Thermostat Template. The ExpandObjects EnergyPlus tool was used to generate executable EMS code to represent the HVAC systems. For SVACH, we ran ExpandObjects through the EPlaunch utility, and then copied the content from the .expidf file into our permanent .imf files.

The objects created by the ExpandObjects utility include the Zone Terminal Units and the VRF System for the VRF system. The HPfau system included the Unitary Heat Pump, DX Cooling Coil, DX Heating Coil, and Supplemental Heating Coil objects.

Whole Dwelling Ventilation Airflows and Flow Targets

Whole house target and mechanical fan airflows were calculated using the ASHRAE 62.2-2016 ventilation standard. These whole-house flows were divided among the occupied zones, proportional to their floor area fractions, as in Table 5. Mechanical flows will be less than this, because of credit taken for infiltration. These do not include local exhaust flows specified in ASHRAE 62.2 for kitchens and bathrooms. Methods for sizing and assessing zonal ventilation systems are not currently included in the ASHRAE standard or in California Title 24 Building Energy Code. Therefore, this approach represents our best effort at a zonal extension of the approaches currently specified by the governing standards.

The mechanical ventilation fan flow requirements for the whole dwelling were calculated for the single-family prototypes including reductions using the infiltration credit based on envelope airtightness following the procedures in ASHRAE 62.2. The target mechanical ventilation fan flow in each zone was weighted by the fraction of dwelling floor area in that zone.

Because ASHRAE 62.2 and Title 24 do not allow credit for infiltration in sizing mechanical fan flows for multifamily buildings, the target mechanical ventilation fan flow for whole the dwelling was set to the total flow required by the standard, and the zone fan airflows to the target zone flows, exactly as in Table 5. Airflows used by the controller at each time step for the multi-family dwellings did not include infiltration. That is, we assumed that the controller accounted for mechanical flows only. Of course, the concentrations of pollutants and the energy calculations used actual mass balance values from CONTAM.

Table 5: Target Airflow (Qtotal) For Each Zone And Prototype Building.

	Prototype Building		
	1-story	***2-story***	***Apartment***
Target Airflow per 62.2 (L/s, Q_{total})	**43**	**54**	**22.6**
Bedrooms	12.4	15.6	8.3
Wet Rooms	6.9	8.6	1.8
Other	18.7	23.5	9.9
Kitchen	5.0	6.3	2.6

For the non-zonal balanced ventilation system with ducted supply and exhaust flows, the supply and exhaust flows were balanced (equal). Supply air was delivered to Bedroom and Other zones, while the same flow rate of air was exhausted from the Wet Rooms and Kitchen. This requires that we calculate new floor area fractions for the supply zones and the exhaust zones, so those flows can be apportioned properly (see Table 6).

Table 6: Floor Area Fractions For Supply Air Zones And Exhaust Air Zones In Non-zonal Balanced Ventilation Systems.

Fractional Floor Area for Supply and Exhaust Zones (%)				
Zone	**Zone Type**	**1-story**	**2-story**	**Multifamily**
Bedrooms	Supply	40%	40%	40%
Other	Supply	60%	60%	60%
Wet Rooms	Exhaust	58%	58%	58%
Kitchen	Exhaust	42%	42%	42%

Ventilation System Types

The basic ventilation system types are exhaust, supply, or balanced (both exhaust and supply). Each of these system types can be either zonal (referred to as `MP` for multi-point), or non-zonal (referred to as 'SP' for single-point):

- SPexhaust
- SPsupply
- SPbalanced
- MPexhaust
- MPsupply
- MPbalanced

For example, a non-zonal exhaust system (SPexhaust) type contains a single exhaust fan located in the Common area of the dwelling, which is intended to ventilate the whole dwelling. In contrast, the zonal version of this system (MPexhaust) would provide an exhaust device in each zone, sized such that the total extract airflow is identical to that of the matching single-point system. These flows are distributed between the zones according to their floor area fractions.

The single-point balanced system supplies outside air to "dry" zones (e.g., bedrooms and common areas), and extracts flow from "wet" zones (e.g., bathrooms, kitchen and laundry). This is representative of ducted ventilation systems with heat recovery, as are commonly used in Passive House-type dwellings. While flows are extracted or supplied to/from different zones in this system type, it still operates as a whole dwelling, non-zonal system. This is because as soon as the flow is changed to any one of the zones (e.g., curtailing extract flow from the kitchen), then the system becomes unbalanced, so it can no longer be considered a balanced system. Once unbalanced, this system simply becomes an uncoordinated grouping of supply fans in dry rooms and exhaust fans in wet rooms. Any zonal smart control that varies zonal flows according to control inputs (e.g., occupancy or outside temperature) would no longer be a balanced system. The zonal version of this system type (MPbalanced) is balanced within each zone, with both an extract and supply flow to/from each zone in the dwelling. This could be achieved, for example, using single-point balanced fans where the supply and extract flows shared a single fan housing, which are placed in each zone and are then controlled independently based on control input signals.

Ventilation fan energy is accounted for using a fixed conversion rate 436.1 Watts per m^3/s. This is equivalent to 14.4 watts for a 70 cfm exhaust fan. This relationship is treated as linear over the fan flows used in these simulations.

Supply fan flows are dealt with differently, due to their need for tempering (i.e., mixing of outside ventilation air with re-circulated air from within the dwelling) in order to avoid thermal discomfort for occupants near the supply air outlet. We do not simulate this re-circulation of zone air for tempering, but we do account for it in supply fan energy use, which we treat with a multiplier of 4 (i.e., 1744.4 $W/m^3/s$), to represent the ventilation fan flow plus three units of corresponding re-circulation flow for tempering. This increased fan energy use for tempering applies to all supply fan airflows, whether part of supply-only or balanced ventilation system types.

In all likelihood, this underrepresents the fan energy of typical system set-ups in new California homes, where the central air handler fan is operated in concert with a supply fan ducted into the air handler's return plenum. Very efficient air handler fans operated at low speed are likely represented adequately by our 4x multiplier, but older AHU fans, operated at standard speeds, surely use much more energy for ventilation.

Ventilation Fan Airflows

All baseline ventilation fans are sized according to the current calculation method in ASHRAE 62.2-2016. This means a target ventilation rate (Q_{tot}) is calculated based on home floor area and the number of occupants/bedrooms, as in Equation 2. An effective annual average infiltration airflow (Q_{inf}) is then estimated using the results of a blower door pressurization test as in Equation 3. Finally, a mechanical fan airflow (Q_{fan}) is calculated using the target airflow and estimated infiltration per Equation 4. The required whole dwelling flows, effective annual infiltration rate, and fan airflows are calculated for each baseline case in Table 7.

$$\boldsymbol{Q_{total} = 0.03A_{floor} + 7.5(N_{br} + 1)} \qquad (1)$$

Q_{total} = Total required ventilation rate, cfm

A_{floor} = floor area of residence, ft^2

N_{br} = number of bedrooms (not less than one)

$$\boldsymbol{Q_{inf}(cfm) = \frac{NL(wsf)A_{floor}}{7.3}} \qquad (2)$$

Q_{inf} = Effective annual infiltration rate, cfm

NL = normalized leakage, derived from blower door testing

wsf = weather and shielding factor from Normative Appendix B 62.2-2016, varies by climate zone

A_{floor} = floor area of residence, ft^2

$$\boldsymbol{Q_{fan}} = \boldsymbol{Q_{total}} - \emptyset(\boldsymbol{Q_{inf}} \times \boldsymbol{A_{ext}}) \quad (3)$$

Q_{fan} = required mechanical ventilation rate, cfm

Q_{total} = Total required ventilation rate, cfm

Q_{inf} = Effective annual infiltration rate, cfm

A_{ext} = 1 for single-family detached homes

ϕ = 1 for balanced ventilation systems and otherwise: Q_{inf}/Q_{tot}

Mechanical ventilation fans used in the smart control cases are usually over-sized relative to the baseline fan flows. This allows the controller to shift ventilation rates over time, while still achieving long-term equivalent pollutant exposure. For most smart control cases, the maximum mechanical ventilation flow rate was 85 L/s (180 cfm) for 1-story prototypes and 58 L/s (124 cfm) for apartment prototypes. These are meant to align with larger-flow products on the market. Exceptions to this sizing rule include:

- varQmz - 65 L/s (138 cfm) for the 1-story and 27 L/s (57 cfm) for apartment cases.
- varQ - 40 L/s (85 cfm) for the apartment.
- occupantVenter - fixed 50% over-sizing relative to the baseline fan flow.

These adjusted fan sizes were determined based on trial and error in smart control performance testing.

Table 7: Target Airflow, Effective Annual Infiltration And Required Fan Airflow For Each Prototype.

Prototype	*ACH50*	*CZ*	*Fan Type*	*Qtotal (cfm)*	*Qinf (cfm)*	*Qfan (cfm)*
1story	0.6	1	Exh/Bal	92	5	91
		1	Balanced	92	5	86
		3	Exh/Sup	92	5	91
		3	Balanced	92	5	87
		10	Exh/Sup	92	4	92
		10	Balanced	92	4	88
		16	Exh/Sup	92	4	91
		16	Balanced	92	4	88
	2	1	Exh/Sup	92	17	88
		1	Balanced	92	17	74
		3	Exh/Sup	92	17	89
		3	Balanced	92	17	75
		10	Exh/Sup	92	13	90
		10	Balanced	92	13	79
		16	Exh/Sup	92	14	90
		16	Balanced	92	14	78
	3	1	Exh/Sup	92	26	84
		1	Balanced	92	26	65
		3	Exh/Sup	92	25	85
		3	Balanced	92	25	66
		10	Exh/Sup	92	20	87
		10	Balanced	92	20	72
		16	Exh/Sup	92	21	87
		16	Balanced	92	21	71
apt	3	1	Exh/Sup	48	12	48
		1	Balanced	48	12	48
		3	Exh/Sup	48	11	48
		3	Balanced	48	11	48
		10	Exh/Sup	48	9	48
		10	Balanced	48	9	48
		16	Exh/Sup	48	9	48
		16	Balanced	48	9	48

Occupancy

Representative occupancy schedules were developed for each of the prototype houses. Weekday schedules corresponded to notional "workday" and "school day" patterns. Weekend schedules featured higher occupancy throughout the day. The occupancy pattern for one adult included longer presence in the kitchen for cooking.

Occupant Schedules in 1-Story Dwelling

We assumed four occupants in the 1-story house. Two occupants follow a notional workday pattern and two occupants follow a notional school day pattern. Table 8, Table 9, and Table 10 show a typical workday, school day, and weekend schedule, respectively. The two occupants following the workday pattern and the two occupants following the school day pattern are respectively similar, and small changes (e.g., when showering occurs) are not shown here.

Table 8: Typical Workday Schedule For 1-Story House

Begin	*End*	*Location*	*Sleeping*	*Showering*
0:00	7:00	brm	y	n
7:00	7:15	wet	n	y
7:15	7:30	wet	n	n
7:30	8:30	kit	n	n
8:30	8:50	com	n	n
8:50	9:00	wet	n	n
9:00	18:00	out	n	n
18:00	18:15	com	n	n
18:15	19:00	kit	n	n
19:00	19:45	com	n	n
19:45	20:00	kit	n	n
20:00	21:45	com	n	n
21:45	22:00	wet	n	n
22:00	24:00	brm	y	n

Table 9: Typical School Day Schedule For 1-Story House

Begin	*End*	*Location*	*Sleeping*	*Showering*
0:00	7:00	brm	y	n
7:00	7:30	brm	y	n
7:30	7:45	wet	n	y
7:45	8:00	wet	n	n
8:00	8:30	kit	n	n
8:30	8:50	com	n	n
8:50	9:00	wet	n	n
9:00	18:00	out	n	n
18:00	18:15	com	n	n
18:15	19:00	com	n	n
19:00	19:45	com	n	n
19:45	20:00	wet	n	n
20:00	22:00	com	n	n
22:00	24:00	brm	y	n

Table 10: Typical Weekend Schedule For 1-Story House

Begin	**End**	**Location**	**Sleeping**	**Showering**
0:00	7:00	brm	y	n
7:00	7:15	wet	n	y
7:15	7:30	wet	n	n
7:30	8:00	kit	n	n
8:00	8:30	kit	n	n
8:30	8:50	com	n	n
8:50	9:00	wet	n	n
9:00	10:00	com	n	n
10:00	10:15	wet	n	n
10:15	10:45	brm	n	n
10:45	11:45	com	n	n
11:45	12:10	kit	n	n
12:10	13:00	com	n	n
13:00	13:15	wet	n	n
13:15	14:00	brm	n	n
14:00	16:00	com	n	n
16:00	16:15	wet	n	n
16:15	18:00	com	n	n
18:00	18:15	com	n	n
18:15	19:00	kit	n	n
19:00	19:45	com	n	n
19:45	20:00	kit	n	n
20:00	21:45	com	n	n
21:45	22:00	wet	n	n
22:00	24:00	brm	y	n

Occupant Schedules in 2-Story House

We assumed five occupants in the 2-story house. Two occupants follow a notional workday pattern and three occupants follow a notional school day pattern. Table 11, Table 12 and Table 13 show a typical workday, school day, and weekend schedule, respectively. As in the 1-story case, occupant schedules are similar so are not shown here.

Table 11: Typical Work Day Schedule For 2-Story House

Begin	End	Location	Sleeping	Showering
0:00	7:00	brm	y	n
7:00	7:15	wet	n	y
7:15	7:30	wet	n	n
7:30	8:00	kit	n	n
8:00	8:30	kit	n	n
8:30	8:50	com	n	n
8:50	9:00	wet	n	n
9:00	18:00	out	n	n
18:00	18:15	com	n	n
18:15	19:00	kit	n	n
19:00	19:45	com	n	n
19:45	20:00	kit	n	n
20:00	21:45	fam	n	n
21:45	22:00	wet	n	n
22:00	24:00	brm	y	n

Table 12: Typical School Day Schedule For 2-Story House

Begin	End	Location	Sleeping	Showering
0:00	7:00	brm	y	n
7:00	7:30	brm	y	n
7:30	7:45	wet	n	n
7:45	8:00	wet	n	y
8:00	8:30	kit	n	n
8:30	8:50	com	n	n
8:50	9:00	wet	n	n
9:00	18:00	out	n	n
18:00	18:15	com	n	n
18:15	19:00	fam	n	n
19:00	19:45	com	n	n
19:45	20:00	wet	n	n
20:00	22:00	fam	n	n
22:00	24:00	brm	y	n

Table 13: Typical Weekend Schedule For 2-Story House

Begin	End	Location	Sleeping	Showering
0:00	7:00	brm	y	n
7:00	7:15	wet	n	y
7:15	7:30	wet	n	n
7:30	8:00	kit	n	n
8:00	8:30	kit	n	n
8:30	8:50	com	n	n
8:50	9:00	wet	n	n
9:00	10:00	fam	n	n
10:00	10:15	wet	n	n
10:15	10:45	brm	n	n
10:45	11:45	fam	n	n
11:45	12:10	kit	n	n
12:10	13:00	com	n	n
13:00	13:15	wet	n	n
13:15	14:00	brm	n	n
14:00	16:00	fam	n	n
16:00	16:15	wet	n	n
16:15	18:00	fam	n	n
18:00	18:15	com	n	n
18:15	19:00	kit	n	n
19:00	19:45	fam	n	n
19:45	20:00	kit	n	n
20:00	21:45	com	n	n
21:45	22:00	wet	n	n
22:00	24:00	brm	y	n

Occupant Schedules in Apartment

We assumed three occupants in the apartment. Two occupants follow a notional workday pattern and one occupant follows a notional school day pattern. The occupancy patterns are similar to the occupancy schedules presented for the one- and two-story home, with the notable difference that two occupants sleep in room brm and one occupant sleeps in room brc. These schedules are not shown here, for brevity.

Activities

We modeled four special activities occurring in the homes: cooking, showering, laundering, and dishwashing. Each activity triggers appropriate changes in the emission rates and ventilation schedules in the affected zones. Cooking events last for 30 minutes, and occur in the mornings and evenings. Showering events last for 15 minutes; examples of showering activity are shown in the occupancy schedules, see for example Table 8. Laundering occurs each day in the evening and lasts for 30 minutes. Laundering occurs in the "wet" zone. Dishwashing occurs each day in the evening and lasts for one hour, also in the kitchen zone.

Emission Rates

LBNL estimated emissions rates for carbon dioxide and moisture using data from the research literature. Formaldehyde and particle emission rates were extracted using time-series data gathered in the HENGH field study of IAQ in new California homes using natural gas (Chan, Kim, Less, Singer, & Walker, 2018).

Generic contaminants

The generic contaminant corresponds to the pollutant emission assumptions embedded in the current equivalence calculations in ASHRAE 62.2 and Title 24. It acts as an IAQ performance benchmark, which allows us to assess the zonal simulations in a manner consistent with the non-zonal simulations. The generic contaminant was emitted into each zone according to its floor area, at a constant rate of 18 μg/m^2/hr. There were no outside sources of this generic contaminant, and no removal mechanisms other than outside air exchange.

Formaldehyde

For this study we focused on formaldehyde because it is a key contaminant of concern in homes: it is universally present and often at concentrations that could lead to health impacts. However, the variability of emission rates with ventilation rates (and temperature and humidity) means that it is not a good surrogate for the continuously-emitted, generic contaminant assumed for the ASHRAE 62.2 equivalence calculations – that we have investigated previously by assuming constant emission rates. We consider that it is more important to treat this specific contaminant in this rigorous way then to ignore this variability in emission rate because this study is focused on variable ventilation rates.

We estimated Formaldehyde emissions using time-series data from the HENGH field study in new California homes. A total of 56 homes provided the data, from which we extracted the apparent emission rates at 30-minute intervals. We then did a multiple linear regression model to the data, in order to model the variability of formaldehyde emissions as a function of the current airborne concentration, the ventilation rate, room temperature, and room humidity. The emission rates are estimated at each simulation time-step in EnergyPlus using the regression equation shown in Table 14. All regression parameters use a 30-minute running mean value in EnergyPlus, so as to align with the measured data time interval.

Table 14: Multiple Regression Model Parameters Relating Formaldehyde Emission Rates In New California Homes With Their Ventilation Rate, Change in Ventilation Rate, Change In Formaldehyde Concentration, Indoor Temperature And RH.

Variable	**Estimate**
Intercept	-45.6287871
House Temperature (C)	1.1699174
House RH (%)	0.5190551
House Air Exchange Rate (hr^{-1})	41.3104020
Rate of Change of Dwelling Air Exchange Rate (hr^{-1})	6.1696677
Rate of Change of Dwelling Formaldehyde Concentration ($\mu g/m^3$)	-2.3609866

This model reflects current thinking in the variability of formaldehyde emission rates in dwellings. It shows that emission rates increase as ventilation rates increase and as indoor temperature and RH increase. Conversely, emission rates decrease with increasing airborne formaldehyde concentration.

The median formaldehyde emission rate from HENGH homes, based on DNPH integrated passive samplers, was 22 $\mu g/m^2/hr$. The median from all time-series-derived emission rates was 20 $\mu g/m^2/hr$.

Past LBNL research (Hult et al. (2015).) suggested that formaldehyde emission rates in low-emitting homes were on the order of 23 $\mu g/m^2/hr$. Emission rates from conventional new California homes in the early/mid 2000s were roughly 40 $\mu g/m^2/hr$ (F. Offermann, 2009). Similarly, Hodgson, Rudd, Beal, & Chandra (2000) reported geometric mean formaldehyde emission rates in seven new (at the time) site-built homes of 31 $\mu g/m^2/hr$, ranging from 10 to 58 $\mu g/m^2/hr$. Rudd's measurements occurred 1-2 months after homes were completed. On average, the emission rates are substantially lower in new California homes, than they were roughly one decade prior, which is likely due to the regulation of formaldehyde emissions from engineered wood products in the state of CA by the Air Resources Board (CARB).

Others have similarly recorded increased formaldehyde emissions in the same dwellings with systematically varied ventilation rates (Hult et al., 2015; Liu et al., 2019; F. J. Offermann, Maddalena, Offermann, Singer, & Willem, 2012). The HENGH data suggest that this effect can be observed both cross-sectionally and in-time. Offermann et al. tested three ventilation rates in a CA home (0.21, 0.41 and 0.64 hr^{-1}), and observed formaldehyde emissions increase from 17 to 24 to 31 $\mu g/m^3/hr$ (note these are normalized by volume, not floor area; we multiplied by 2.5 to get comparable floor area normalized values). A number of other compounds increased emissions with higher ventilation rates (Texanol, Phenol, Hexadecane and Tetradecane), but their increases were much smaller, with slopes of 0.85 to 5.55 μg /m^3/hr/ACH, compared with 32.4 μg /m^3/hr/ACH for formaldehyde. Offermann notes that these findings are "consistent with mass transfer theory for emissions from materials such as composite wood where mass transfer is limited by gas-phase diffusion across the boundary layer."

Hult et al (2015) reported similar findings in 9 homes in which they systematically achieved three different ventilation rates in new homes. They compared observed reductions in formaldehyde concentrations as ventilation increased, versus expected reductions based on assuming fixed emission rates. They found that up to 60% of the benefit of increased ventilation (assuming fixed emissions) was lost due to corresponding increases in emission rates. Typical values were roughly 30% less benefit than expected from increased ventilation rates, due to increased emissions.

Liu et al (2019) recently completed a detailed time-resolved assessment of VOC emission rates (including formaldehyde) in a Northern California residence, and they found that emission rates increased with household ventilation rates and with temperature.

In contrast, Hodgson et al. (2000) reported the formaldehyde emission rates in a single home under two ventilation rates (0.32 and 0.14 hr^{-1}), and emissions were only marginally higher at the higher ventilation rate (29 vs. 27 μg /m^2/hr).

CO_2

We based emission rates on the analysis provided by the National Institute of Standards and Technology (NISTIR-7212, 2005) for the modeling of indoor air quality. Their analysis of CO_2 emissions provided in AHRAE Fundamentals (2001a) suggests average CO_2 generation rates as:

- Adult: 10 mg/sec (awake); 6.5 mg/sec (asleep)
- Child: 6.5 mg/sec (awake); 4 mg/sec (asleep)

We treat male and female occupants as simply "adults", so as to avoid any gender biases in scheduling of activities and emissions. Similarly, all children are treated the same, regardless of age. This again lessens the specificity of our occupancy scenarios.

Water Vapor (H_2O)

Event- and occupancy-based water vapor generation rates are similar to those reported in NISTIR-7212 (2005) and NISTIR-6162 (1998). We assumed that ventilation during cooking and showering captured half of moisture released during the activity. For example, NISTIR-7212 suggests water generation during cooking, on average releases 280 mg/sec into the area above the range. We posit that 50% of that moisture is exhausted immediately through the range hood with 50% capture efficiency, resulting in a modeled emission rate of 140 mg/sec. Lastly, we estimated background moisture generation to be approximately 20 mg/sec throughout the house (ASHRAE 160-2016), and distributed by area-weight.

Resulting emission rates are:

- Adult: 15 mg/sec (awake); 9 mg/sec (asleep)
- Child: 10 mg/sec (awake); 6 mg/sec (asleep)
- Dishwashing: 130 mg/sec
- Cooking: 140 mg/sec
- Showering: 330 mg/sec
- Background emission: 20 mg/sec

Particles ($PM_{2.5}$)

We estimated generation of particulate matter as $PM_{2.5}$ equivalents using data derived from a field study conducted by LBNL (Chan et al., 2018).

In the HENGH study, LBNL measured $PM_{2.5}$ concentrations near the cook range and outdoors. We used a data analysis approach called Random Forest to differentiate the indoor concentrations as contribution from the outdoors, indoor cooking, and "other" particle generation. We then estimated the indoor loss of $PM_{2.5}$ due to settling and ventilation, by fitting a regression model to the decaying indoor concentration after cooking. With concentrations, loss rate, and cooking events identified, we estimated mean emission rates for cooking and "other" events. The details of the experiments are provided in the above reference, and a report on the data analysis is in preparation.

Particle emission rates varied widely. This study used an average emission rate of 0.0416 mg/sec for cooking, and 0.00007 mg/sec for other background emissions when occupants are present and not sleeping (e.g., due to walking around the house). We assumed that a fan near the cook range captured 50% of the emissions, giving:

- PM2.5 cooking: 0.0208 mg/sec
- PM2.5 other: 0.00007 mg/sec

Local Exhaust Fan Flows

We used a combination of the minimum local exhaust flows from ASHRAE 62.2 for cooking (kitchens) and showering (bathrooms), together with typical flow rates for clothes dryers:

- Clothes dryer: 0.07079 m^3/s
- Cooking: 0.0472 m^3/s
- Showering: 0.0236 m^3/s

These fans were operated according to the occupancy and activity schedules, such that if the bathroom was occupied and a shower was occurring, the bathroom exhaust fan was operated. Similarly, the kitchen fan was operated during scheduled cooking events, and the laundry exhaust was operated during scheduled laundry activities.

Sensible Heat Gains

We assumed heat loads for occupants, cooking, dishwashing, laundering, showering, and background loads. Acknowledging that loads are quite variable and uncertain, we used the following loads as our best engineering judgment:

- Occupancy: 160 W (awake); 80 W (asleep)
- Cooking: 1500 W (two burners each operating at 1500 W, and ventilation removing 50% of the load)
- Dishwashing: 200 W
- Laundering: 200 W
- Showering: 0 (all heat removed by ventilation)
- Background: 200 W, area distributed
- Lighting: 1 W/m^2

Ambient Air Quality

Ambient concentrations were used for all contaminants emitted in the living space of the CONTAM models—CO_2, water vapor, $PM_{2.5}$ and formaldehyde.

CO_2

We assumed a constant outdoor concentration of 400 ppm, which represents the current global annual average outdoor concentration. This ignores possible localized emissions that could affect a home depending on its location relative to major roadways and other outside combustion sources, as well as intra-annual variability.

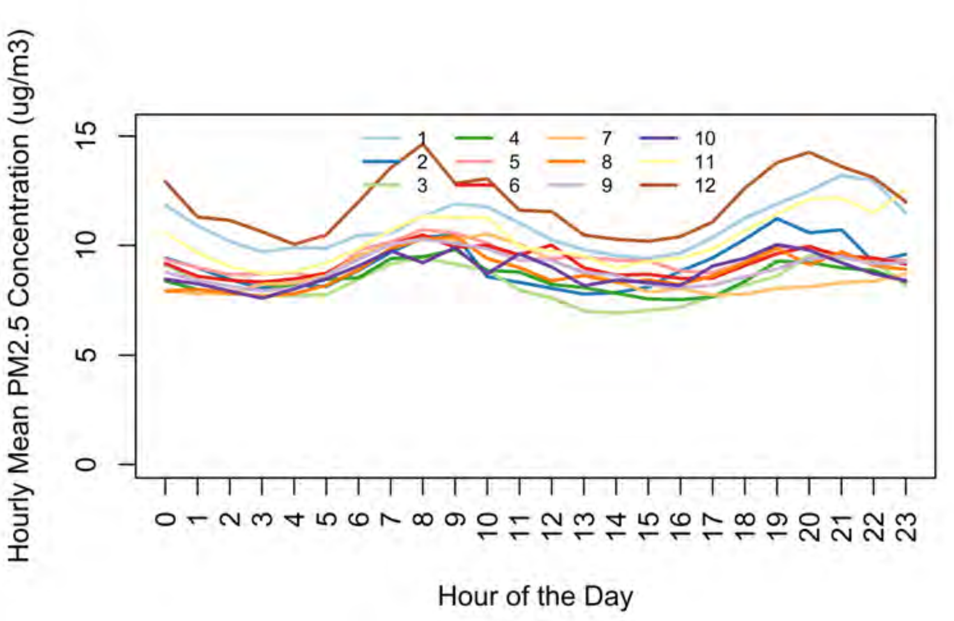
Water Vapor

We used the hourly ambient humidity data from the Title 24 CBECC-Res compliance weather files for each climate region.

Particles

Outdoor particle concentrations varied by season and diurnally. We used pre-generated annual hourly ambient $PM_{2.5}$ data from the US EPA AQS system, including all national measurement sites for full calendar years of 2013 – 2018. These data are quality assured and controlled by the EPA, and they provide great levels of spatial and temporal resolution. We identified the available monitoring sites for the County of each representative city of the CEC Climate Regions 1, 3, 10 and 16. This included six sites in Alameda county (CZ3), three sites in Riverside county (CZ10), two sites in Humboldt county (CZ1) and one site in Placer county (CZ16). For each individual monitoring site, data were aggregated by weekday/weekend status, hour of the day, and month of the year. This produced diurnal hourly mean values for ambient fine particles for each month of the year on weekends and weekdays. For locations with more than one monitoring site, each entry was averaged across the sites to create a single value to be used for each CEC climate region. An example plot is shown for weekdays in Alameda county, in Figure 5. We observe seasonal trends, with higher ambient particles in the winter, as well as daily patterns, potentially related to traffic conditions. Across these climate regions, the seasonal differences can be as much as 10 μg/m^3, which could have important interactions with the seasonal shifting of ventilation rates by smart controllers.

Figure 5: Example Monthly Diurnal Patterns Of Ambient $PM_{2.5}$ For Alameda County Weekdays.



For comparison, the mean outdoor $PM_{2.5}$ value measured directly outside of 70 new California homes in the HENGH project was 9 µg/m^3. This value falls squarely within the monthly diurnal values derived from our method described above. Note these outdoor particle levels do not include acute wildfire events. The ability for smart ventilation to shut down during these events and ventilate more at other times is a topic for future research.

Formaldehyde

Ambient formaldehyde concentrations are typically between 2 and 3 ppb. We used a fixed value of 3 ppb in our modeling. The Technical Support Document published by OEHHA in justification of their non-cancer Reference Exposure Level for formaldehyde states that ambient levels in CA average 2.69 ppb (with the highest annual mean in the

LA basin of 3.76 ppb) (OEHHA, 2008). Propper et al. (2015) show that this has been a stable ambient value for several years up to 2012, and that overall, the ambient levels declined 2.6% per year for the period between 2003 and 2010.

Control Metrics

Most of the zonal ventilation controller uses some control inputs to estimate the real-time IAQ in the dwelling or zones, and to control the ventilation airflows accordingly. The Contaminant control types simply use the zone contaminant concentrations predicted by the CONTAM model, as if the controller were connected to pollutant sensors in each zone. Select other control types use only zone occupancy patterns to make ventilation decisions (e.g., occupantVenter), or they use outdoor temperature signals combined with zone occupancy patterns (e.g., varQmz). All other control types required zonal control metrics, which are each described below.

Relative exposure and dose, dwelling and zone

A number of control types rely on the current equivalence calculations in ASHRAE 62.2-2016, but they adjust them to a zonal ventilation context. Controllers that use these metrics include the varQmz, occExposure and zoneExposure controllers. For these control types, the relative exposure and relative dose are estimated for each individual zone and the whole dwelling. As in the single-zone SVACH simulations, the relative exposure represents the ratio of two generic contaminant concentrations: (1) the concentration that would occur under a time-varying ventilation pattern, and (2) the reference concentration that would occur under a constant ventilation pattern that meets the whole dwelling requirement of 62.2. In the single-zone simulations, each controller estimated the dwelling relative exposure at each time-step using the sum of the ventilation fan flows, combined with the dwelling infiltration flows. Infiltration was either a fixed annual average value, or it was predicted in real-time using the AIM-2 infiltration model (also embedded in 62.2 calculation procedures). The controllers then used the real-time relative exposure for determine ventilation fan operation.

For zonal controllers using 62.2 relative exposure, we extended this concept so that it could be applied to each zone independently. The controller knows the mechanical fan airflows in each zone (in and/or out). The controller must then estimate the infiltration flow rate for each zone. We did this by using the same AIM-2 infiltration model from ASHRAE 62.2 to predict the whole dwelling infiltration rate. This whole dwelling value was then subdivided amongst each of the zones according to their floor area fractions.

The zonal airflow was then determined using the same calculation procedure used to combine mechanical and natural flows in the single-zone work. For balanced fan types (now balanced within the zone), the fan flow and the zone’s infiltration flow estimate are simply added together to get the zone total flow. For unbalanced fan types (e.g., supply and exhaust fans), we treated the fan and infiltration flows as sub-additive, just as the 62.2 calculation procedure requires.

With the real-time total flow rates calculated for each zone, these were then compared against the reference flow rate, which in the single-zone work, was the whole dwelling target ventilation rate (Qtotal). For each zone, we simply divided the whole dwelling reference flow rate according to the zone floor area fraction. The zone real-time flow rate and reference flow rates were then used in the relative exposure calculation in 62.2.

This procedure is highly imperfect in a zonal context, but it was the best available estimate that we felt a ventilation controller could make in real-time using information possibly available to it. First, infiltration into zones in a dwelling is not based solely on floor area fraction. Other factors that determine zone natural infiltration are critical, including the orientation of the zone with respect to incoming winds, the zone height (1st floor vs. 2nd), and exterior envelope leakage areas. Second, for a whole dwelling, the outgoing flow from an exhaust fan is always matched by an equal inflow through leaks in the building envelope. All outgoing and ingoing flows are to/from the whole dwelling volume. But this is not true in a zonal context. In a zoned dwelling, the flow from an exhaust fan in a zone is partially made-up by air that enters the envelope through leakage paths in the zone itself, and also partially through other leakage paths located in adjacent zones, which are then transferred to the zone containing the fan through inter-zonal leakage paths. But the exhaust fan outgoing flow is not equal to the outside air that enters the zone, instead the amount of outside air entering the zone is always less than the exhaust fan flow rate. The extent of this effect depends on the zone size, leakage distribution, door position, etc. Supply fans behave very differently. For a supply flow into a zone, the outside air ventilation rate equals the fan flow rate. So, for the zone containing the fan, this is straightforward, but the supply flow into one zone also affects other zones. Needless to say, the dynamics of inter-zonal airflows and fan type interactions are very complex, and are not adequately reflected in the zone 62.2 relative exposure calculation described above. We expect the above method to be most appropriate for supply fan flows, and least appropriate for exhaust fan flows.

Our simulations should demonstrate how poorly (or not poorly) this metric works to reflect the actual flow dynamics in multi-zoned dwellings.

ASHQ relative exposure and dose

Initial simulations suggested that the 62.2 zone relative exposure approach described above did not lead to zonal controls that were able to maintain personal pollutant exposures below those in the baseline constant flow reference case. We developed a surrogate method to estimate a relative exposure-like metric, which used CONTAM's real-time predicted concentrations of the generic contaminant in each zone. The relative exposure described above is, in essence just a ratio of concentrations. So, for this metric, we use the actual real-time generic concentration and compare that against the steady-state concentration that would occur in the whole dwelling if it were ventilated constantly at the target whole dwelling flow rate (Qtotal), assuming the same constant whole dwelling emission rate. We estimated that steady-state concentration for the reference case as the whole dwelling emission rate (μg/second) divided by the whole dwelling target flow rate (m^3/second), which gives the whole dwelling concentration (μg/m^3).

With this new ASHQ relative exposure in place, the zoneASHQexposure controls exactly mimics the behavior of the zoneExposure controller, and the occASHQexposure control exactly mimics the occExposure controller.

Smart Ventilation Controls

In total, sixteen ventilation control types were simulated. This included 14 smart control types and two baseline cases with either no ventilation fan operation (baseNoFan) or constant code-minimum ventilation (baseFan). The sub-sections below briefly describe each of these control types.

Zonal smart ventilation controls are intended to reduce energy use and maintain equivalent IAQ, to improve IAQ and maintain equivalent energy use, or do both.

Zonal ventilation control schemes fall into three broad categories:

- Those that improve overall IAQ, and reduce occupant pollutant exposure, without any impact on HVAC energy use. For example, controls could maintain a constant whole dwelling ventilation rate, but direct the flow to the occupied zone(s), ensuring that fresh air is delivered to the zones where people are. We hypothesize that this will reduce personal contaminant exposures, with essentially no impact on energy use. The core question here is: "how much can we improve occupant health without using additional energy"? Examples of this control type include the supplyTracker and the occupantTracker controls (described in more detail in subsections below).
- Those that reduce HVAC energy use while maintaining equivalent (neither better nor worse) overall IAQ and personal contaminant exposures. The core question here is: "how much energy can we save while not worsening occupant health"? Examples of this control type are the varQmz, zoneExposure and occExposure.
- Those that seek to both save energy and improve overall IAQ and reduce occupant exposures. These strategies will save less energy than control types that are designed to only maintain, rather than improve, IAQ and health. However, they should have the added benefit of saving some energy and improving IAQ. An example of this approach is the varQmzSingleZoneOpt controller, which varies the ventilation flow rate based on outside temperatures, and then uses zonal ventilation system types to direct the majority of mechanical fan flow to the occupied zone. This control's parameters are designed to save energy while maintaining equivalent whole dwelling IAQ, and we maintain the energy savings and improve IAQ by then adding the ability to direct ventilation airflows where they are most beneficial to the occupants in the dwelling.

The control types simulated in this work are outlined in the bulleted list below, and each controller is described in greater detail in its own subsection. The controls are organized by five control-type themes, including Baseline, Baseline + IAQ controls, Outdoor Temperature controls, Zone Occupancy controls, Contaminant controls, and Aereco RH Demand Controls. Controls are characterized by how (and if) they attempt to save energy, how they impact annual ventilation airflows, and what the controller inputs are.

- **Baseline**
    - **baseNoFan** – No IAQ fan is operated, but local exhaust s are operated.
    - **baseFan** – All fan types. Constant flow IAQ fan sized to ASHRAE 62.2-2016.
- **Baseline + IAQ Controls.** Intended to improve IAQ while not affecting energy use.
    - **supplyTracker** – For supply and balanced systems the supply air flows are directed to occupied zones. There is no reduction in total system airflow. The total system air flow is directed to each occupied zone in proportion to its floor area. It is possible for a single occupied zone to receive the full dwelling air flow rate. Annual ventilation air flows are unchanged.
    - **occupantTracker** – This is the same as the supply tracker, but also includes exhaust air, such that the exhaust is taken from occupied zones only and the total dwelling air flow is maintained. Annual ventilation air flows are unchanged.
- **Outdoor Temperature Controls.** Use outdoor temperature in control decision to shift ventilation flows to mild weather periods. Some versions layer temperature control on top of occupancy sensing and zonal ventilation equipment to maximize either IAQ or energy savings.
    - **varQ** – For single-point unzoned systems the whole dwelling IAQ fan flow rate is varied according to outdoor dry-bulb temperature, using pre-optimized temperature scaling factors. This leads to increased annual ventilation flow.
    - **varQmzSingleZoneOpt** – For multipoint zoned systems, this control has the same airflow as varQ, but zone airflows are directed to occupied zones only. This leads to increased annual ventilation flow.
    - **varQmz** – For multipoint zoned systems, this control has the same calculation procedures as varQ, but temperature scaling parameters are optimized for a two-zone dwelling using assumed occupancy patterns. This approach can decrease annual ventilation flow.
- **Zone Occupancy Controls.** Unlike the above **tracker** controls, these controls apportion the whole dwelling flow to each zone and then only vent occupied zones, and only apply to multipoint zoned systems. This reduces annual

ventilation airflow for the dwelling. Controls use either estimated relative exposure and dose (as calculated in 62.2-2016) or actual contaminant predictions.

  - **zoneExposure** – The controller tracks relative exposure and relative dose in each zone, and operates the IAQ fan to maintain both metrics below 1 during occupied periods, otherwise exposure is controlled to less than 5 to avoid acute exposures.
  - **zoneASHQexposure** – This is the same control strategy as zoneExposure, but instead of using controller estimates of relative exposure and dose, uses the ratio of the actual zone Generic contaminant concentration (from CONTAM) over the steady-state zone concentration that would occur at the baseFan annual ventilation rate.
  - **occExposures** – Tracks controller estimated relative exposure in each zone and integrated 24-hour relative dose for each occupant. Zones are vented if any person in the zone has an integrated relative dose greater than 1, or if the zone relative exposure is greater than 1. Unoccupied zone relative exposure is controlled to less than 5. This controller ensures that a personal exposure in one zone can be compensated for by increased ventilation in another zone.
  - **occASHQexposure –** This is the same control strategy as occExposure, but instead of using controller estimates of relative exposure and dose, uses the ratio of the actual zone Generic contaminant concentration (from CONTAM) over the steady-state zone concentration that would occur at the baseFan annual ventilation rate.
  - **occupantVenter –**Fan airflow is distributed to occupied zones, and is otherwise maintained at some minimum flow rate. No tracking of controller estimated exposure, dose or contaminants.

- **Contaminant Controls.** This controller uses actual contaminant concentrations in each zone and ventilates when they exceed health-relevant thresholds. These controls apply to all multipoint zoned systems.
  - **contaminantDwelling** – The hole dwelling is vented if any contaminant exceeds health thresholds in any zone.
  - **contaminantZone** – Each zone is vented if any contaminant in the zone exceeds health thresholds.
  - **contaminantZoneOcc** - Each zone is vented if it is occupied and any contaminant in the zone exceeds health thresholds.
- **Aereco RH Demand Controls**. Use only the multi-point exhaust (MPexhaust) fan type to extract from wet zones according to the zone RH, while at the same time, varying dry room air inlet opening areas according to dry room RH. The control uses zone RH as a surrogate for occupancy, and it modulates zone

ventilation flows in response. This control is based on an existing European demand-controlled ventilation controller produced by Aereco.

Minimum Zone Airflow

The smart ventilation controls maintained a minimum flow rate in each zone, irrespective of the zone's occupancy or demand. Exceptions to this rule were the variants of the varQ control, which could have a minimum flow rate determined by the pre-optimization, or used a minimum of 0. The minimum flow was specified as 20% of the whole dwelling required flow rate (Qtotal). If all zones were simply calling for their minimum flow rates (e.g., during a period of vacancy from the dwelling), then each zone received the minimum. But if one zone in the dwelling was calling for more than its minimum flow rate, then the minimum flows delivered in each zone were reduced further as described below.

Zone Fan Capacities

In all smart control cases, each zone could be ventilated at the whole dwelling smart ventilation fan flow rate (typically 85 or 65 L/s for the 1-story and apt prototypes). For example, if all persons were in the bedroom zone, then that zone would call for the whole dwelling fan flow rate, as needed. When multiple zones are calling for ventilation, the flow remains limited to the whole dwelling fan flow rate, and this total is distributed according to the flow rates requested in each zone, relative to the total flow rate requested by all zones.

Baseline Controls

baseNoFan

The baseNoFan control type contains no IAQ fan to provide dilution ventilation for the dwellings. These cases still have some ventilation airflow, from both natural infiltration and from local exhaust fan operation (in the kitchen and bathrooms, and from the vented clothes dryer in the wet zone). The baseNoFan cases serve as energy reference cases for the baseFan cases, described below.

baseFan

The baseFan control type represents controls in dwellings under current Title 24 codes which do not require ventilation controls, but are instead operated at a constant mechanical fan flow rate, for all hours of the year, sized according to the ASHRAE 62.2-2016 ventilation standard. The fan sizes are adjusted using the annual effective infiltration rate (Qinf) for each dwelling and location, such that the total ventilation airflow required by 62.2 is achieved in each dwelling from the combined mechanical fan airflow and natural infiltration flows. This means that the mechanical ventilation airflow differs in each prototype dwelling, level of envelope leakage, and climate region.

The ventilation energy associated with compliance with the ventilation requirements of the energy code is calculated as the difference between the baseFan and the corresponding baseNoFan cases. This ventilation energy use includes all HVAC end-use energy consumption, including heating, cooling, central air handler (if one exists), and ventilation fan energy. As such, it includes both the fan energy and the space conditioning loads (positive or negative) introduced by baseline code-compliant ventilation.

The baseFan cases also serve as the reference cases for assessing the performance of the smart ventilation control cases.

Baseline + IAQ Controls

supplyTracker

The supplyTracker controller is used only with SPbalanced ventilation system types. It continuously ventilates the whole dwelling at the code-required mechanical fan flow rate. Exhaust flows always extract from the Wet and Kitchen zones according to their floor area fractions. When the dwelling is vacant or all occupants are currently in extract zones, the supply airflows are directed according to the occupied zone floor area fractions. When the supply zones are occupied, the supply flow is directed to each supply zone based on how many occupants are in the zone relative to the total number of occupants currently in all supply zones combined. So, for example, if all four occupants are in the Bedrooms zone, then all supply airflow from the SPbalanced system is directed into the bedrooms. If one of the four persons then left and entered the Common zone, then 25% of the supply flow would be directed to the Common zone (1/4 occupants) and 75% of the flow would remain in the bedroom (3/4 occupants).

This controller is intended to maintain equivalent energy use while improving IAQ and reducing personal contaminant exposures.

occupantTracker

This controller continuously ventilates the whole dwelling at the code-required rate, but it directs the flow to the zone(s) based on their occupancy. Each occupied zone is directly ventilated based on the number of persons in the zone relative to the total number of persons in the dwelling. When the dwelling is vacant, flow is distributed to all zones according to their floor area fractions.

This controller is intended to maintain equivalent energy use while improving IAQ and reducing personal contaminant exposures.

Outdoor Temperature Controls

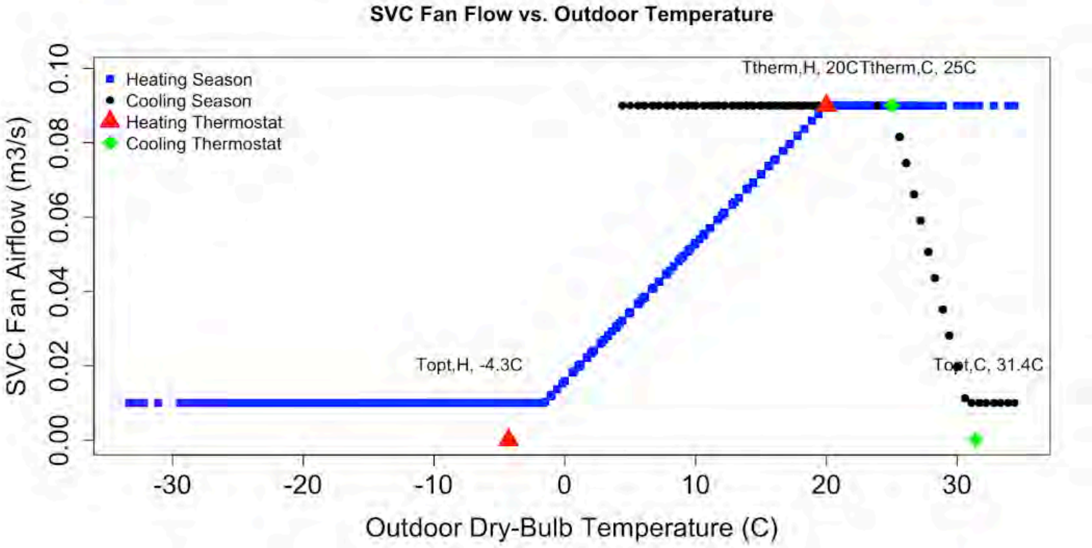
VarQ

The varQ controller saves energy by shifting ventilation flows to mild weather periods, but this shifting of flows requires that the total outside airflow be increased to provide equivalent pollutant exposure. It uses a variable speed fan to shift mechanical ventilation airflow to milder weather by season, hour of the day, etc. It ventilates at higher than the code-compliant reference rate during mild periods, and at less than the reference airflow during cold or hot periods. It uses a real-time outdoor temperature measurement, a variable speed fan (or variable fractional hourly runtimes), and a pre-calculation tool that selects energy-optimized scaling parameters for the controller to use.

The basic strategy of the controller is shown in Figure 6, which shows outdoor temperature values on the x-axis and smart fan flow rates on the y-axis. Heating season values are in blue, and cooling season values are in black. The optimization automatically selects the optimal temperatures for heating (Topt,H) and cooling (Topt,C) seasonal conditions. These are used to scale fan airflows between maximum and minimum flow rates based on the current outside temperature. The minimum in this case was user-selected to be 0.010 m^3/s (roughly 20 cfm). In heating season, if outdoors is colder than Topt,H, the fan operates at its minimum flow. Between Topt,H and the heating thermostat setting, the fan flow is scaled linearly from minimum to maximum. At outdoor temperatures above the heating thermostat setpoint, the fan flow is at maximum (i.e., free heating). The opposite happens in cooling season, where outdoor temperatures below the cooling thermostat setting give maximum airflow (i.e., free cooling), which is then scaled down to minimum flow at higher temperatures.

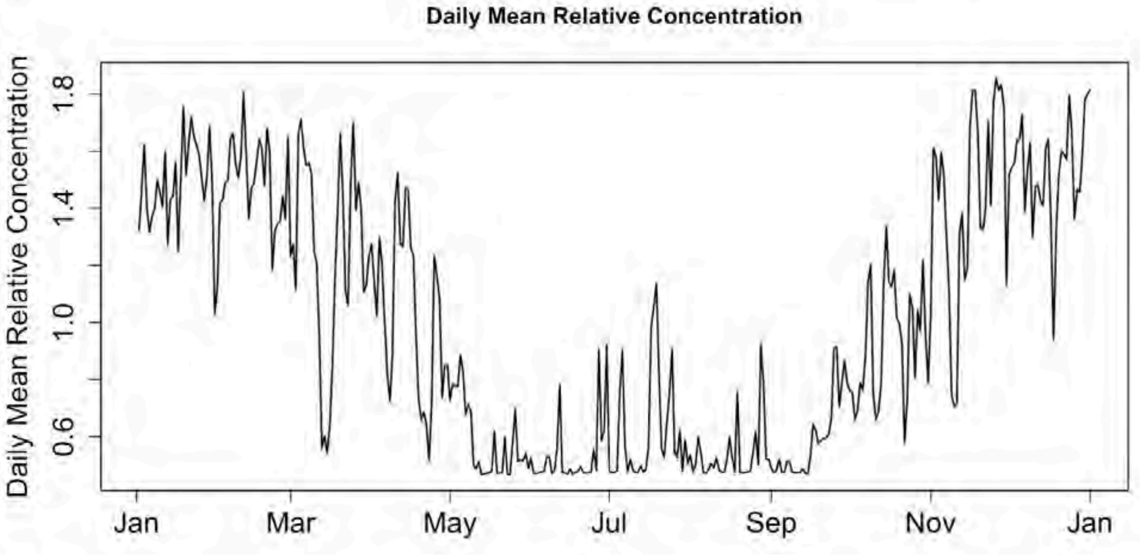
The optimal temperatures selected are those that maintain annual relative exposure (see detailed note at the end) less than or equal to 1.0, and where the annual heating and cooling energy use associated with ventilation flows is minimized. The relative exposure annually being less than 1 is the primary requirement of the smart controls compliance option in ASHRAE Standard 62.2-2016. Controls must also never exceed a relative exposure of 5 (that could occur with extended periods of under-ventilation), which is also included in our optimization algorithm.

Figure 6: Example Optimized Relationship Between Outdoor Temperature And Ventilation Fan Flow Rate In Heating And Cooling Seasons. Example 2,100 ft^2 Home In Madison, WI.



From an air pollutant perspective, this means that concentrations of some pollutants will be higher in the home during the heating season, and lower in the cooling season. The daily mean relative concentration for this control case is shown below in Figure 7. Overall, the highest indoor concentration any day reaches with this controller is a relative exposure of about 1.6 to 1.7. In other words, an indoor contaminant concentration is at most 60-70% higher than it would have been using a constant flow fan. For formaldehyde, a long-term value might be 20 $\mu g/m^3$, and this controller would result in a worst day around 34 $\mu g/m^3$, which is also well within the range typically measured in new homes. The same home's formaldehyde concentration might then be roughly 10$\mu g/m^3$ in the summer months, compensating over the period of one-year for those higher wintertime exposures.

Figure 7: Daily Mean Relative Concentration Of Generic Contaminant For Example Optimized varQ Control Scheme.



This type of controller was also studied in the non-zonal Phase 1 SVACH simulations. In Phase II, we adjusted the control optimization, mainly to optimize the heating and cooling optimal scaling temperatures independently of one another. In the Phase 1 simulations, the heating and cooling values were forced to be equidistant from the annual minimum and maximum outdoor temperatures. For example, if annual temperatures varied between 0 and 35°C, then the difference between Topt,H - 0°C was forced to be the same as the difference between 35°C - Topt,C. The single optimal offset was selected that minimized estimated HVAC energy use and maintained annual relative concentrations less than 1. No such constraint exists in the zonal varQ control, and Topt,H and Topt,C are selected as the combination that minimizes HVAC energy use and maintains annual relative concentration below 1. This change increased optimization time requirements, but also improved energy performance substantially.

VarQmz

As with the varQ controller, the varQmz saves energy by shifting ventilation flows to mild weather periods, but by directing ventilation flow more efficiently to where the occupants are in the dwelling, this control can also reduce the total outside airflow required to provide equivalent pollutant exposure. This reduction in flow has ventilation fan energy benefits, particularly for higher-energy using supply and balanced fan types. It operates on the same control and pre-optimization principle as the varQ control, but it extends the controller to have zonal ventilation capabilities and it is aware of zone occupancy during optimization and operation. The varQmz control is simulated with only 2 control zones, the Bedrooms versus all other zones (e.g., the Kitchen, Wet and Common zones). Compared with the non-zonal varQ control, the varQmz should increase energy savings by directing the controller-specified fan flows into the occupied zones, which reduces the relative concentration in the zone where people are. By making the ventilation flows more effective for the dwelling occupants, the control parameters can be further refined to reduce total airflow and increase energy savings. When the optimization is performed using this occupied zone relative concentration, the Topt,H and Topt,C parameters are pushed further away from the annual maximum and minimum temperatures than they are for non-zonal varQ, which means the required whole dwelling airflows are reduced for the same outdoor temperature.

When the dwelling is occupied, the flow called for by the controller is divided between the occupied and unoccupied zones with an 80/20 split. This directs most of the airflow to the occupied zones. The 20% flow to the unoccupied zones helps to limit contaminant levels there. The Bedroom zone is controlled independent from the other zones, so when it is occupied, it receives 80% of the whole dwelling flow, and 20% when unoccupied. The Other zones are a combination of the Kitchen, Common and Wet zones. When any one of those zones is occupied, the 80% is split between the non-bedroom zones according to their floor areas (and the same is done at the 20% flow rate when these zones are vacant). If the dwelling is vacant, or people are in both the Bedroom and Other zones, then the required fan flow is split according to floor area fractions.

When selecting optimized control parameters for the varQmz controller, we use closely matched zone occupancy patterns for the Bedrooms, Other zones, and whole dwelling occupancy. The optimization estimates the relative concentration in each of the two zones based on the fan flow at each time-step, the natural infiltration flows for each zone, the zone target 62.2 ventilation rate, and the zone volume. The fan flows are determined by the varQ control calculation. The natural infiltration was determined for each zone using the whole dwelling infiltration prediction from the AIM-2 model. This whole dwelling flow was then assigned to either the Bedroom or Other zones based on the floor area fractions. The whole dwelling ventilation rate target was calculated using 62.2-2016, which was divided between zones by the floor area fractions. The zone volumes followed directly from the specified dwelling volume and the zone floor area fractions.

varQmzSingleZoneOpt

The varQmzSingleZoneOpt uses the same control code as the varQmz controller, but it uses control parameters calculated using the non-zonal varQ control. The intention is to maintain the energy savings from the varQ non-zonal controller, but to provide that flow more effectively to where occupants are located in the dwelling. This could potentially reduce their personal contaminant exposures, while saving energy.

Zone Occupancy Controls

zoneExposure

For each zone, the ventilation system is operated under two conditions: (1) if the zone is currently occupied and the zone relative exposure or relative dose exceeds 1 (i.e., the relative exposure or dose is greater than its corresponding base case); or (2) if the zone is unoccupied and the zone relative exposure exceeds 5. The fans are off in all other conditions. This control type is most similar to the occupancy controls simulated in the single zone, Phase I simulations, but in Phase II, it is applied on a zonal rather than a whole-dwelling basis. In the non-zonal work, when the dwelling was vacant, the relative exposure was controlled to a limit of 5, and when occupied, the dwelling relative exposure and relative dose were controlled be less than or equal to 1. This same approach is used here for each zone independently.

This controller is not aware of where occupants were before entering the zone of interest or the state of their current integrated contaminant exposure. If, for example, a person was exposed to high contaminant levels in the kitchen, this level of concentration exposure is not considered in the ventilation control when they move to another zone.

This controller is intended to maintain equivalent IAQ while reducing HVAC energy use. Savings are achieved by reducing the total outside airflow required to provide equivalent pollutant exposure.

zoneASHQexposure

The zoneASHQexposure controller behaves identically to the zoneExposure controller described above, but it uses a different relative exposure metric. As described in Section: Control Metrics, the zoneExposure control uses 62.2 relative exposure estimated for each zone, where the zoneASHQexposure uses a relative exposure value estimated from CONTAM's prediction of the zone generic contaminant concentration, compared against the steady-state generic concentration that would occur at the whole dwelling target ventilation rate from 62.2 (Qtotal).

occExposure

The occExposure control type is similar to the zoneExposure control, except that the controller has perfect knowledge of each occupant's exposure history, and this information partially determines the ventilation fan operation in each zone. For each zone, the person with the highest relative dose (i.e., integrated 24-hour exposure) is treated as the worst case, and the zone's ventilation is controlled in an effort to reduce that person's integrated exposure to less than 1. Ventilation is operated in a zone if the zone is currently occupied, and either the zone relative exposure is above 1, or the worst-case zone-occupant's relative dose is greater than 1. This is assessed for each zone independently. So, unlike the zoneExposure controller, if a person had high exposure in the kitchen, and they then moved into the common zone, the ventilation equipment in the common zone would actively account for and operate in order to reduce the personal exposure that occurred in the adjacent zone.

This approach requires that a controller be aware of each individual's exposure history, which would be more challenging to implement than a sensor that merely assesses if anyone is in the zone. While technologically unlikely, the occExposure controller represents what a smart control could do if it had perfect knowledge of each occupant's zone-contaminant history.

This controller is intended to maintain equivalent IAQ while reducing HVAC energy use. Savings are achieved by reducing the total outside airflow required to provide equivalent pollutant exposure.

occASHQexposure

The occASHQexposure controller behaves identically to the occExposure controller described above, but it uses a different relative exposure metric. As described in Section: Control Metrics, the occExposure control uses 62.2 relative exposure estimated for each zone, where the occASHQexposure uses a relative exposure value estimated from CONTAM's prediction of the zone generic contaminant concentration, compared against the steady-state generic concentration that would occur at the whole dwelling target ventilation rate from 62.2 (Qtotal).

occupantVenter

This controller delivers the zone's floor area weighted ventilation flow, but only when the zone is occupied. For example, if the Bedroom is 28% of the total dwelling floor area, then 28% of the whole dwelling ventilation airflow is directed to/from the Bedrooms when they are occupied. With a ventilation system sized to provide the code-minimum airflow, this control would worsen occupant pollutant exposures and degrade IAQ. To ensure that IAQ is equivalent, the ventilation system flows are over-sized in this control type, initially by a factor of 50%. Further refinement of this over-sizing will surely be needed to ensure equivalent IAQ in all cases.

This controller is intended to maintain equivalent IAQ while reducing HVAC energy use. Savings are achieved by reducing the total outside airflow required to provide equivalent pollutant exposure.

Contaminant Controls

contaminantDwelling

The contaminantDwelling smart control uses real-time pollutant measurements to control ventilation operation and flow rates. This control operates on two different time-scales — chronic and acute. Chronic exposure is assessed using 24-hour average concentrations, while Acute uses the instantaneous concentration (as predicted by the simulation tool at one-minute time steps). The ventilation fan operates if any contaminant in any zone exceeds its Chronic or Acute threshold. Thresholds are based on health-relevant limits or guidelines from international jurisdictions (e.g., the World health Organization, the US EPA, OEHHA). This control type is operated using all ventilation system types, including both zonal and non-zonal system types.

All contaminant-based ventilation controls (contaminantDwelling, contaminantZone, contaminantZoneOcc) used the time-step and 24-hour pollutant thresholds detailed in Table 15.

Table 15: Contaminant Control Threshold Limit Values, Time-step And 24-hour.

Contaminant	***Time-Step Threshold***	***24-Hour Threshold***
Formaldehyde (μg/m$^{3)}$	55 (OEHHA 1-hr)	9 (OEHHA 8-hr and Chronic)
Particles (μg/m^3)	25 (WHO 24-hr)	10 (WHO Chronic)
CO2 (ppm)	5000	1100
Relative Humidity (%)	60	60

contaminantZone

The contaminantZone control operates using the same Chronic and Acute thresholds and time-periods as the contaminantDwelling controller, but it does so independently for each zone in the dwelling. This control ventilates a zone if any contaminant in the zone exceeds its 24-hour Chronic or its instantaneous Acute control thresholds. This decision is made independently for each zone in the dwelling, such that zero, one, or more than one zone could be ventilated simultaneously. The contaminantZone control is only simulated using zonal ventilation system types, as mechanical flows must be capable of being controlled independently in different zones.

contaminantZoneOcc

The contaminantZoneOcc controller builds upon the logic of the contaminantZone control, but it adds the additional condition that the zone must be occupied, and it must exceed its threshold concentration (Chronic or Acute) for at least one contaminant type. Again, this control type is simulated using only zonal ventilation system types, as zones must be controlled independently of one another.

Aereco RH Demand Controls

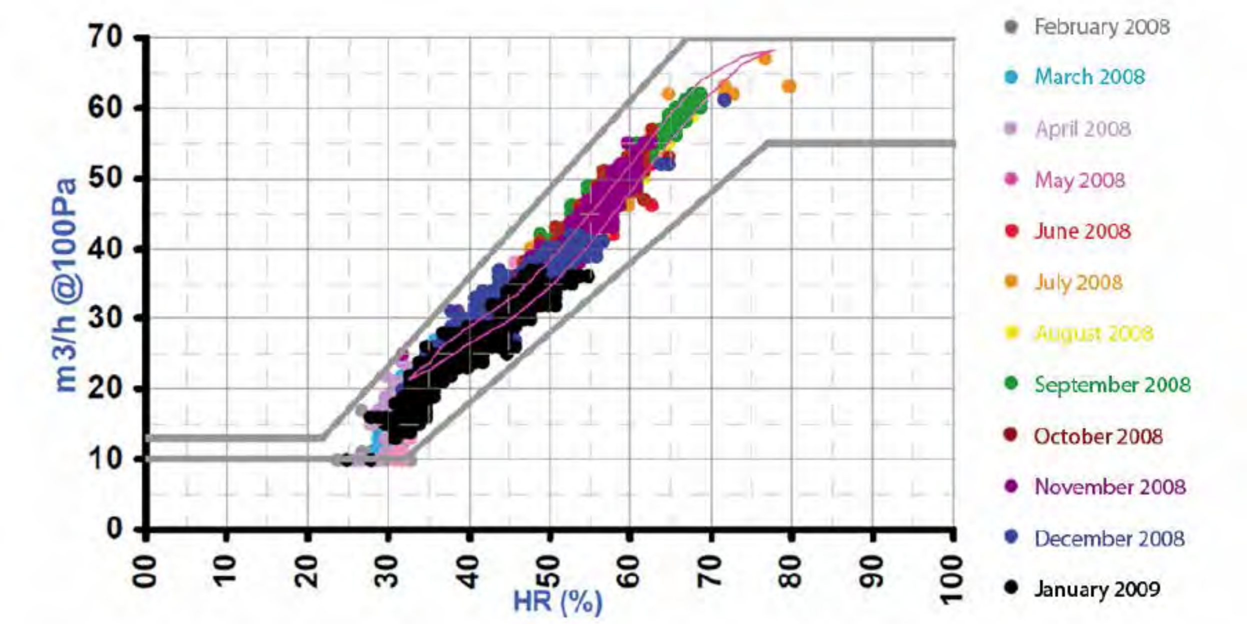
aerecoRH

The aerecoRH controller is an implementation of an existing smart ventilation control product produced by the European company Aereco. The product works with three components, a central exhaust fan, which is connected to exhaust inlet devices in each wet room, and finally, variable-opening supply inlets placed in exterior walls of dry rooms (bedrooms, living room, etc.). The exhaust fan was oversized, the same as other smart controllers. As implemented in this work, the variable supply inlets and variable exhaust units are all relative humidity sensitive, such that they get reduce airflows and inlet openings during dry conditions, and they increase ventilation and inlet sizes during humid indoor conditions. The control assumes that the zone RH is a surrogate for occupancy and for occupant-driven pollutant emissions. Figure 8 shows how the airflow varies with humidity for an Aereco control. Notably, the controlled inlet paths located in the dry zones did not include any particle removal, which distinguishes them from the other envelope leaks, which assumed a removal efficiency of 50%.

At each time-step, each wet zone votes for an extract flow rate based on the zone relative humidity. The extract zone votes are summed to determine the whole dwelling extract flow rate. The total flow cannot exceed the extract fan flow limit. Also at each time-step, the inlets located in the dry rooms adjust their opening area according to the RH in the zone they are located in. The exhaust unit flow rates and inlet opening areas were linearly scaled between minimum and maximum values that were recommended by Aereco engineers.

We expect that future work will refine these inputs and aerecoRH assumptions to ensure the control performs adequately in US dwellings and climate regions. Future development can also include exhaust unit and air inlet sensitivity to other parameters, such as measured CO_2, particles or zone occupancy signals.

Figure 8: Illustration of Aereco Controller Air Flow Changes With Humidity



From Aereco – Performance Project – Large Scale Study of Demand-Controlled MEV in Occupied Dwellings. Grey lines indicate manufacturers tolerance envelope and the dots are measured field data.

Metrics

Baseline Reference Cases

Each smart control case is compared against a code-compliant baseline constant flow case, using the baseFan control type. This reference case is used for energy savings calculations, and also for derivation of personal relative contaminant exposures. These values are scaled against the baseline reference case, such that values less than one mean personal exposure was reduced, and values above one mean personal exposure was increased.

For smart controls, the reference baseline case is the dwelling with exactly identical features that is operated using baseFan. So, for a zonal smart control case using an MPexhaust fan, it is compared against the exact same dwelling operating an MPexhaust fan at constant flow. If the control uses an MPsupply fan, so does the baseline. Conversely, for the non-zonal varQ control type, if the dwelling uses an SPexhasut fan, then this case is compared against the baseline case using that same SPexhaust fan type, sized to 62.2 and operated constantly.

What is critical to remember is that all of these cases use a different reference point, so we cannot simply compare the personal relative contaminant exposures to figure out if one control was better than another, at least not in cases where the reference is different. Instead, we can only tell how each control performed relative to its particular reference case. For example, an SPexhaust reference case might lead to a personal formaldehyde exposure of 20 µg/m^3, while the control case is 18 µg/m^3. This control case would show up as having a personal relative formaldehyde exposure of 18/20 = 0.9. The same dwelling with a MPsupply fan might have reference concentration of 16 ug/m3 and a control concentration of 17 µg/m^3, and its personal relative formaldehyde exposure would be 17/16 = 1.0625. In this example, the control with an MPsupply system actually led to a lower personal concentration than the same control with an SPexhaust, but the SPexhaust has a relative value less than one, while the MPsupply is above one. This illustrates how each case is accurate relative to its baseline condition, but that comparison between cases with different baseline cases is not possible.

In some of our data plots and in the summary tables we include the actual personal concentrations, so that some of these differences can be observed.

Energy Metrics

We use several energy metrics in this work, primarily HVAC ventilation energy savings and HVAC total energy savings, which can be expressed as absolute kWh savings, or as relative % savings. Our energy estimates include only HVAC energy end uses, including heating, cooling, ventilation fans, and HVAC recirculation fans.

The ventilation energy savings is the energy savings relative to the energy use added to the dwelling by baseline compliance with the ASHRAE 62.2-2016 standard. We refer to the HVAC energy added by baseline ventilation as the "ventilation energy use", which includes both fan energy and all associated HVAC loads. Ventilation energy use is calculated as the difference between total HVAC for the baseFan case minus the baseNoFan case.

Ventilation Energy = (baseFan – baseNoFan)

The smart control savings are calculated as the difference between the total HVAC for the smart control Case minus the baseFan energy use.

Ventilation Energy Savings (kWh) = (Case – baseFan)

The fractional savings are calculated as follows:

Ventilation Energy Savings (%) = (Case – baseFan) / (baseFan – baseNoFan)

In some cases, we also report the total HVAC energy savings, which are the ventilation energy savings relative to the whole dwelling baseFan HVAC energy use.

Total Energy Savings (%) = (Case – baseFan) / (baseFan)

These basic saving calculation approaches are used for different HVAC energy metrics, including site, TDV (using CEC TDV compliance values), and time-of-use (based on time-of-use structure described by CAISO-proposed time-of-use periods).

IAQ Metrics

The primary IAQ metric that we use is **personal contaminant exposure**, which we define as each person's exposure history in the dwelling to each contaminant of concern. Each zone has a slightly different concentration, and as the people are scheduled to move around from one zone to another, their personal exposure history tracks the concentrations in the zone they are in at each time-step for the entire year. Periods absent from the dwelling are treated as NA-values. In post-processing, this time-series of personal concentration is then averaged or otherwise summarized. For example, we extract the 95th percentile personal exposure for each contaminant to assess potential acute pollutant exposures in each dwelling. Unless otherwise stated, we have only reported p1 personal exposure values in this report, because we determined that p1 was almost always the worst-case person in the model, as they were involved in all cooking events.

This metric aligns with the aims of zonal ventilation controllers that include occupancy signals, because the main idea of these control types is that a controller might only need to provide adequate ventilation in the occupied zones. In this case, we only want to assess concentrations in the zones that are occupied, because the unoccupied zones or dwelling are being purposefully under-ventilated and are intended to have higher contaminant concentrations.

Results

The following sections provide a summary of the IAQ and energy performance results for the zonal smart ventilation control simulations and a more detailed results description for the best control types. The IAQ and energy impacts are discussed for each of the simulation parameters, such as dwelling prototype, envelope leakage, ventilation fan type, etc. For simplicity, the occupant exposures are for the occupant following the workday pattern who does the cooking (i.e., the occupant that has the highest potential exposure to indoor contaminants).

Smart Control Performance

14 individual ventilation control strategies were simulated in this work. These strategies fall into one of several categories.

- Baseline + IAQ Controllers
- Zone Occupancy Controllers
- Outdoor Temperature Controllers
- Contaminant Controllers

We will discuss the performance of the controls based on these categories, because they exhibit distinct IAQ and energy behaviors that are most usefully discussed separately. Tabular summaries of IAQ, site energy and TDV energy performance are provided in Tables 16-59 for each control type tested in this work.

In Figure 9, we compare the personal generic contaminant relative exposure (x-axis) against the whole dwelling annual HVAC energy savings (y-axis) attributable to the smart ventilation controls in all simulations executed in this work. Plot symbols are colored according to the control type, and plot shapes represent the ventilation system type. Successful controllers would be in the upper-left hand quadrant of the plot, indicating positive energy savings and reduced personal exposure. Very few cases both saved energy and provided acceptable or improved IAQ. Many cases saved energy but at the expense of worse IAQ (higher exposure) or improved IAQ by using more energy (negative energy savings). The generic contaminant has a somewhat linear relationship with HVAC energy savings, because the generic exposures respond nearly linearly with changes in ventilation rates and associated energy savings. All contaminants responded differently to changes in ventilation rates, and these same results are plotted along with personal particle exposures in Figure 10 to illustrate the lack of a linear relationship.

Zonal smart ventilation controls were not effective in the multi-family apartment dwellings. This was largely because in all but two scenarios (multi-point and single-point balanced fan types in CZ16), the baseline constant flow fan cases actually provided sufficient ventilation cooling that annual HVAC energy use was decreased, rather than increased by code-compliant ventilation. This rendered most of the zonal smart controls ineffective, as many rely on reducing outside airflow to save energy. These effects are discussed in greater detail in the Dwelling Prototype section examining simulation parameters.

Figure 9: Site Energy Total HVAC Savings (%) and Personal Generic Relative Exposure for All Prototypes.

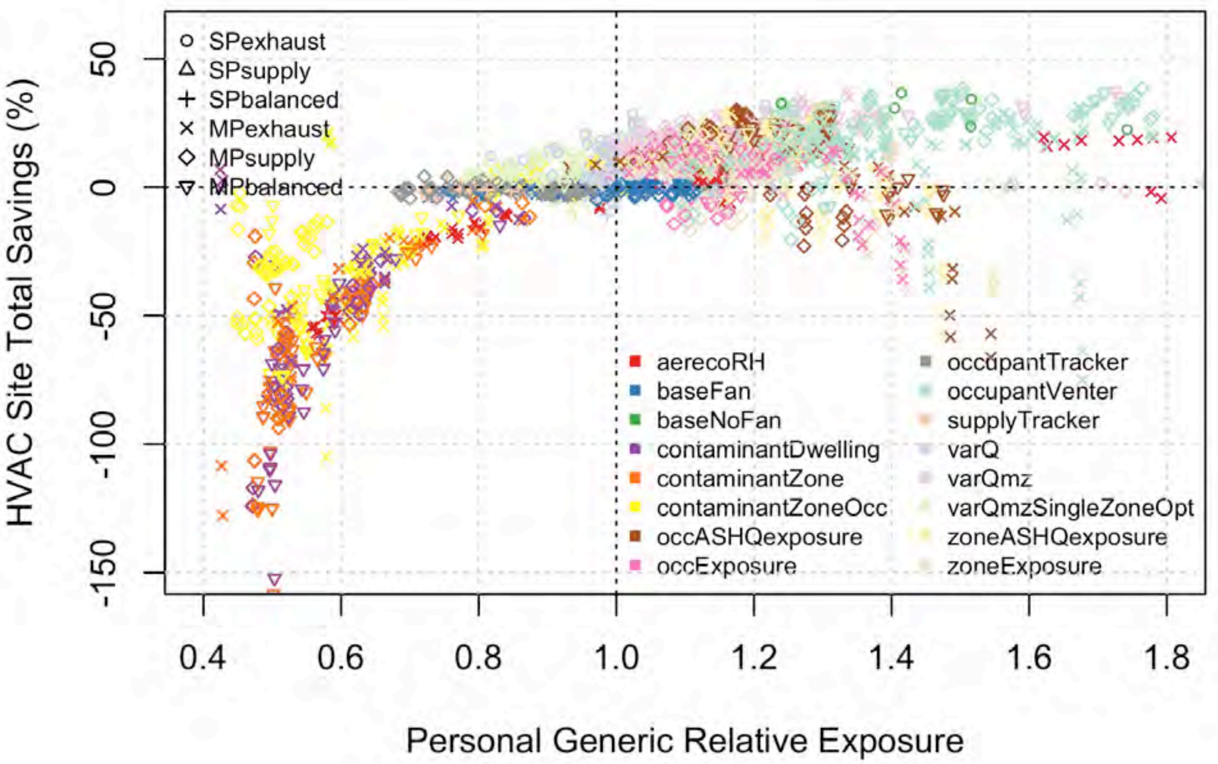
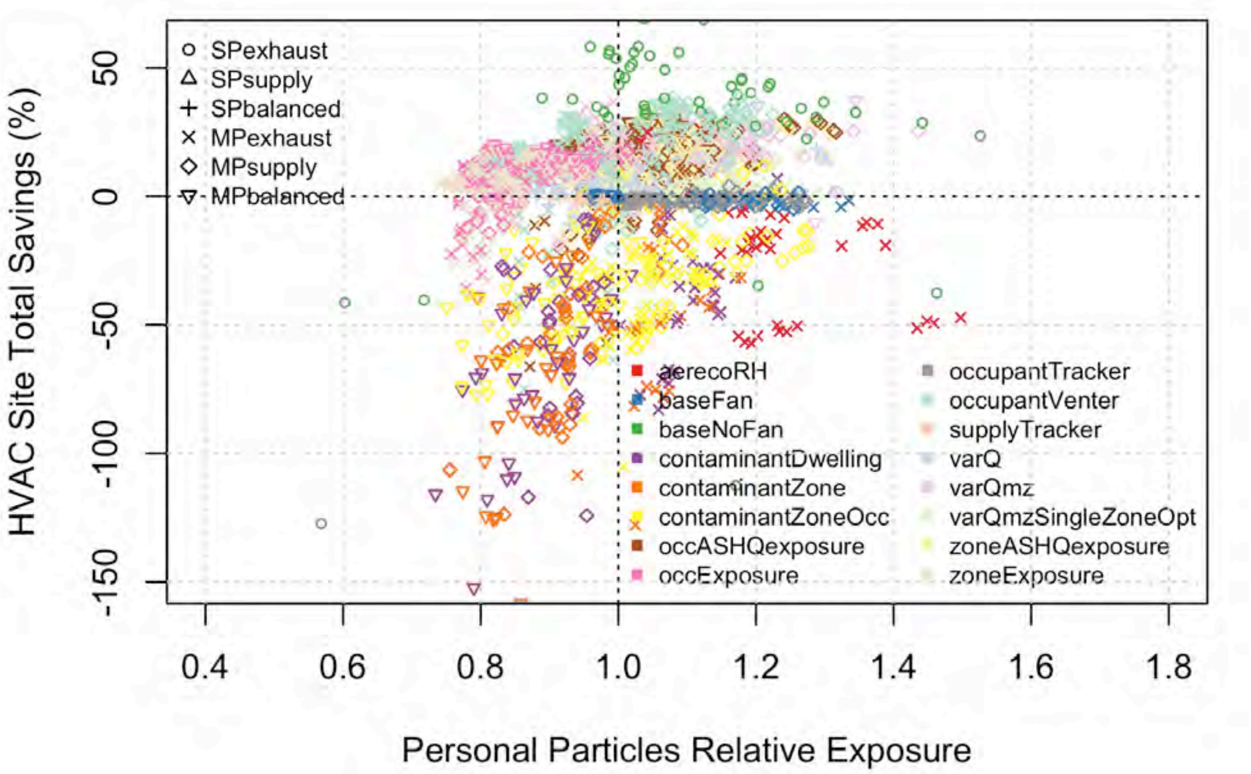


Figure 10 Site Energy Total HVAC Savings (%) and Personal Particle Relative Exposure for All Prototypes.



We used the **Baseline** constant flow ventilation fan cases to compare the performance of zonal and non-zonal ventilation equipment without any controls. Balanced fans had the highest ventilation rates and typically the lowest personal pollutant exposures. These were followed by exhaust fans, which tended to have marginally lower exposures and higher ventilation rates than supply fans. CO_2 was an exception, where supply fans outperformed exhaust. When zoned, balanced fans worsened pollutant exposures (from 0.1 to 4%, on average) compared with the non-zonal balanced fan cases. When exhaust fans were zoned, they slightly worsened generic and particle exposures (by 0.6 to 2%, on average), while slightly reducing formaldehyde (0.3%) and reducing CO_2 (3.5%) exposures. For zoned supply fans, the personal exposures dropped for the generic contaminant, formaldehyde and CO_2 (by 1 to 4%, on average), and got worse for particles (9%). These results indicate that zoning has small effects, and we do not suggest strong support in the building codes to encourage zonal ventilation systems for whole dwelling ventilation.

The **Contaminant** controls achieved the greatest exposure reductions, but they increased the annual HVAC energy use by between 0 and 150%. These controls were dominated by their inability to control formaldehyde concentrations to below the 9 µg/m^3 OEHHA target, so they more than doubled the dwelling ventilation rate during all time-steps. The **Baseline + IAQ** control types (occupantTracker and supplyTracker) were designed to have no effect on HVAC energy use, and indeed they are aligned at 0% savings on the y-axis. They were designed to deliver ventilation flows to occupied zones to make the ventilation more effective at providing good air quality, and for the generic contaminant they decreased personal exposures by roughly 5-25%. Other non-particle contaminants were reduced typically by 5-10%. Personal particle exposure for these occupant-tracking controls was worsened by 0 to 20%, particularly for supply and balanced fan types.

The **aerecoRH** controller has been developed for heating-dominated climates and based on increasing ventilation when indoor humidity is high. The scaling of the inlet openings and exhaust flows with zone relative humidity was not optimized for some of the California climates that we assessed. The mild climates in CZ1, 3 and 10 had substantially increased ventilation rates compared with the constant fan baseline cases because the aereco control was able to ventilate at up to twice the baseline air flow rate. This did reduce median non-particle exposures by 8-24%, but total HVAC energy use also increased, by 6 to 20%. CZ16 in the colder dryer mountain regions was the only case where ventilation rates were reduced and energy savings were achieved (median of 19% whole dwelling HVAC savings), but this worsened all personal exposures (from 8 to 78%, depending on the contaminant of interest). Any future development of the aerecoRH controls will require an optimization effort to identify appropriate methods to scale ventilation with RH, such that energy savings and adequate IAQ performance are achieved. The IAQ performance of the inlets would be improved compared to the other systems. In this study, the envelope removed outdoor particles at 50% efficiency and the supply systems at 90% efficiency. Note that this level of particle removal is rare in current supply systems but is a new requirement in California.

The three **Outdoor Temperature-Based** controls (varQ, varQmz and varQmzSingleZoneOpt) achieved a range of ventilation energy savings, from roughly 0 to 80%. TDV ventilation energy savings were even greater than site savings, because these controls reduced ventilation flows during peak cooling and heating demand periods. Whole dwelling HVAC savings for exhaust fan cases averaged 14% for single-zone optimized controls and 22% zonally optimized controls. The varQ and the varQmzSingleZoneOpt controls always delivered the same dwelling airflows at each time-step, so their energy performance is nearly identical. The varQ was a non-zonal control using single-point fan types, while the varQmzSingleZoneOpt was a zonal control that used multi-point fan types to distribute the same ventilation flows to occupied zones. This zonal distribution of the same outside airflows reduced the personal generic contaminant exposures by roughly 5-20%. The non-zonal varQ achieved the same energy savings, but its personal generic exposures were arranged reasonably tightly around the reference value of 1, meaning they neither made exposure better or worse. Individual cases sometimes worsened exposure, but always by less than 10%. These two control types increased the annual outdoor ventilation airflows, and attempted to reduce energy use by shifting to mild weather periods. This worked for low-energy exhaust fan types, but savings were drastically reduced for both supply and balanced fan types (both zonal and non-zonal), whose increased fan power requirements for moving more air over the year offset the potential energy savings. The varQmz controller used the same strategy to vary ventilation flows with outdoor temperature, but it was optimized assuming zonal ventilation capabilities and zonal occupancy patterns. The design intent was to increase HVAC energy savings beyond the varQ cases, but to still maintain equivalent contaminant exposures by more effectively delivering outside air to occupied zones. Unfortunately, while energy savings did in fact increase substantially, so did exposure to the generic contaminant, which was worsened by anywhere from 0 to 50%. This controller clearly showed promising energy savings, and it may be possible to further refine the optimization of the control parameters to find a balance between improved energy performance and acceptable personal pollutant exposures. Notably, this outdoor temperature controller reduced annual outside airflows, so it actually had increased energy savings when using the supply and balanced fan types, because it reduced fan energy on top of reducing heating/cooling loads.

The remaining control types are considered **Zone Occupancy Controllers**, and they all used zone occupancy signals with zonal ventilation equipment to attempt to ventilate only occupied spaces, which would lead to reduced annual outside airflows and energy savings. They used different strategies in their attempts to track personal exposures and to manage them to acceptable levels. For example, the occExposure and zoneExposure controls both used a version of the relative exposure calculation methods contained in ASHRAE 62.2-2016 to estimate relative exposure in the different zones of the dwellings, and to then control the zone fans based on either zone exposure or integrated occupant exposures. They met their design intent and reduced exposure to a generic continuously emitted contaminant, but they often increased exposure to specific contaminants. The occASHQexposure and zoneASHQexposure controls instead used the real-time generic contaminant zone concentrations from CONTAM to estimate a similar relative exposure metric for each zone and person in the dwelling. These controls were not more effective than occExposure and zoneExposure. They did effectively reduce annual outside airflows and save substantial HVAC energy (typically from 0 to 35% of total HVAC energy), but almost universally increased personal generic pollutant exposures. This worsening of personal exposure ranged anywhere from 5-10% worse to upwards of a 75% increase in contaminant exposure for the dwelling occupants.

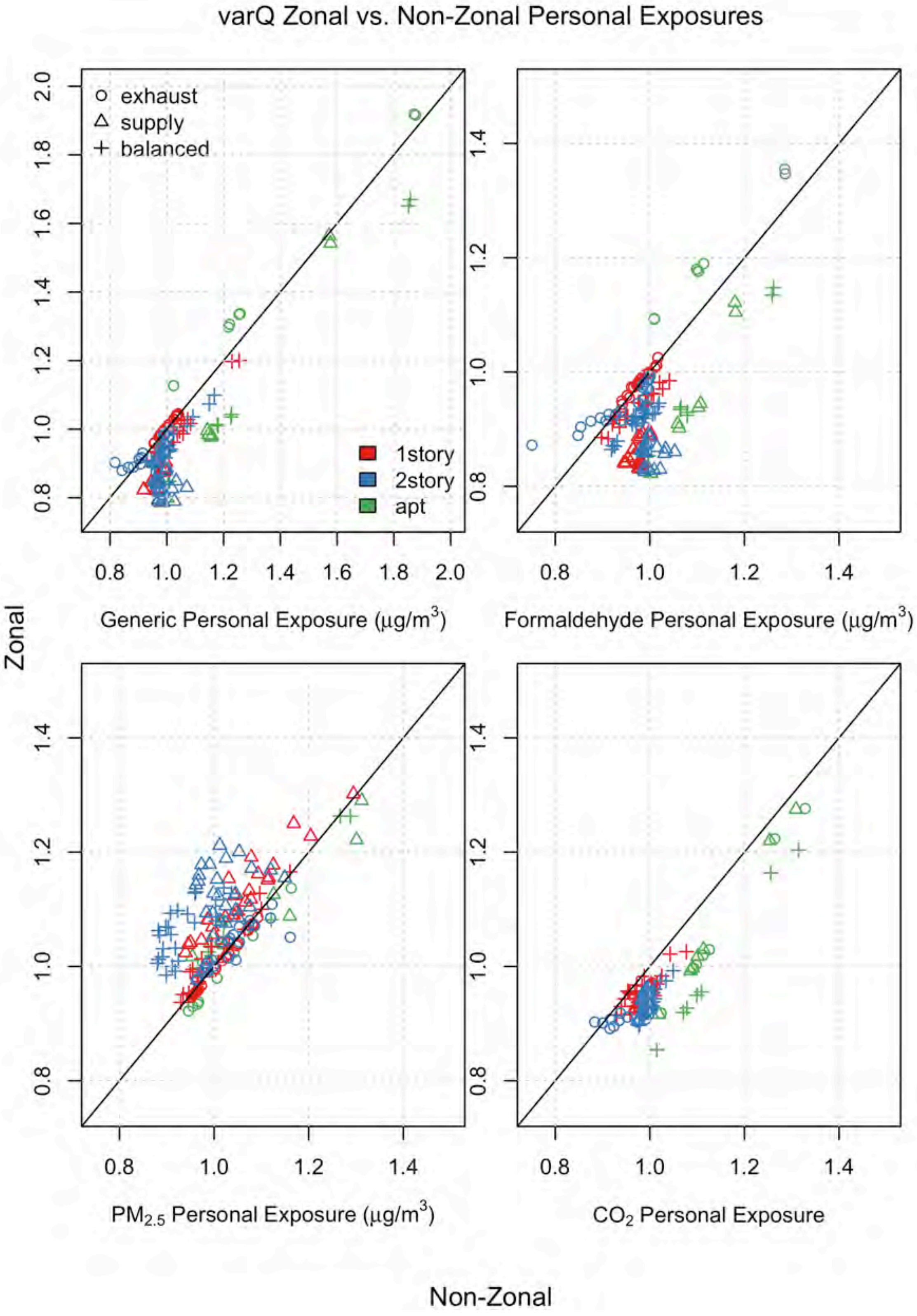
Other contaminants behaved distinctly from the generic contaminant results shown above, as they have different emission rates, locations, removal mechanisms and associations with occupancy patterns. For example, formaldehyde exposure followed similar patterns to the generic contaminant shown above, but the changes in personal exposure were generally much smaller—both in terms of the benefits and the harms—and they were never improved or worsened by more than 30%. This was the result of the formaldehyde emission rate model used in this work, which tended to increase formaldehyde emissions as ventilation rates increased and to decrease emissions as ventilation rates decreased. Similar feedbacks were embedded in the emission rate model based on the dwelling formaldehyde concentration. The result was that formaldehyde concentrations were generally much less sensitive to ventilation rates or zonal controls than was the case for the generic contaminant.

Personal particle exposures were distinct from the other three contaminant types. For many control types that appeared to worsen generic contaminant exposures, the personal particle exposures were actually reduced or maintained at or near 1. This was especially the case for control types that targeted reduced annual outside airflow, such as the occExposure or occupantVenter controls. These showed increased personal generic exposures that averaged 32% worse, but they reduced particle exposures by 2%. Reduced ventilation rates tended to reduce particle exposure, because outdoor particle concentrations were non-negligible. Consistent with this, control types that increased annual outside airflows (e.g., varQ and varQmzSingleZoneOpt), which maintained good personal generic contaminant exposures consistently increased personal particle exposures, typically by 5-20%.

Furthermore, because particles had substantial outdoor concentrations, the improved zonal effectiveness of multi-point, zonal balanced and supply fan types meant that they often increased occupant particle exposures. This was the case even for the Baseline + IAQ control types, which otherwise successfully reduced exposures without increasing energy use. They worsened personal particle exposures, because they were more effective at delivering the outdoor pollution to the dwelling occupants.

This variability by contaminant type is pictured in Figure 11, where the varQ personal exposures (x-axis) are plotted against the varQmzSingleZoneOpt personal exposures (y-axis) for each contaminant. We see that in 1-story dwellings (blue symbols), the zonal controller with zoned ventilation equipment reduced personal exposures for the generic contaminant, formaldehyde and CO_2 (lower right quadrant), but it consistently increased particle exposure (upper left quadrant). We also observe that the benefits and the harms are greatest for supply fan types, and are typically the least for exhaust fan types, except for CO_2.

Figure 11: Comparison of Zonal and Non-Zonal varQ Controller.



Overall Best Control Types

Many zonal smart controls were tested, and only a subset of them achieved their design intent, and effectively all of them (even those that achieved their intent) had mixed personal exposure impacts on the different contaminants. No controller could be said to always maintain equivalent personal exposures for all contaminant species. Particles are cited as the dominant contaminant of concern for chronic health outcomes in dwellings (Logue, Price, Sherman, & Singer, 2012), so one could very well argue that any increase in particle exposure likely outweighs the benefits from reducing exposures to the other contaminants. Without a unifying metric for evaluating the overall health impacts of these changes in personal exposures, we cannot reliably say which controls offer the best IAQ performance.

Many of the zonal occupancy controls had the greatest energy savings (e.g., varQmz, zoneASHQexposure, zoneExposure, occupantVenter, occExposure or occASHQexposure), but they also had substantial negative impacts on personal contaminant exposures. The non-zonal varQ control tended to maintain most non-particle exposures to near-equivalent levels, while providing consistently good energy performance. Yet, the overall increase in outside airflow often increased particle exposures by 5-10%. If particles dominate chronic health effects in dwellings, then this may be an unacceptable outcome. In contrast, the zoneExposure controller that reduced the annual air flow provides a mirror image for changes in contaminant exposures. All non-particle exposures are increased, but particle exposure tended to be reduced by between 0 and 20%. To the extent that particles dominate health, this control could provide substantial health benefits while also consistently saving energy. The occExposure control performed similarly, with marginally higher energy savings.

Based on these results, we consider it difficult to justify the additional cost and complexity of zonal ventilation systems and controls. If evaluated using a unified metric that properly balances reductions in particle exposure against increases in other contaminants, then these controls might be justifiable in some contexts.

For now, the non-zonal varQ controller provides the strongest energy savings, while maintaining fairly consistent relative contaminant exposures. We show the varQ site ventilation energy savings for each case for the 1-story central forced air home in Figure 12, along with the personal exposures for each contaminant. The same results are shown for TDV ventilation energy savings in Figure 13. The corresponding plots for the 2-story dwelling are shown in Figure 14 and Figure 15. The varQ achieves ventilation energy savings in most climate zones and envelope leakages, but energy savings are nearly eliminated in most climates when using supply or balanced fan types, due to their much larger fan energy uses and the tendency for the varQ control to increase annual ventilation airflow. The heating and cooling loads are sufficient in CZ16 to over-come these supply fan energy penalties, whereas in the other milder climates of CA, the fan energy increase overwhelms the heating and cooling load savings. When using an exhaust fan in the 1-story dwelling, the varQ controller consistently achieves between 50 and 75% TDV energy savings, and roughly 50% site ventilation energy savings. Savings are marginally lower in the 2-story dwelling with exhaust fans, with most cases in CZ3, 10 and 16 achieving between 30 and 50% site ventilation savings, and 40 to 50% TDV savings in CZ3 and 16. Much higher TDV savings >70% were found in the 2-story cases in CZ10. These savings represent anywhere from 0 to 25% of whole dwelling HVAC energy use. Median (calculated across all prototypes) on-peak whole dwelling HVAC site energy savings were 14% when using exhaust fan types, and super on-peak whole dwelling savings of 11%.

Figure 12: 1-story, HPfau Cases. varQ Controller Site Ventilation Energy Savings, Plus Personal Relative Exposure For Each Contaminant.

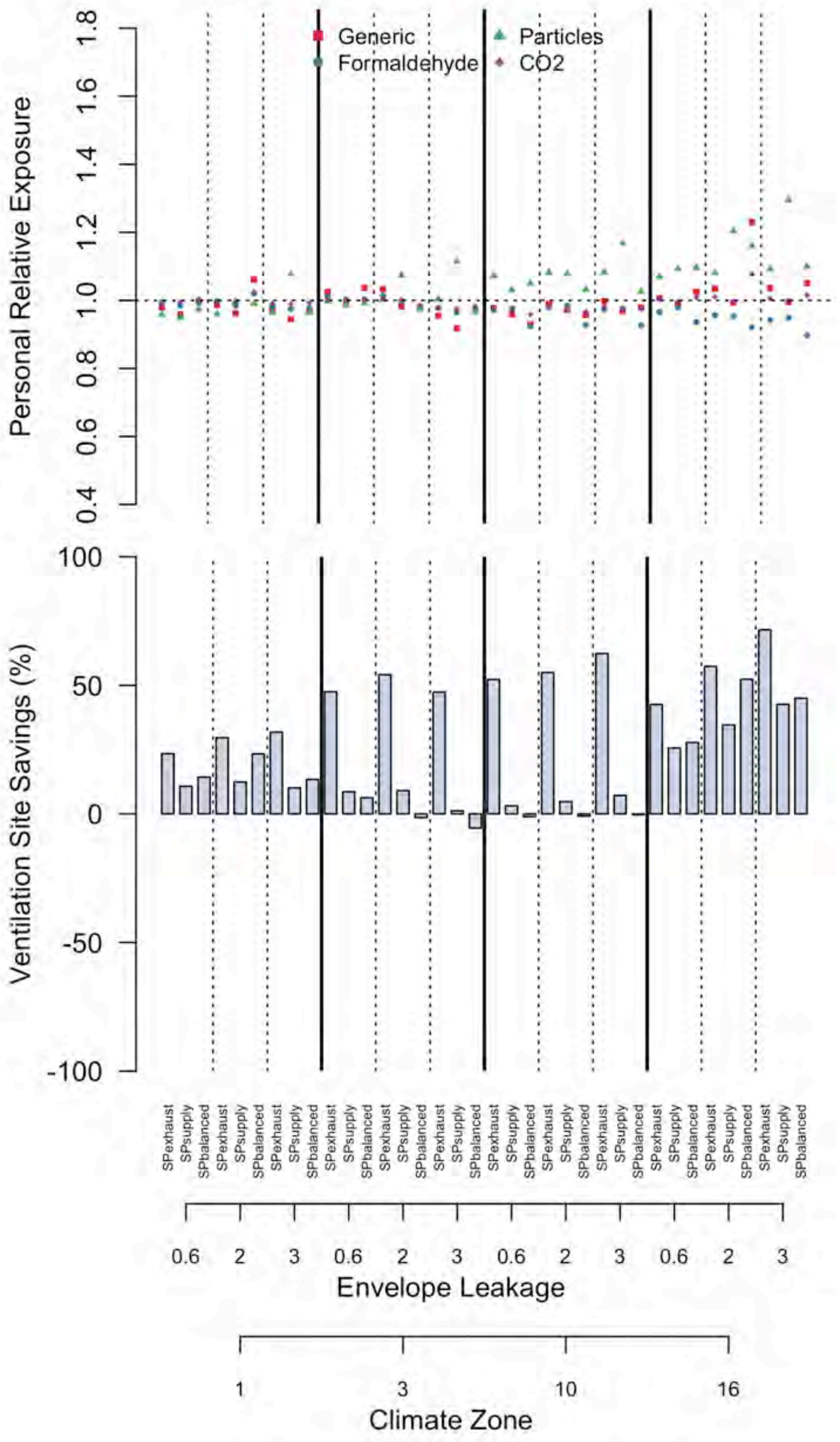


Figure 13: 1-story, HPfau Cases. varQ Controller Ventilation TDV Energy Savings, Plus Personal Relative Exposure For Each Contaminant.

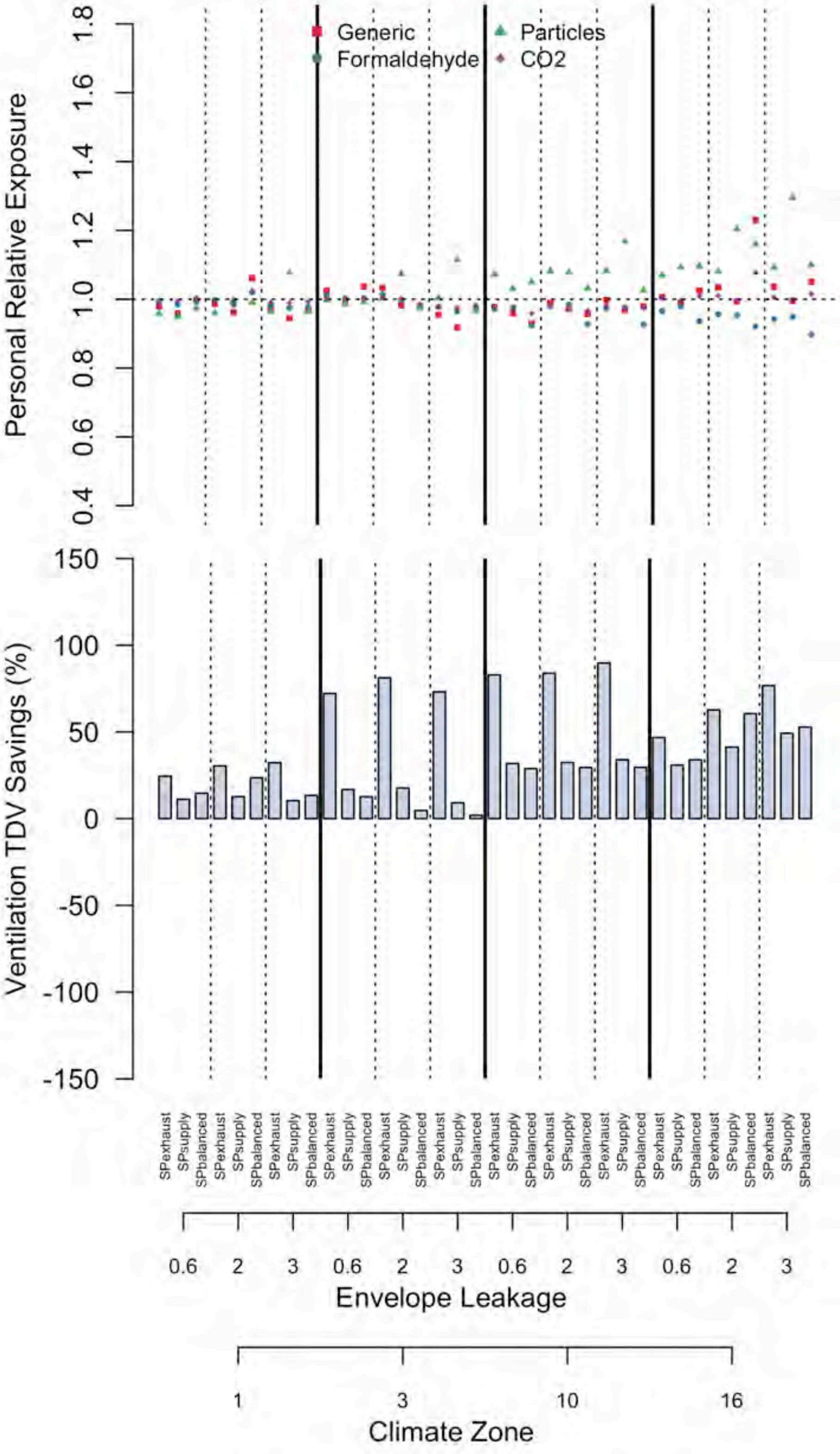


Figure 14 2-story, HPfau Cases. varQ Controller Site Ventilation Energy Savings, Plus Personal Relative Exposure For Each Contaminant.

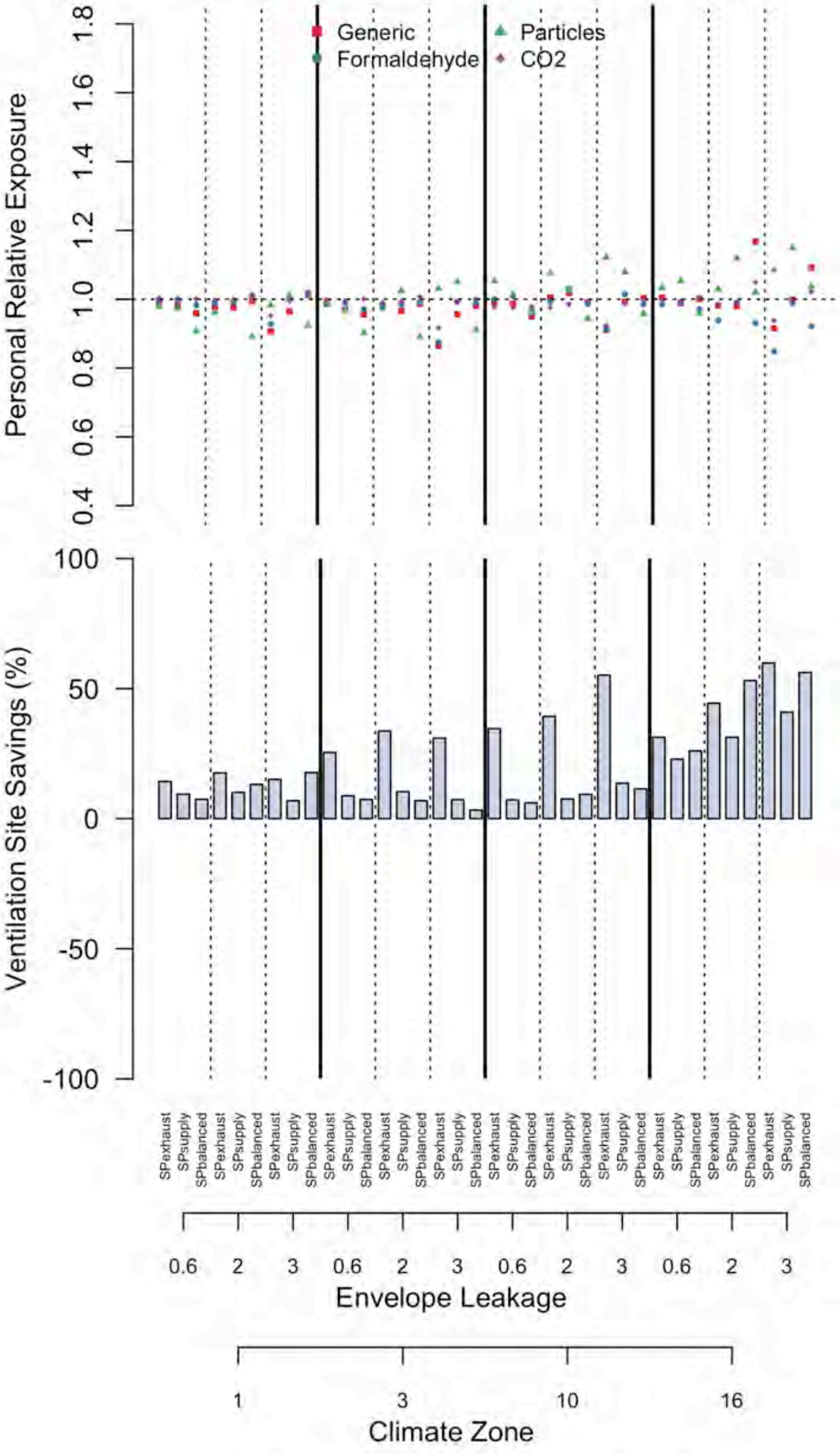
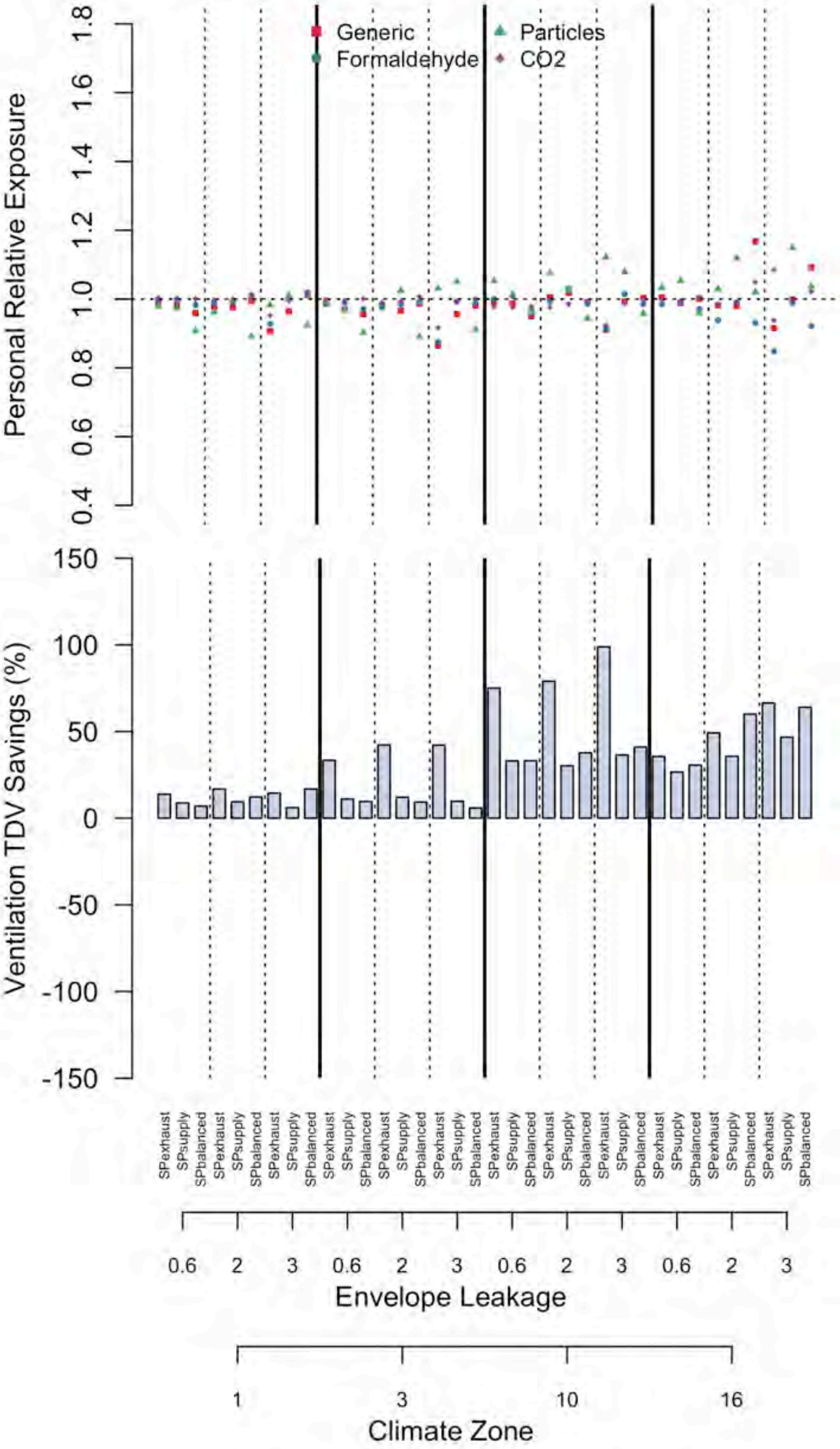


Figure 15 2-story, HPfau Cases. varQ Controller TDV Ventilation Energy Savings, Plus Personal Relative Exposure For Each Contaminant.



Factors Assessment

Our simulations were varied across a number of parameters. These included:

- HVAC System Type
- Ventilation System Type
- Dwelling Prototype
- Envelope Leakage
- Climate Zone
- Number of Control Zones

We explore the impacts of each of these parameters in the subsections below, typically with a focus on the IAQ and energy impacts of the parameter. Where appropriate, we attempt to add further nuances related to other important factors, for example, the different impacts by dwelling prototype of the varying ventilation fan types.

HVAC System Type

Two HVAC system types were simulated in this work—ductless mini-split heat pumps (VRF) and a forced air unit heat pump (HPfau). The HPfau system includes a MERV13 filter, which will remove particles from the dwelling during HVAC system operation, while the VRF system has no filtration benefit. The HPfau system utilizes a typical air hander configuration, with a single central return in the Common zone and distributed supply flows to each zone. When this system operates, it drives inter-zone mixing. Mixing by a forced air handler can reduce the differences in contaminant levels between the zones in a dwelling, by making it more well-mixed and uniform. This mixing can distribute to adjacent zones pollution from point-source events, such as cooking and bathing, which can either increase or decrease personal exposures, depending on where the person is in the dwelling. The VRF mini-split systems do not intentionally drive inter-zonal mixing between the zones in the dwelling.

The type of HVAC system had little impact on personal pollutant exposures, with the exception of personal particle exposure, which was always lower when using the HPfau systems, which were equipped with MERV 13 filtration. The zone-to-zone mixing provided by the HPfau systems had no apparent benefit for personal exposures to the other contaminants. In most climate regions, the value of the central filtration was low in single-family dwellings, largely due to the very low system runtimes (at most 7% annual heating runtime for baseline 1-story cases) and low system airflows in these high performance low-load homes. CZ10 and 16 showed the greatest benefit in terms of reduced particle exposure with the HPfau system type. Apartment dwellings had the greatest personal particle exposures, and they correspondingly had the greatest benefits from the filtration provided by the HPfau equipment. We expect that in locations or dwellings with greater HVAC runtimes, these benefits would be more evident.

The HPfau systems had higher annual HVAC energy use (see Figure 16 for a comparison of site energy by HVAC system type), which we attribute in equal parts of improved VRF system efficiency and to the HPfau air handler energy use. The elevated HVAC energy use of baseline HPfau systems meant that absolute energy savings from smart controls were somewhat higher for HPfau system. Similarly, if HVAC energy use was increased by smart controls (as in the contaminant control types), the energy use increases were magnified when using the HPfau system type. The relative percent ventilation energy savings were higher for HPfau systems for control types that used outdoor temperature to time-shift flows, but were nearly identical for control types that reduced outside airflow through occupancy tracking and zonal controls. Despite the apparent greater savings for HPfau cases, the lowest energy consuming approach was to combine the VRF system with smart controls.

Figure 17 shows a comparison of the personal contaminant exposures for each pollutant using the HPfau (x-axis) and the VRF (y-axis) HVAC systems. Point shapes represent the prototype (circle for 1-story, triangle for 2-story, and plus sign for apartments), and color represents the climate zone. Points falling to the upper left of the unity line represent cases where personal exposure worsened with the VRF system. The generic contaminant and formaldehyde are uniformly emitted throughout the dwelling and are not affected by filtration or mixing, so we expect the impacts of HVAC system type to be marginal. In Figure 17, we observe that the HVAC system type has very limited impact on the generic contaminant, CO_2 or formaldehyde personal exposures, as most points fall on top of the unity line. CO_2 is only emitted in occupied zones, yet based on the CO_2 personal exposures, we observe that mixing from the HPfau system contributes little to reducing exposure to localized pollutant sources. In contrast, the VRF system increased personal particle exposure in almost all cases (see the lower left hand pane in Figure 17), which supports our argument that the predominant non-energy impact of HVAC system type was due to particle filtration in the HPfau systems, and not from increased mixing. In single-family dwellings, the greatest increases in exposure for VRF systems occurred in CZ16. The increased particle exposures with the VRF system were even more notable in the apartment prototypes, where CZ10 cases were most negatively impacted. This is likely because the apartment dwellings were typically cooling dominated, and CZ10 has the highest cooling loads. These benefits for the HPfau system type are likely a combination of particle filtration in the forced air handler, along with the distribution of cooking contaminants to other zones away from the cook. Personal CO_2 exposures were just slightly lower when using the HPfau system, but we would not consider these differences to be meaningful. Again, the CO_2 impacts are greatest in the CZ10 apartment dwelling cases. The effects for all four contaminants described above were similar for 95th percentile personal exposures as well, with small benefits attributable to the HPfau system for personal particle exposure.

Overall, these IAQ impacts are marginal in most cases, though particle exposures were reduced in select climates and prototypes. Very low HVAC system runtimes are responsible for these limited impacts. For baseline constant fan cases, the median heating runtimes were 6.2% and 3.6% for the VRF and HPfau systems, respectively. Cooling runtimes in these cases were 2.4% and 1.6%. Forced air unit HVAC systems do not mix the dwelling or provide filtration when they are not operating, and these systems simply did not operate enough to meaningfully impact the IAQ in the simulated dwellings. These low runtimes reflect the low loads due to very well-insulated and sealed envelopes along with California's mild climates. We observe that the VRF systems had roughly double the runtime, though even these runtimes are very low. We considered runtime to be any period during which heating or cooling energy use was not 0. We hypothesize that the VRF systems had more runtime, because each zone was conditioned independently from the others (though to an identical set-point schedule). Because conditioning in the zones was not perfectly aligned in time, we expect this makes the system runtime appear much longer, even though the heating/cooling output is similar or less.

Despite higher runtimes, the VRF systems used less annual HVAC energy for baseline constant flow fan cases (see Figure 16). For example, median baseline constant fan energy use was 1,551 kWh for the VRF dwellings compared with 2,007 kWh for HPfau cases. This reduced energy use for VRF systems has three potential causes. First, is the improved efficiency of the variable refrigerant flow system compared with the unitary heat pump model in EnergyPlus. Second, is the zoning of space conditioning, which restricts the delivery of heating and cooling loads to only those zones outside temperature set-points. This ensures only the zones requiring conditioning receive it. These first two explanations reduced the heating energy use in baseline cases from a median of 1,181 kWh to 810 kWh per year in HPfau vs. VRF systems, respectively. Finally, the air handler energy use is substantial for the HPfau cases. For baseline constant fan cases, the median HPfau air handler fan energy use was 203 kWh, compared with only 28 kWh per year for fan energy in the VRF system. The improved efficiency of the VRF system and the reduction in air handler energy use appear to be roughly equal in effect, and both contribute together to higher energy use for HPfau systems.

Consistent with this, HPfau cases simulated with smart controls that used outdoor temperature (e.g., varQ, varQmz, varQmzSingleZoneOpt) had higher absolute and percentage ventilation energy savings. For the varQ controller, the median ventilation energy savings for all of the HPfau system cases averaged 18% compared with only 10% for the VRF system (193 vs. 77 kWh site energy savings). This distinction does not appear to exist for the control types that used occupancy sensing to reduce annual outside airflow. For example, the median site ventilation energy savings are 25% for both the VRF and HPfau system types when using the occExposure controller. This lack of distinction by HVAC system type is also the case for occupantVenter, zoneExposure and other such control types. For these control types, the absolute kWh savings are somewhat higher for the HPfau systems, for example, 435 vs. 356 kWh saved each year for the occupantVenter cases. Again, while the relative and absolute savings appear greater for the HPfau systems, the VRF system using the smart control appears to always be the scenario that uses the least energy.

Figure 16 Comparison of Site Energy Performance by HVAC System Type. All Prototypes.

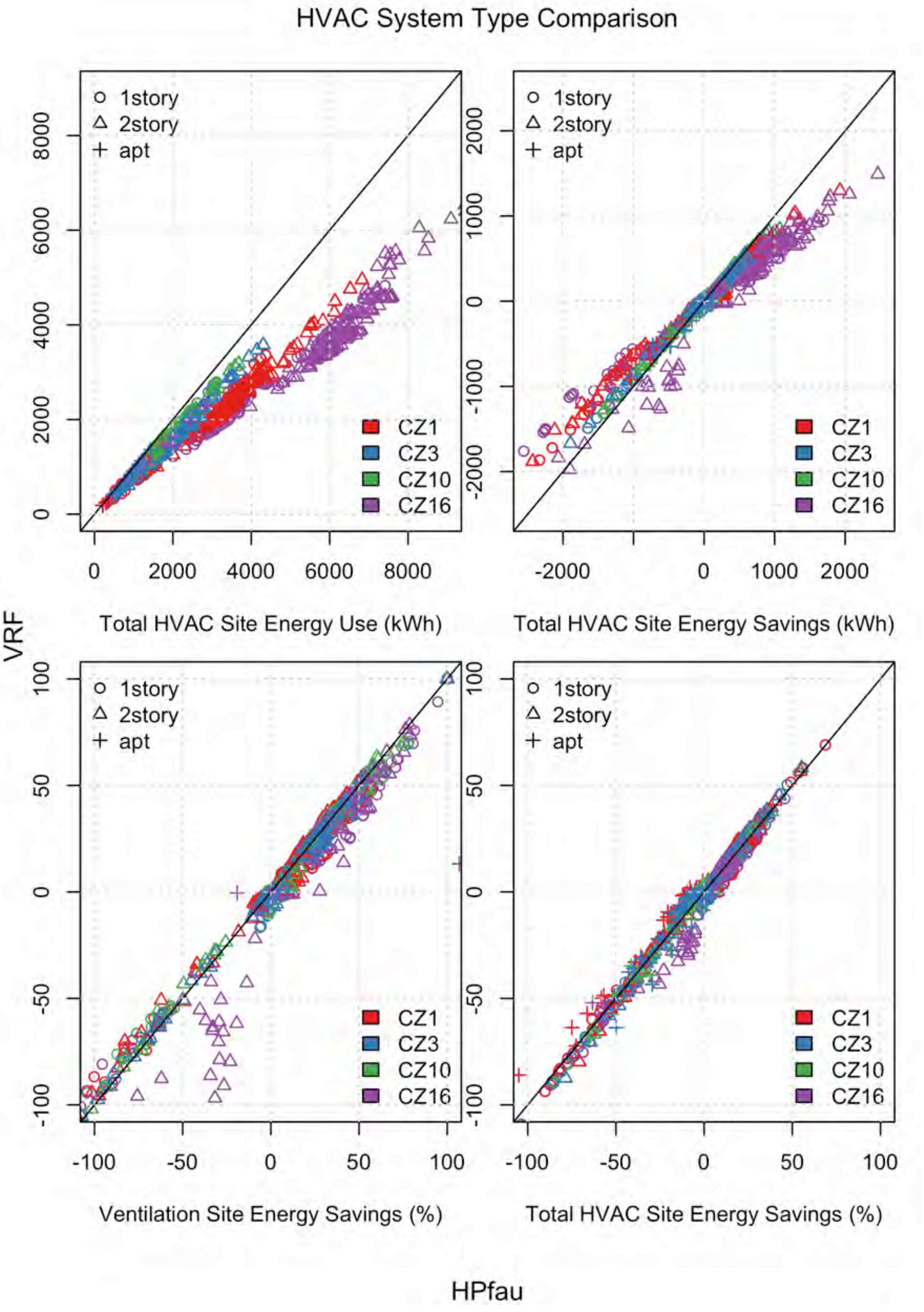
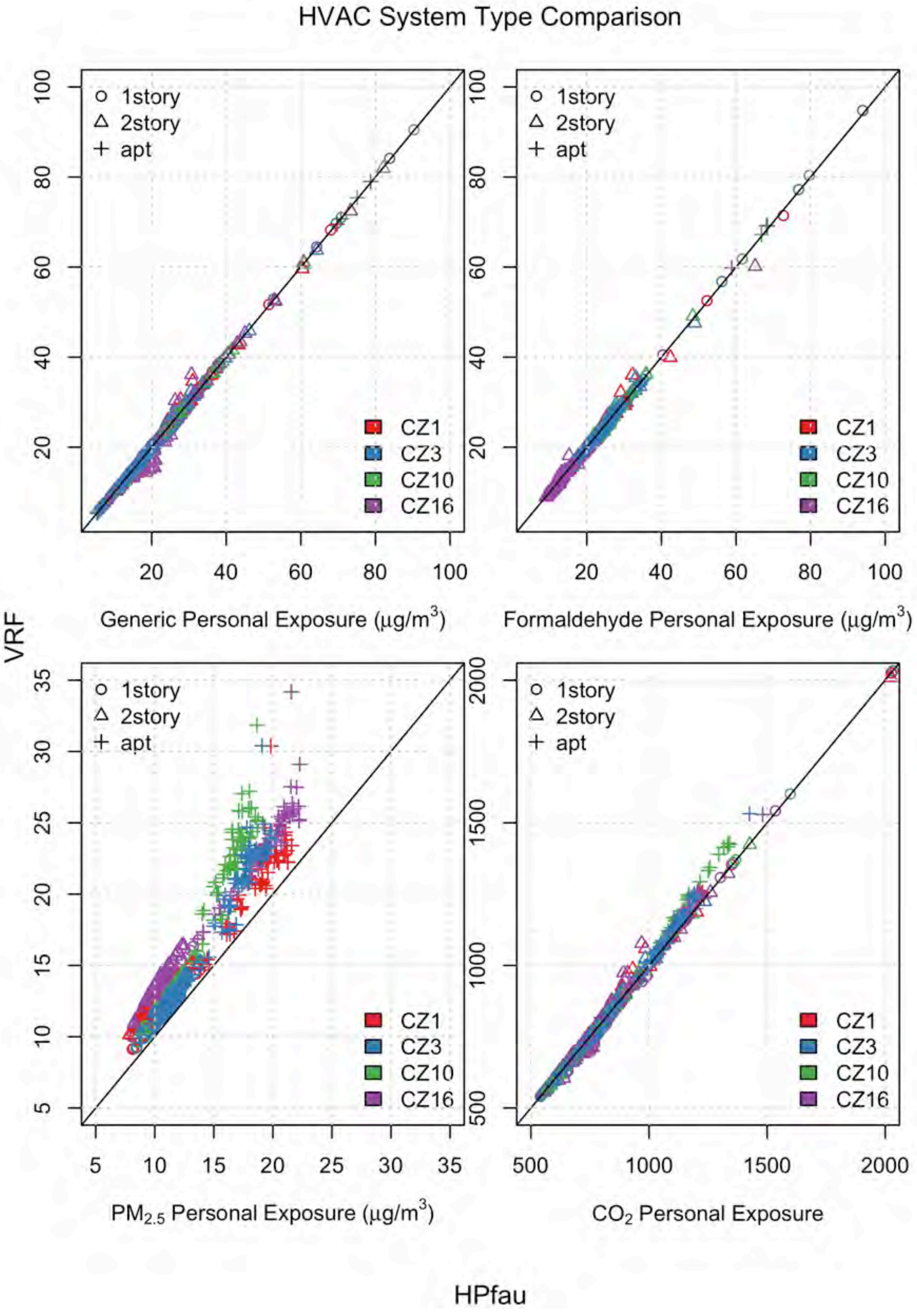


Figure 17: Comparison of Personal Contaminant Exposures by HVAC System Type. All prototypes.



Ventilation System Type

We identified that ventilation system types have very different behavior in terms of their ability to ventilate zonally, their energy performance, and IAQ impacts. These impacts are important in both baseline constant flow fan scenarios, as well as in smart control cases. All of these factors are discussed in detail in the sub-sections below.

Overall, we observe the following about the three fan types:

1. **Exhaust fans** behave the least zonally, and, in most cases, have little impact on personal exposure through being zoned. The primary exception is any scenario where large concentration gradients exist between zones, in which case, the exhaust fan located in the zone with the higher concentrations is very effective at reducing personal exposure. CO_2 personal exposures are an example of this, because they are dominated by exposure while sleeping in bedrooms with doors closed, making bedroom exhaust fans very effective. The other example is the 2-story dwelling, where the 2nd story contaminant concentrations tended to be elevated compared with the 1st level. When exhaust fans were placed in zones on the 2nd level of the dwelling, their efficacy greatly increased. Cases using exhaust fans have the lowest energy use. For smart controls that increase annual outside airflow, but do so during mild weather periods, exhaust fans have the greatest savings, because the increase in fan energy is typically small. For smart controls that track occupancy and reduce annual outside airflow, the marginal benefit is smallest for an exhaust fan, though when paired with these controllers, exhaust fan dwellings still use less energy than balanced and supply fan cases. The whole dwelling ventilation rates and personal exposures provided by exhaust fans lies between supply and balanced fan types.
2. **Supply fans** are highly capable of providing zonally directed outside airflow, and as a result, using a zoned supply fan can reduce personal pollutant exposures for the generic contaminant, formaldehyde and CO_2 compared to a single-point non-zonal supply. Like the other fan types, zoning the supply fans tended to increase personal particle exposure, likely due to non-negligible outdoor particle concentrations paired with the supply fan's ability to more effectively deliver outdoor pollution to the occupants. This occurred despite the use of MERV13 filtration on the supply ventilation flows. Supply fan cases achieved the lowest mean dwelling infiltration rates, but their high fan energy made them the second highest energy using scenarios, just slightly below balanced fan cases. This high fan energy meant they achieved greater levels of savings when using smart controls that reduced annual outside airflow, but they performed poorly (in most climate zones) for control types that increased annual outside airflow (e.g., temperature-based or contaminant controls). This may not be the case in climates with greater heating and/or cooling demand, or with supply systems with lower fan energy.

3. **Balanced fans** were similarly capable of zonally directed outside airflow, and they provided the highest dwelling ventilation rates. Typically, this meant the balanced fan cases provided the lowest personal exposures, with the highest annual HVAC energy use. Yet, the balanced fan types tended to worsen personal exposures when they were zoned (balanced flows within each zone), compared with the non-zonal balanced cases (balanced flows within the dwelling). This may be due to increased supply airflows to the most commonly occupied zones in the non-zonal balanced fan configuration. As with supply fan types, balanced fans had the greatest ventilation energy savings for controls that reduced annual outside airflow, and the worst performance for controls that increase annual flows.

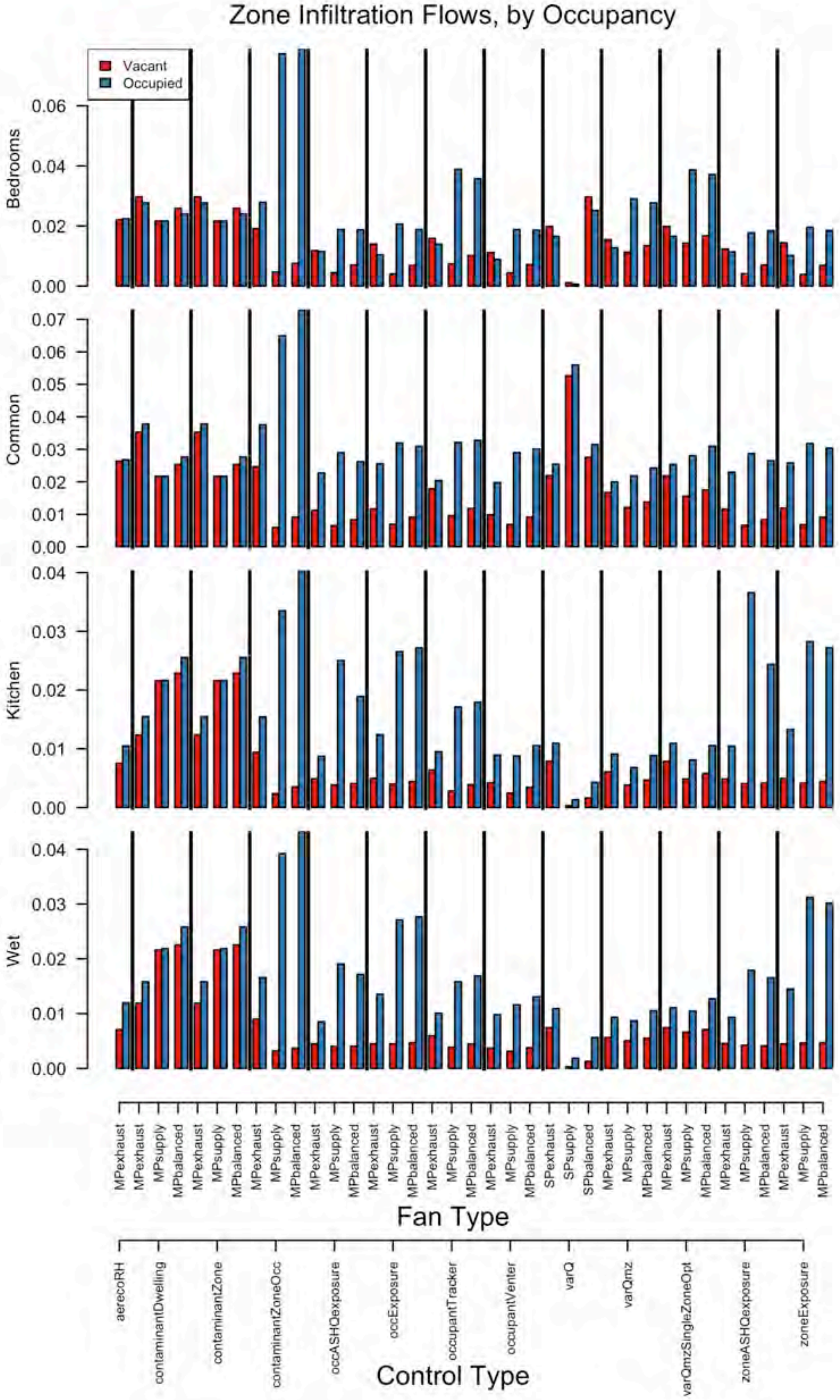
Ability to Act Zonally

In most scenarios, supply and balanced fan types are more capable of acting zonally. By "acting zonally", we mean they are able to direct outside airflow to the desired zone when it is occupied. Supply airflows are directly moved from outdoors to the supply fan outlet, which for a zonally controlled ventilation system, can be directed to exactly where the occupants are located. By contrast, an exhaust fan located in a zone does not deliver outside flow to the zone that is equal to 100% of the exhaust fan flow rate. Instead, exhaust fans tend to evenly distribute make-up airflows across the leaks in the envelope based solely on the pressure induced across the leaks by the exhaust fan. The result is that an exhaust fan behaves less zonally, because it tends to distribute its flow throughout the entire dwelling, rather than focus it in the zone containing the exhaust fan inlet. The outside flow to the zone containing the exhaust inlet may be less than half the fan airflow. This is a benefit of exhaust fan ventilation, in that fan placement in the dwelling is not critical to the ventilation flows in the zones, but this same behavior limits this fan type's ability to behave zonally.

An exception to this is when large contaminant concentration gradients exist between the zones in the dwelling, due to either localized emissions (kitchens, bathrooms and bedrooms) or to pressure and outside airflow patterns in the home. In this scenario, a zonal exhaust strategy with a fan located in the zone with an elevated concentration works much more effectively than a non-zoned exhaust strategy located elsewhere in the dwelling. As noted above, examples of when local, zoned exhaust fans were effective in the zonal simulations include: (1) the removal of cooking and bathing emissions, (2) the removal of CO_2 from within closed bedrooms during sleeping hours, and (3) the removal of contaminants from the 2nd floor of the 2-story dwelling, where low outside airflows in non-zonal cases led to elevated concentrations. These situations all support the efficacy of exhaust fans as appropriate for zonal ventilation control.

A ventilation fan type that achieves zonal ventilation should be able to maintain different outside air ventilation rates in a zone based on its occupancy status. In Figure 18, we show the mean outside air infiltration rates for each zone when vacant and when occupied, averaged for each control type using each of the three ventilation fan types. Each controller ventilates the occupied zone(s) preferentially in an attempt to make ventilation flows more effective. For most cases shown, the exhaust fan type maintains similar infiltration rates during both vacant and occupied periods. In contrast, both the supply and balanced fan types have large differences in zone outside air infiltration when occupied vs. vacant. These fan types are able to behave zonally and actually deliver outside airflow to the desired zone, whereas the exhaust fan, though it operates in a zone that is occupied, does not substantially change the zone's outdoor air infiltration flow rate. Placing the exhaust fan in a different location does not meaningfully move ventilation to different zones of the dwelling, as it tends to ventilate all zones according to their leakage areas and pressure differences. Again, this remains true for all zonal exhaust fans, but sometimes localized elevated concentrations mean the localized fans still function effectively from a personal exposure perspective, even though they do not substantially boost the zone infiltration.

Figure 18: Infiltration (m^3/s) For Each Zone When Vacant vs. Occupied, by Control Type. 1-story dwellings, HPfau.



Differences in IAQ and Exposure

For assessing the importance of fan type and zoning configuration, we look solely at the baseline constant flow fan results, so that we can isolate fan-type impacts without introducing effects from ventilation controls.

In Figure 19, we show matching cases for exhaust, supply and balanced fan types for their single-point (x-axis) and multi-point (y-axis) configurations for 1-story dwellings with VRF HVAC systems (though all HVAC types behaved similarly). The same plot is provided for the 2-story dwelling in Figure 20. The personal contaminant exposures are plotted with a unity line, with fan type indicated by plotting symbol. Any points to the bottom right of the unity line represent reduced exposure for multi-point zonal fan types, and any points above the unity line indicate worsened personal exposure for multi-point zonal fan types.

We observe that the zonal vs. non-zonal fan configuration has differing impacts for each fan type, contaminant type and prototype. First, we will discuss the 1-story dwelling behavior, and then we compare that with the 2-story dwelling.

In the 1-story dwelling, the generic contaminant and formaldehyde exhibit similar behavior. For these contaminants, the supply fan type reduces personal exposure for the MP zonal configuration, the exhaust fan type has no effect from MP vs SP, and the balanced fans appear to marginally worsen personal exposure when in the MP zonal configuration. For particles, all fan types appear to worsen personal exposures when using the MP zonal configuration. As noted earlier, we hypothesize that this is the result of outdoor particle pollution being more effectively delivered directly to occupants when the ventilation system is configured to be zonal. Conversely, for CO_2 personal exposure, numbers are largely improved when fan types are in the MP zonal configuration. The greatest improvements are for exhaust fan types in the MP configuration, and select other supply and balanced fan cases have marginally worsened exposures in the MP zonal configuration.

Overall, the supply fans appear to have the largest changes when being zoned, and they more often than not, reduce personal exposures. The only exception was for particles, but each fan type worsened particle exposure when it was made zonal.

Exhaust fan behavior is the result of the effects we discussed above in terms of their ability to “act zonally”. The exhaust fans do not appear to meaningfully improve outdoor air delivery to the occupants. The exceptions, once again, are in bedrooms with closed doors during sleeping hours and in other zones with localized emissions, where we see a clear value to an exhaust device extracting from the bedroom/polluted zone.

When comparing the MP zonal and the SP non-zonal configurations, balanced fan types appear to perform worse in terms of personal exposure when zoned. Recall, that for the SPbalanced cases, air is supplied to bedrooms and common zones, and air is extracted from the wet rooms and kitchen. For the MPbalanced, each zone has both a supply and exhaust flow. The question is, why the balanced fans do not appear to get the benefit of supply flow delivered to each zone, similar to the MPsupply? The answer may simply be that when compared with the SP non-zonal balanced fan configuration, the supply flows to the most commonly occupied zones (i.e., the bedrooms and common) are actually reduced for the MP zonal balanced fans, which increases personal exposures. The total ventilation supply and exhaust flows remain the same, but in the MP zonal systems, they are distributed to each zone according to its floor area, whereas for the SP non-zonal cases, all of the supply flow is directed into either the bedrooms or common zone. This means that in the SPbalanced cases, more supply air is delivered to the most commonly occupied spaces, so the SPbalanced is actually better than the zonal version of the same fan type.

In the 2-story dwelling, the effects of zoning on the three fan types were markedly different for the baseline constant flow fan cases, as shown in Figure 20. Namely, the zonal exhaust and supply fan types show substantially reduced personal pollutant exposures relative to their matching non-zonal versions. An exception to this was the worsening of personal particle exposure when using the zonal exhaust fan. The balanced fan type showed the least difference in personal exposure when comparing zonal and non-zonal configurations, though the zonal versions tended to increase personal exposures very marginally for all contaminant types. These reductions in personal exposure associated with zonal ventilation systems are attributable to the different pressure and airflow distribution in the 2-story building – where the natural infiltration air flows and pressure distributions lead to significant differences in in and out flow for the two stories. In addition, there are substantial internal airflows occurring independently of the ventilation system for the 2-story home. For example, in the heating season stack and wind pressures act to increase inflow for the 1st story and outflow for the second story. For the non-zonal systems, the fan was always located on the 1st floor in the common zone. The exception is for the balanced non-zonal system, where supply and exhaust would have existed in the wet and bedroom zones on the 2nd level of the home. These balanced fan cases did not behave differently when fully balanced within each zone of the 2-story dwelling.

For non-zonal fan types, the placement of the supply or exhaust fan in the common zone on the 1st floor led to drastically lower ventilation rates on the 2nd level of the dwelling. Accordingly, formaldehyde concentrations are much higher on the 2nd floor than the 1st floor for all non-zonal ventilation types, especially for the SPsupply (15-17 μg/m^3 difference between floors), the SPexhaust (5 μg/m^3 difference) and the SPbalanced (3 μg/m^3 difference). The differences between the 2nd and 1st floors are entirely eliminated for the MPsupply fans, which have nearly identical concentrations in each zone/floor of the home. For MPexhaust, the 1st vs 2nd story differential remains static at ~5 μg/m^3, but concentrations in all zones go down by ~2 μg/m^3 when zoned. The MPbalanced concentrations increase marginally when zoned, but the difference between floors remains static.

In some cases, we observe much higher contaminant concentrations on the 2nd floor or the 2-story prototype dwelling. This effect varies predominantly by the ventilation fan type, fan zoning and envelope leakage. Exhaust fans in the most airtight dwellings (0.6 ACH_{50}) produce consistent contaminant concentrations throughout the dwelling, because the fan strongly depressurizes all envelope leaks, and the resulting outside airflow into each zone is simply proportional to its leakage area. When a home is tight enough to be so strongly exhaust fan-dominated, zoning the exhaust ventilation equipment makes no difference in contaminant levels whatsoever, because the airflows do not change in each zone. But as the single-point exhaust fan is used in leakier homes, the pressures induced by the exhaust fan begin to contend imperfectly with stack and wind pressures, which are typically positive at the top of the home (counter-acting some of the depressurization induced by the exhaust fan). The result is that the exhaust fan located in the 1st floor Common zone provides much more outside air exchange on the 1st floor compared with the 2nd floor. This leads to higher contaminant levels on the 2nd floor.

For baseFan cases in 3 ACH_{50}, 2-story dwellings, the generic Ashq contaminant concentration on the 2nd floor averaged approximately 32 $\mu g/m^3$, while the 1st floor in these same homes was only roughly 21 $\mu g/m^3$. This difference in concentrations was the result of a higher ventilation rate for the 1st floor zones. In an example case using a single-point exhaust fan in CZ3, the annual mean outside airflow into the 1st floor was 36 L/s (71% of the total in-flow for the dwelling), and the mean in-flow on the 2nd floor was only 15 L/s (29%).

When the exhaust fan type is made zonal in the 3 ACH_{50} 2-story dwelling, the difference between the 1st and 2nd floors remains similar (a rough 10 ug/m^3 difference between levels), but the concentration in all zones goes down (from roughly 32 to 27 $\mu g/m^3$ on the 2nd floor, and from 21 to 17 $\mu g/m^3$ on the 1st floor). This non-intuitive effect results from the increased effectiveness of the exhaust fan flows in each of the zones. This allows the same outside airflow to reduce concentrations in all zones. As part of a zonal exhaust system, the 2nd floor exhaust fans extract air at a higher concentration of contaminant, and the 1st floor zones do not receive contaminant mass transported from the 2nd down to the 1st floor, because inter-zonal mass flows are reduced by the consistent depressurization throughout the dwelling. We only observe this large exposure benefit from zoning the exhaust fan, when the dwelling is leaky enough to create concentration differences between zones. We do not observe this in the 1-story dwellings, because stack and wind pressures are never enough to substantially impact zone airflows.

As discussed in the Fan Type section above, the impact of adding zoning to a ventilation system (e.g., from single-point to multi-point exhaust) depends on the variability in contaminant concentrations between zones in the dwelling. If there is substantial variability in concentrations between zones, then zoning can provide a beneficial reduction in exposure. Contaminant levels vary between zones for two primary reasons: (1) emissions are localized in some zones and not in others (e.g., cooking or bathing), and (2) airflow patterns in the home and with outside are uneven between the zones, leading to localized high concentrations.

Figure 19: Comparison of Personal Contaminant Exposures for Multi-Point and Single-Point Fan Types. 1-story, VRF.

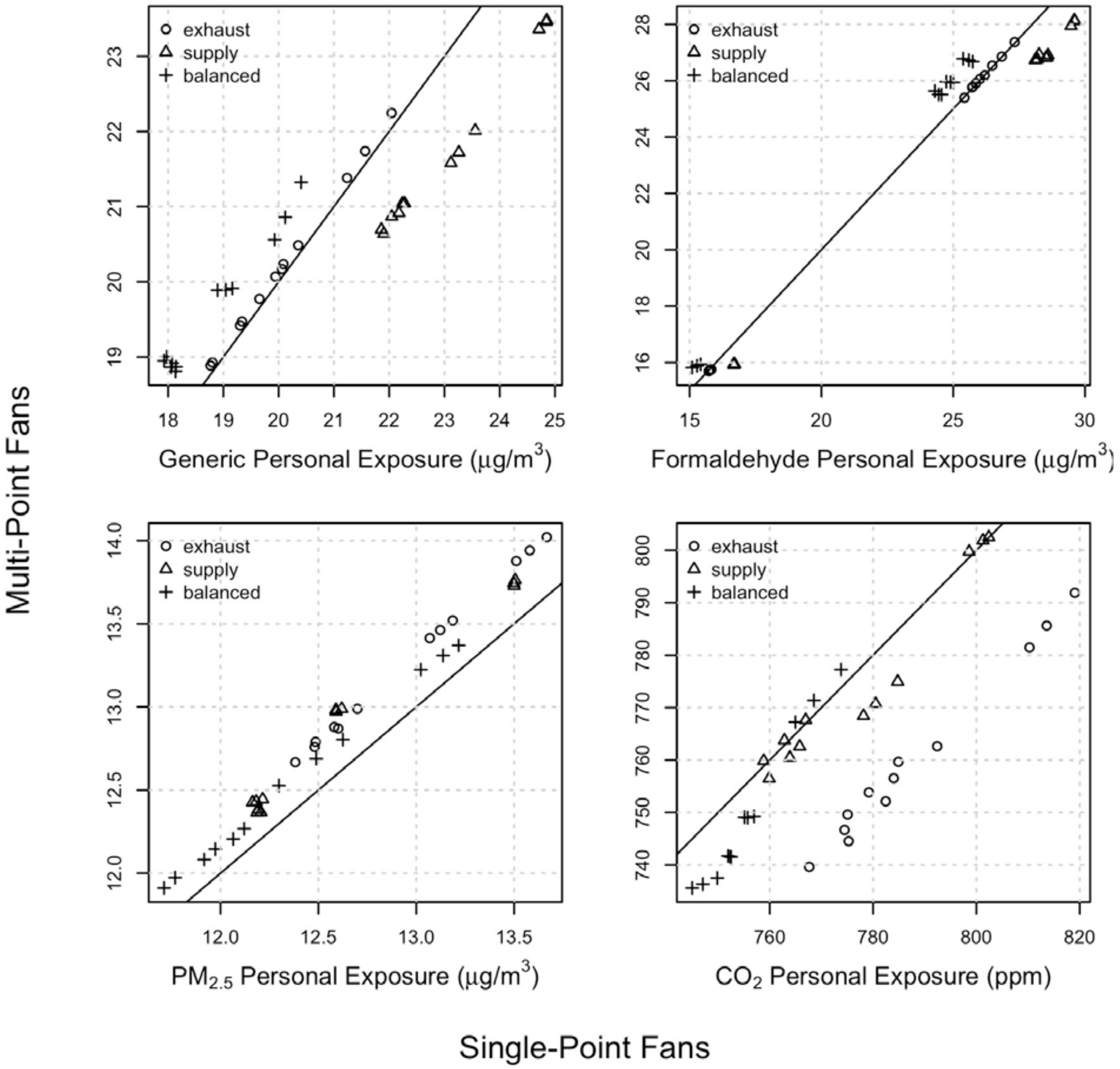
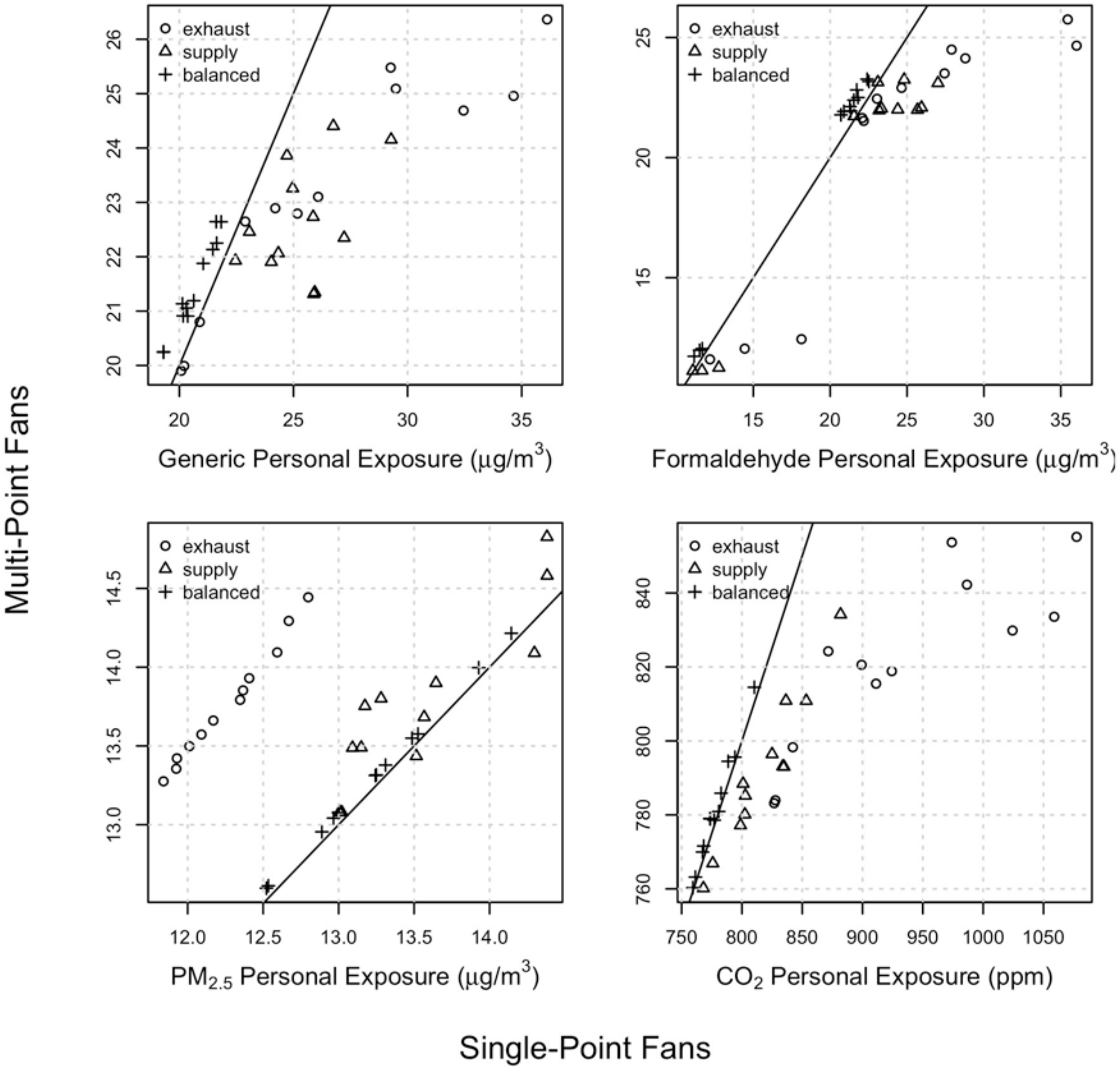


Figure 20 Comparison of Personal Contaminant Exposures for Multi-Point and Single-Point Fan Types. 2-story, VRF.



The prior discussion for 1- and 2-story single-family dwellings applies only to comparing the zonal and non-zonal version of matching fan types, and we concluded that supply fans had the most benefit from being zoned, exhaust fans had little impact in 1-story and large impacts in 2-story dwellings, and balanced fans tended to worsen exposure when they were zoned. But that analysis does not allow us to compare between the fan types themselves—exhaust, supply and balanced.

In Figure 21, we compare the three fan types side-by-side, both multi-point zonal and single-point non-zonal, for each contaminant, showing the personal contaminant exposure along with the dwelling's mean infiltration rate. We observe that balanced fan types achieve the highest ventilation rates, and commonly provide the lowest personal exposures, as a result. But overall, each of the three fan types delivers very similar flow rates from a whole dwelling perspective. Supply fan types appear to deliver the lowest whole dwelling ventilation rates, and exhaust fan types are between supply and balanced. The lower ventilation rates for supply fans appears to worsen personal exposure for the generic contaminant and formaldehyde, while particles and CO_2 appear to be minimally impacted by the ventilation rate. The sources of particles and CO_2 are time-varying and zonally diverse, which means that the exposures are less dependent on whole dwelling airflows and are more dependent on the zonal effectiveness and configuration of the ventilation equipment. The generic contaminant and formaldehyde have no zonal diversity and much less time diversity, so the personal exposures to these contaminants are clearly reflected in the dwelling's ventilation rate.

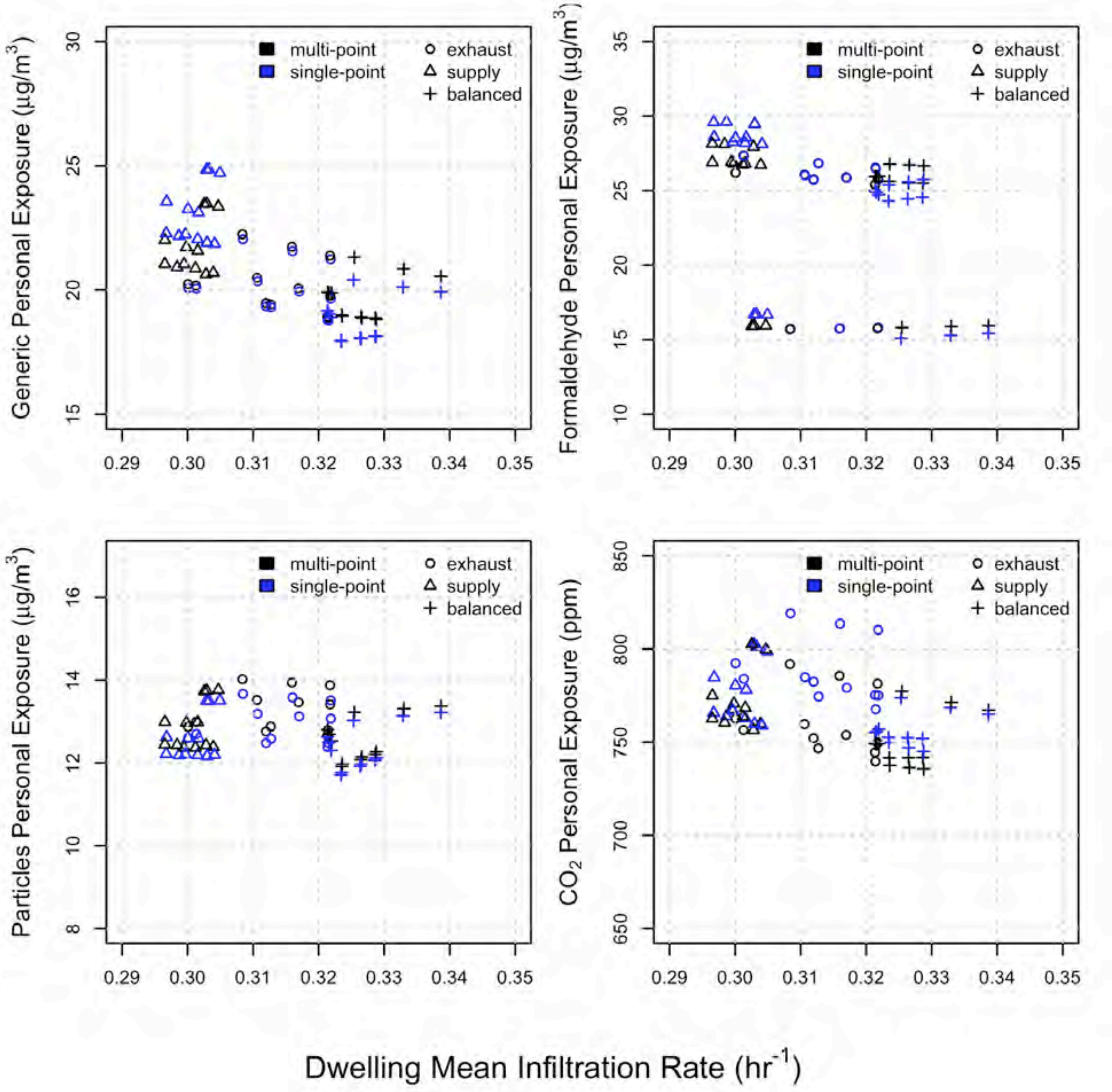
Balanced fan types appear to have higher personal exposures when they are MP zonal (black characters) compared with SP non-zonal (blue characters), though they still appear to have higher ventilation rates and lower personal exposures compared to other fan types. Exhaust fan types appear to behave similarly whether SP and MP, and supply fans have an apparent exposure benefit when zonal for generic, formaldehyde and CO_2. Again, as discussed above, exceptions to this include increased particle personal exposures for all fan types when made zonal, and substantially reduced personal CO_2 exposure for zonal exhaust fans.

Energy Performance Impacts

Fan type is an important determinant of annual HVAC energy use, both for baseline constant flow fans and for smart ventilation controls.

Ventilation fan type has large impacts on the baseline constant fan case energy use, due to differences in fan energy and impacts of HVAC loads. As explained in the Methods section, we have simulated supply fan airflows (in both supply-only and in balanced ventilation systems) with a 3-to-1 tempering air assumption, which effectively quadruples the ventilation fan energy when compared with an exhaust fan for similar fan efficiencies.

Figure 21: Ventilation Rate And Personal Contaminant Exposures For Each Fan Type (exh, sup And bal) And Zoning Type (MP vs SP).



Balanced fans use the most fan energy, because they require both supply an exhaust fans. In addition to fan energy, as shown in Figure 21, balanced systems deliver the highest dwelling ventilation rates, which also translates to increased HVAC loads. Overall, heating energy use is lowest for supply fans, consistent with their lower ventilation rates. These are followed by exhaust and balanced fan types, which have the highest consumption. Conversely, cooling energy use is highest for supply fan cases, because many cases benefit from ventilative cooling, and lower ventilation rates marginally lessen this benefit. The net-effects of fan energy and HVAC loads is that balanced fan cases use the most HVAC energy, followed by supply and exhaust fan cases, with median annual HVAC energy use of 2,071 kWh, 1,928 kWh and 1,444 kWh, respectively.

Ventilation fan type has a large impact on the energy performance of smart ventilation controls, both zoned and non-zoned. The relative benefits of one fan type over another depend on the strategy that the ventilation controller uses to save energy. Overall, controllers use one of two strategies to save energy:

- Reduce the annual outside airflow required to comply with ventilation standards by tracking occupancy or contaminants.
- Increase the annual outside airflow required to comply with ventilation standards and to save energy by providing this increased flow during mild weather periods, when the impacts on building loads are minimized.

The differences noted above in fan energy use interact with the two energy saving strategies outlined above in predictable ways.

For controls that increase the annual outdoor airflow, fan energy use increases, and the penalty is four times larger for supply fans and five times larger for balanced fan types. In many simulation cases, this additional fan energy penalty effectively eliminated all energy savings associated with ventilating during mild weather periods, because the added mechanical fan energy outweighed load savings. For example, the varQ controller had strong ventilation energy savings of 45% for exhaust fan types, but these savings dropped to only 6% each in supply and balanced fan cases, due to their increased fan energy use (see this effect on individual cases in Figure 12). These net-effects would be different in climates with greater heating and cooling loads, or with lower energy use supply ventilation systems.

In contrast, for control types that targeted reduced outdoor airflows over the course of the year by tracking occupancy, the additional fan energy associated with supply fan flows increased the apparent savings. For example, the zoneExposure cases had average ventilation energy savings of 15%, which increased to 20% for supply fans and 25% for balanced fans. In effect, the increased energy use associated with baseline ventilation makes strategies that reduce annual outdoor airflow much more effective. This benefit is only in comparison to a baseline fan of the same type. It is unlikely that the increased savings for the balanced fan types using the zoneExposure controller actually lead to lower annual energy use than would using the exhaust fan with the same control type. For example, in Table 38, while the ventilation energy savings are highest for MPbalanced fan zoneExposure cases (25%), the annual HVAC energy use is lowest for the zoneExposure MPexhaust cases (969 kWh/year).

Dwelling Prototype

We simulated 1-story and 2-story single-family detached dwellings and a multi-family apartment unit, all of which are designed to reflect the standard California Energy Commission prototype dwellings. The 1-story dwelling is 2,100 ft^2, with four occupants, three bedrooms and two bathrooms. The 2-story dwelling is 2,700 ft2, with five occupants, four bedrooms and three bathrooms. The apartment dwelling is 870 ft^2, with three occupants, two bedrooms and one bathroom. The apartment is unique in that all but one of its exterior faces are treated in the simulations as being perfectly sealed and thermally adiabatic, with the only leakage and heat transfer paths being located on a single exterior wall.

Overall, smart controls were not able to effectively reduce HVAC energy use in the apartment dwellings, whereas the 1-story and 2-story cases showed a consistent ability to save energy. The apartments were cooling-dominated, with on average, very small heating loads. This meant that baseline constant flow IAQ fans actually reduced annual HVAC energy use rather than increase it due to ventilation cooling in summer. This limits the potential value of smart controls that reduce annual airflow through occupant tracking and zonal ventilation (e.g., zoneExposure). Smart controls in apartments that did save energy (e.g., varQmz) likely did not save enough to justify the cost and complexity of zonal smart controls. Apartment units also had overall higher ventilation rates than the 1-story dwellings (0.41 vs. 0.31 hr^{-1}), in part due to their smaller volumes and higher occupancy density, but also to the sizing calculations used for multi-family fans in 62.2-2016, which do not allow for infiltration credit. The higher ventilation rates led to reduced personal exposures in apartments for the generic contaminant and formaldehyde (which were emitted proportional to floor area), but increased exposure to particles and CO_2 (whose emissions were zonal and time-varying). While smart controls did not effectively save energy in apartments, they were able to improve IAQ by targeting outside airflows to occupied zones. In fact, these IAQ improvements were generally greater in apartments than in single-family dwellings for the same control type. Though these effects varied substantially by fan type and contaminant of interest. For example, MPexhaust dramatically increased apartment exposures to the generic contaminant and formaldehyde when using an IAQ controller, while supply fans had much greater exposure reduction benefits in apartments.

Energy

Based on the treatment of most surfaces in the apartment as adiabatic and perfectly air sealed, the heating and cooling loads were very different in the apartment prototype compared with the 1-story and 2-story dwellings. The apartment dwellings were almost entirely cooling-dominated, with very little heating energy demand. This was the result of substantial internal heat gains (from people, equipment, etc.), paired with very limited heat losses through the building envelope, and solar gains through the apartment windows. For example, when averaged across all the simulation factors, the mean heating energy use for an apartment dwelling was 4 kWh, while the cooling energy use was 457 kWh. In contrast, the 1-story dwellings averaged 698 kWh per year for heating and 244 kWh for cooling. In effect, this meant that apartment dwellings were unable to save any heating energy through ventilation controls. An additional important outcome is that due to the dominance of cooling loads in these dwellings, in all but 2 cases (balanced fan types in the coldest location, CZ16), the baseline constant flow ventilation actually reduced annual HVAC energy use in apartments by providing beneficial ventilative cooling (like an economizer). For all single-family detached cases, the baseline constant flow fan increased annual HVAC energy use.

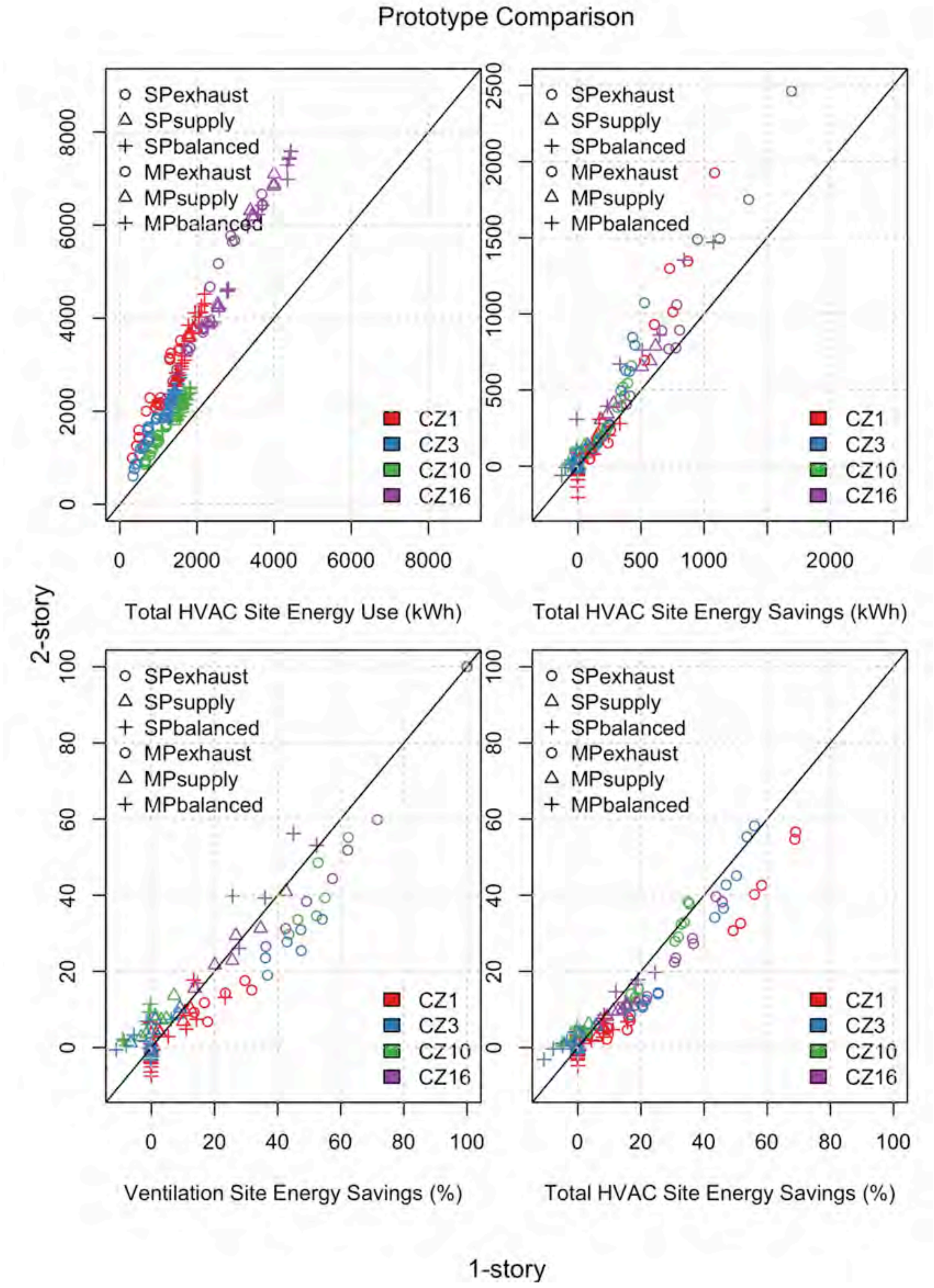
In the vast majority of apartment cases, more ventilation flow actually reduced annual HVAC loads, which makes these dwellings poor candidates for ventilation controllers that attempt to save energy by reducing annual outside airflow (e.g., occExposure, zoneExposure, etc.). Conversely, this could give an additional potential benefit to the control types that increased annual outside flow rates. One caveat with these results is that end-of-unit apartments or apartments on colder climates may not exhibit this cooling-dominated energy behavior.

This economizer effect also means that we cannot calculate percent ventilation energy savings as we traditionally do, because the baseline fan decreases rather than increases HVAC energy use. In that situation, it is not clear what the controller is achieving relative to the baseline. So, for the apartment cases, we will discuss the total relative HVAC savings for the dwelling, which is the fraction of whole dwelling HVAC energy that is saved by the ventilation controller. This should typically be a smaller value than the ventilation energy savings reported for single-family prototypes.

In general, the smart controls were not effective at reducing the energy use of the apartment dwellings. Across all control types, the average absolute kWh savings in the apartment dwellings was never greater than 30 kWh, with annual HVAC savings of at most 5%. In contrast, while IAQ was not always adequately maintained, the 1-story prototypes were clearly able to reduce energy use, with some control types reducing ventilation energy by around 40% on average, along with whole house energy reductions in the range of 8 to 20%, and absolute savings averaging 150-300 kWh.Given the poor energy performance of the smart controls in the apartment dwelling units, we now compare solely the single-family 1- and 2-story prototype dwellings in Figure 22. This plot includes the site energy use (top left), the site energy kWh savings (top right), site ventilation % savings (lower left) and the site total HVAC % savings (lower right). We observe that the 2-story prototypes had consistently higher site energy use, and a much less consistent increase in absolute kWh savings, meaning that overall their percent savings were lower. The absolute site energy savings appear much greater in 2-story dwellings in CZ1 and CZ16, largely in exhaust fan cases. For most other locations and fan types, the additional ventilation site energy savings in the 2-story prototypes were marginal. We see this reflected in the percent ventilation and total HVAC site energy savings in the lower panes, where in many cases the 2-story cases had reduced % savings. Again, this is most pronounced in exhaust fan cases.

For example, the varQ controller in the 1-story dwellings saves an average of 155 kWh of annual energy use (151 kWh in 2-story dwellings), while the same control in the apartment saves only 31 kWh. Yet, both dwellings have similar total HVAC energy savings of 6% (in apartment and 2-story) and 9% (1-story). In contrast, the zoneExpsoure controller, which attempts to reduce annual ventilation flows, increases annual HVAC energy use in the apartments by 31 kWh, while saving 197 kWh and 335 kWh annually in the 1- and 2-story dwellings, respectively. These correspond to a 3% annual increase in HVAC energy use for the apartment, and an 11% reduction in whole dwelling HVAC energy for both single-family prototypes.

Figure 22: Site Energy Performance By Dwelling Prototype.

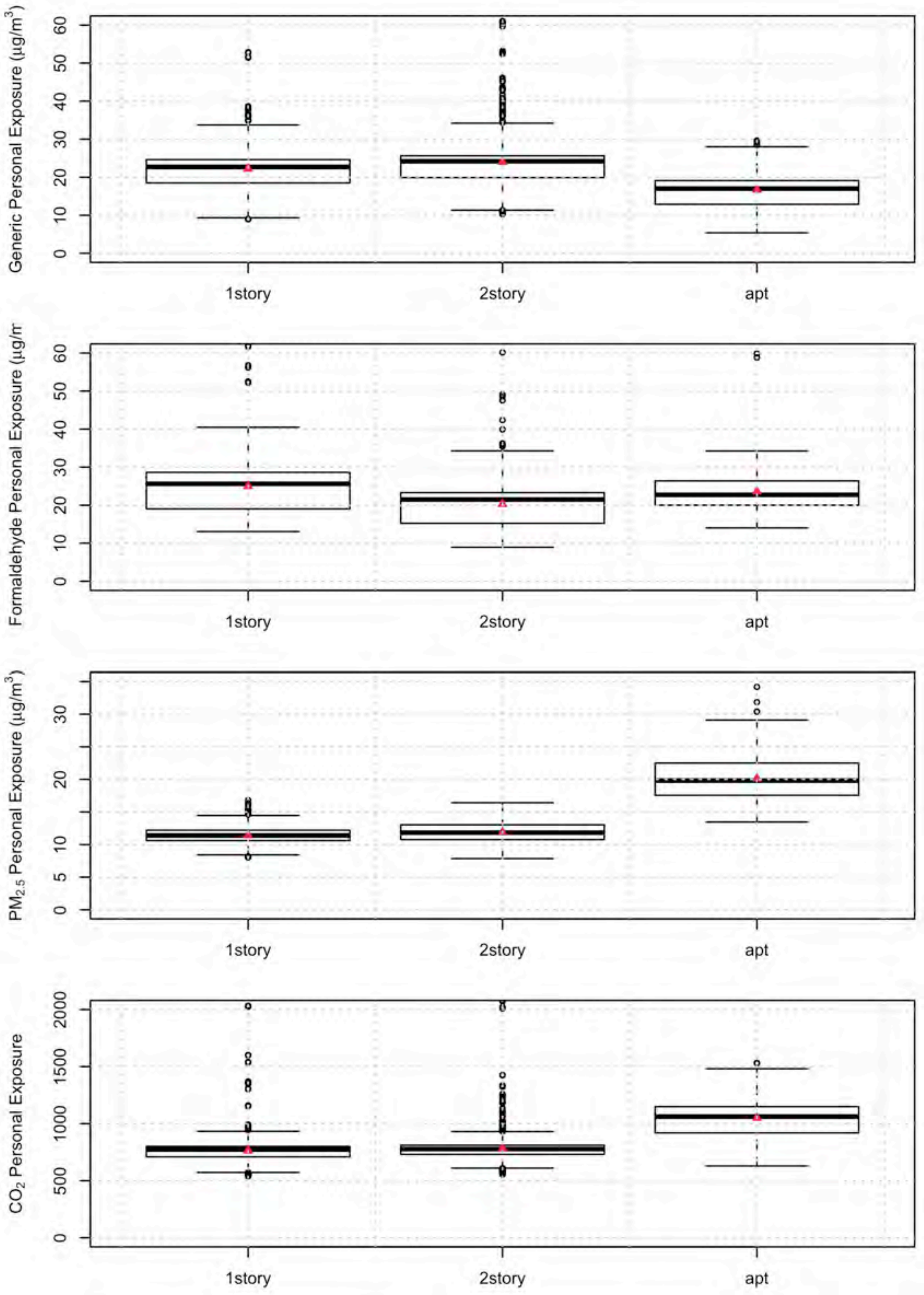


Personal Exposures

In Figure 23, we show the distributions of personal pollutant exposures for all cases in each prototype dwelling. Personal exposures are not consistent across prototypes or contaminants. Personal exposures were generally highest in the apartment dwelling, particularly for particles (nearly double compared with other dwellings) and for CO_2 (averaging over 1,000 ppm). The generic contaminant and formaldehyde showed the opposite behavior. The generic contaminant was lowest in the apartment dwellings, and formaldehyde exposures were second lowest. The 1- and 2-story dwellings have very similar exposure distributions, with the exception of formaldehyde, where the 2-story dwelling had consistently the lowest exposures.

These differences are, in part, because the required ventilation rates specified in ASHRAE 62.2 scale with both the floor area and occupancy of the dwelling unit. In our simulations, the emission of the generic contaminant and formaldehyde scale with floor area, but the required ASHRAE 62.2 air change rate per unit floor area is greater for apartments. For contaminants that scale with occupancy this effect is reversed because the ventilation rate per occupant is lower in apartments. For example, the 1-story prototype has four occupants in 2,100 ft^2, with their associated cooking, bathing and breathing. The apartment units have three people (and their activity-based emissions) in 870 ft^2. So, the floor area-based emissions drop by more than half (from 2,100 to 870 ft^2), while the other emissions associated with occupants drop by only 25% (from 4 to 3 occupants). The net-effects of these emission patterns and ventilation rates drive what we observe in Figure 23, namely higher apartment exposures for episodic and activity-based emissions, and lower exposures to background emissions. The personal exposure to localized, activity-based emissions are not well-managed by the whole dwelling dilution ventilation, so higher flows for the apartment dwelling do not compensate sufficiently. For outdoor particles, the apartment has higher ventilation rate per unit of interior volume leading to higher concentrations of outdoor contaminants (in this case particles). Another contributing factor to increased particle pollution in apartments could be due to their overall reduced energy use, which would lead to less HVAC runtime/airlfow and therefore less particle removal by filtration in the central forced air unit (for HPfau cases).

Figure 23: Personal Pollutant Exposures By Dwelling Prototype.



Given the poor energy savings achieved by smart controls in the apartment dwellings, the only remaining value of smart controls could be improving IAQ through leveraging occupancy sensing and zonal ventilation equipment. Controls that did this were the supplyTracker and occupantTracker, which directed ventilation flows to the occupied zones. These controls were designed to have no impact on HVAC energy use, but to reduce occupant exposures. The occupantTracker, for example, achieved personal contaminant exposures that averaged 12% less than in the corresponding baseline cases (compared with 5-7% improvements in 1-story). The MPexhaust fans using the occupantTracker control worsened the generic and formaldehyde exposures in apartments, but had nearly no effect in 1-story dwellings. For the MPsupply and MPbalanced fan types, the apartments had greater reductions in exposure to the generic and formaldehyde than did the 1-story cases. The zonal supply fan systems were best at directing outside airflow to the occupants, so these fan types achieved the greatest reductions in the generic contaminant and formaldehyde, along with the greatest increases in personal particle exposure. CO_2 exposures were lower in all cases. With the exception of particles, the benefits were greater in the apartment dwellings than in the 1-story. For particles, the distinction between prototypes was not as clear.

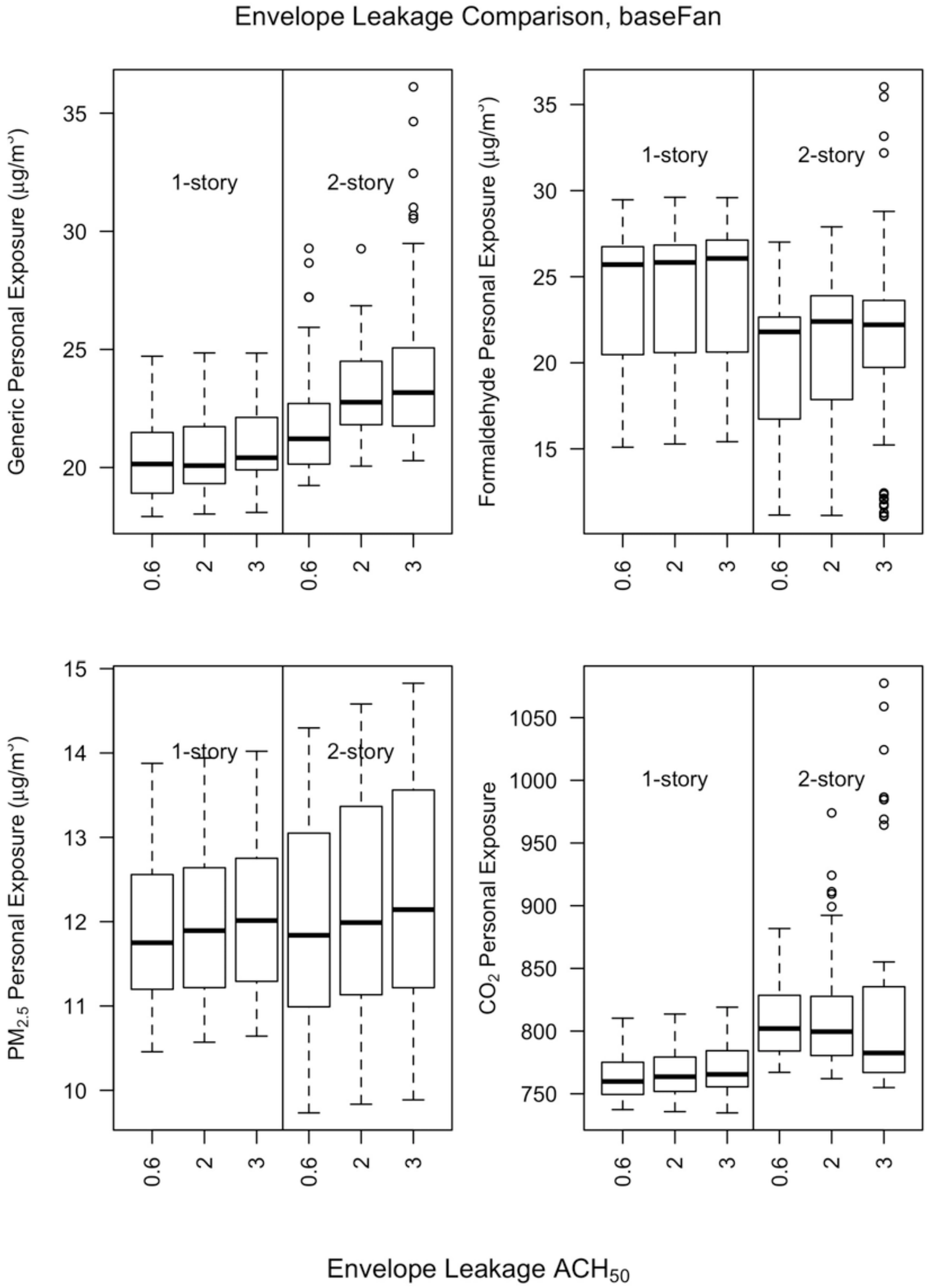
Envelope Leakage

The envelope leakage rates simulated in 1- and 2-story dwellings were 0.6, 2 and 3 ACH_{50}, which are more airtight than is typically achieved in current new California construction. The apartment prototype was only simulated as a very tight case, with the only leakage paths to outside being located in the one exterior wall. All other apartment surfaces above, below and to the sides were treated as perfectly air sealed. This apartment scenario represents an ideally compartmentalized multi-family dwelling unit. The fan sizing used for baseline constant flow cases was ASHRAE 62.2-2016.

These tight envelopes are dominated by the mechanical ventilation. Across all 1-story cases, the mean infiltration rates showed little variability: 0.318, 0.320 and 0.325 hr^{-1} for the 0.6, 2 and 3 ACH_{50} cases, respectively. Ventilation rates were overall lower in the 2-story dwelling, averaging 0.264, 0.270 and 0.279 hr^{-1} for the 0.6, 2 and 3 ACH_{50} cases. Because all prototypes of a given floor area and occupancy are designed to achieve the same annual effective ventilation rate using ASHRAE 62.2-2016 calculation methods, the envelope leakage had typically small but notable impacts on ventilation rates and personal pollutant exposures.

As illustrated in Figure 24 for the baseline constant flow fan cases, personal exposure to each of the four contaminants of concern worsened with increasing envelope leakage. In general, the differences associated with envelope leakage were greater for the 2-story prototype, because the taller, 2-story dwelling has much more interaction between the fan and the natural stack- and wind-driven flows. The variability with envelope leakage is least for formaldehyde and CO_2, while being strongest for the generic contaminant and particles. For particles, the elevated personal exposures associated with more envelope leakage make intuitive sense, because greater amounts of outdoor particles were introduced to the dwelling by higher ventilation rates. But the increase in personal generic contaminant exposures in the leakier dwellings is surprising, because we expect the marginally higher ventilation rates in the leakier dwellings to reduce these exposures to indoor-generated contaminants. This illustrates the complexity of the interaction between dwelling ventilation, zone ventilation and where occupants are in the dwelling. As noted in the sections above, the leakier 2-story prototypes had higher contaminant concentrations on the 2nd level due to lower outdoor air flows into the 2nd level, while the most airtight 2-story dwellings maintained consistent concentrations in all zones. Occupants spent a lot of time in the bedroom zone on the 2nd level, where their exposures were higher, despite the dwelling having an overall higher ventilation rate. This increased their average exposure. When concentrations are uniform between zones, the generic contaminant exposure goes down (or is static) with increasing ventilation rate, but when concentrations are not uniform, then the relationship between ventilation rate and exposure is very dependent on where the people are and when.

Figure 24: Comparison of Personal Exposures by Envelope Leakage and Prototype. baseFan cases.



Percent site ventilation energy savings typically increased with increasing envelope leakage, due to smaller baseline fan sizes in leakier dwellings. The whole dwelling HVAC absolute energy savings were less predictable, though most controllers had the least savings in 3 ACH_{50} cases, while kWh savings were maximized for either the 0.6 or the 2 ACH_{50} cases.

Figure 25 shows the ventilation site energy savings for each case, comparing the 0.6 ACH_{50} cases (x-axis) against the 2 and 3 ACH_{50} cases (y-axis). The top panel shows the percent ventilation energy savings, and the lower panel shows the total HVAC site energy savings in kWh. For most smart control types, the relative percent ventilation energy savings improves as envelope leakage increases from 0.6 to 2 and 3 ACH_{50}. For example, the occExposure controller has average ventilation savings of 22, 26 and 28% for the three leakage levels. On average, the absolute savings were greatest in the most airtight dwellings, but there was lots of variability by control type, as illustrated in Figure 25. We expect that the leaky dwellings have lower savings potential in absolute kWh terms and higher relative percent savings, because their baseline fan flows are the smallest, which means the energy added by complying with the ventilation standards is the lowest in these cases. Also, in the most airtight dwellings, all ventilation is fan driven, so the smart controllers have control over all flows in the dwelling, whereas the fans in the leakier homes only control part of the total outside airflow.

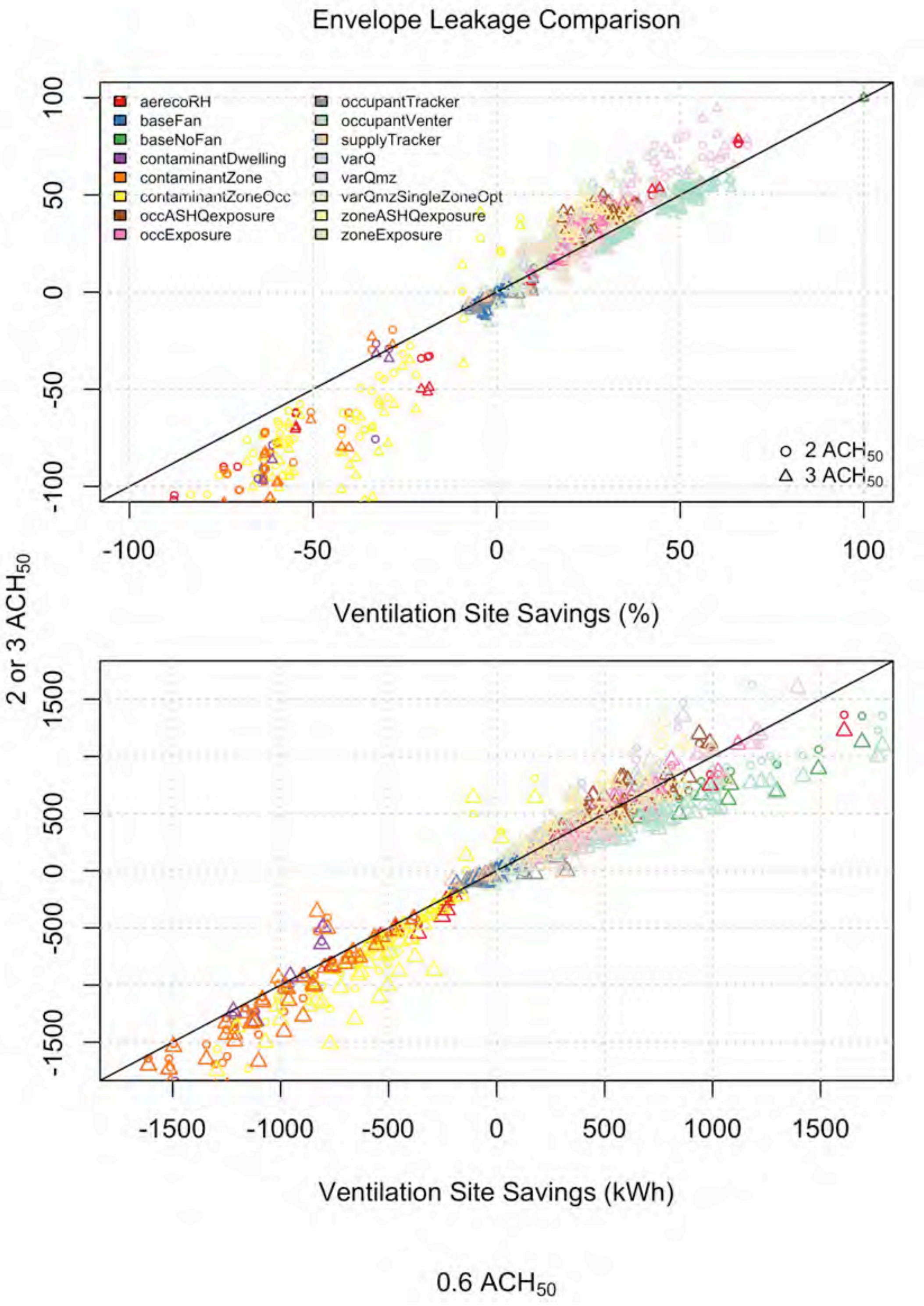
Climate Zone

Four climate zones were simulated to represent the variety of climate regions throughout the state of California: CZ1 (Arcata), CZ3 (Oakland), CZ10 (Riverside) and CZ16 (Blue Canyon). Each climate zone was associated with its standard weather file used for Title 24 energy code compliance, and each region was also associated with a unique outdoor air pollution input file. The outdoor pollution varied for each climate zone only for ambient particles and water vapor, whereas the outdoor formaldehyde and CO_2 were fixed across climates. Climate zones impacted the sizing of baseline ventilation fans due to the use of infiltration adjustments in sizing IAQ fans. They also impact heating and cooling loads, which have substantial impacts on smart ventilation performance.

Overall, the climate region had substantial impacts on personal pollutant exposures, with CZ16 showing the highest average personal exposures for the generic contaminant, CO_2 and particles, while having by far the lowest formaldehyde exposures. CZ16 also had, on average, marginally lower ventilation rates than in the other climate regions, but these differences were not enough to explain the increases in pollutant exposure.

Smart control IAQ impacts were less distinct by climate zone. Climate zone also dominated the variability in annual HVAC energy use, with the coldest location (CZ16) consistently showing both the highest annual consumption, but also the greatest absolute energy savings from smart controls. The relative ventilation energy savings were also greatest in CZ16 for controls that used outdoor temperature measurement, but the other control types had much less variability in percent savings between climate regions.

Figure 25: Comparison Of Total HVAC Ventilation Energy Savings By Envelope Leakage.



Ventilation Rates and IAQ

We observed some variability in personal pollutant exposures that is associated with the climate zone of the dwelling. CZ16 was the most distinct, with the highest personal generic contaminant (7-13% worse), particles (6-10% worse) and CO_2 exposures (3-5% worse), and by far the lowest formaldehyde exposures (roughly 40% lower). Again, as intended by the ASHRAE 62.2-2016 fan sizing method, ventilation rates were consistent across climate regions for each prototype, with the exception that CZ10 and CZ16 2-story dwellings had marginally higher ventilation rates.

The most notable difference is the very low formaldehyde concentrations in the CZ16 dwellings. We attribute this low formaldehyde exposure to the distinct indoor climate conditions in CZ16 dwellings, which are dryer and marginally cooler on average than the dwellings in CZ1, 3 and 10. For example, mean annual relative humidity in the common zone was 49% in CZ1 and 3, 45% in CZ10 and 30% in CZ16 dwellings. CZ16 also had the second lowest annual mean indoor temperatures, but the temperature differences were very small compared to the differences in indoor RH. The dry air conditions lead to much lower formaldehyde emissions in CZ16, because indoor RH is one of the primary variables in the regression model used to determined emissions. Formaldehyde emissions were roughly 25 vs. 16 $\mu g/m^2$-hr in 1 and 3 vs. CZ16.

The other contaminant exposures were all somewhat elevated in the CZ16 dwellings, despite having either similar or higher ventilation rates compared with other climate regions. At first, we hypothesized that elevated exposures in CZ16 are the result of variability in concentrations between zones that are driven by pressure interactions between the ventilation fan and the natural stack and wind envelope pressures. Yet, we observe the higher personal exposures in CZ16 dwellings using all ventilation types, even those that otherwise resolved the imbalanced flows between zones in the 2-story dwelling. We also observe the higher exposures in the 1-story dwellings in CZ16, which were minimally affected by the fan pressure interactions with the envelope. We have no other explanation to offer at this time as to why the exposures are highest in the CZ16 dwellings.

Overall, smart controller IAQ performance does not appear to be strongly dependent on climate zone. There are small differences, but no large or clear trends. The only exception would be for the temperature-based controls (e.g., varQ, varQmz, varQmzSingleZoneOpt), where the CZ16 cases tended to experience marginally more worsening of personal exposures than found in other climate zones.

HVAC Energy Use and Smart Control Savings

As expected, HVAC energy use was strongly dependent on the climate zone, with the greatest baseline HVAC energy use in CZ16 (median of 3,912 kWh), followed by CZ1 and CZ10 (2,002 and 1,612 kWh, respectively), and the lowest annual energy use was in CZ3 (1,393 kWh). CZ1 and 16 were both the most strongly heating dominated, with on average 60% of total HVAC energy used by the electric heat pump. Heating was less dominant in CZ3 at 43% of the total, and in CZ10 heating was only 17% of total consumption. Cooling demand was greatest in CZ10, where it made up 40% of total energy use. Due to the very low heating and cooling loads in these energy efficient dwellings, the ventilation fan energy comprised a substantial fraction of total HVAC use in all cases, ranging from 21% of the total usage in CZ16 to 46% in CZ3.

For the outdoor temperature based smart controls, the ventilation energy savings were highly climate dependent. The varQmz controller mean savings in CZ16 were 59%, while they were only 31-37% in all other locations. CZ16 had the greatest savings for temperature-based controllers both in terms of percent savings and in absolute kWh savings. For other control types, the relative ventilation energy savings appear to be more consistent across climate zones. For example, the minimum and maximum climate zone mean ventilation savings for the zoneExposure and occExposure controllers was roughly 20% and 30%, in CZ1 and 16, respectively. occupantVenter savings were the most consistent across climate zones, varying, between 38 and 43%. In all cases, the absolute kWh savings were greatest for the CZ16 dwellings, due to their greater overall HVAC energy use.

Number of Control Zones

Many of the zonal smart ventilation controls were assessed using two different zoning configurations—one where all four zones were controlled independently, and a second where only two zones were controlled, bedrooms and non-bedrooms. Our reasoning behind this approach was that we felt that zoning might work best when occupants were in one zone of a dwelling for a substantial, continuous period, preferably with the doors closed. The bedroom zone was the only location that fit this characterization. Our hypothesis was that when people moved more rapidly and dynamically between zones, the ability of zonal ventilation systems to be appropriately controlled and to provide value would diminish. The two-zone control types still had fans specified in each zone, but the non-bedroom fans (com, kit, wet, fam) were either all-on or all-off as a unit, depending on the control status and zone occupancy. This distinction between the number of zones is not relevant for baseline constant fan cases (baseFan, baseNoFan), nor for control types that only used a single variant on number of zones (all contaminant control types, all outdoor temperature controls, and supplyTracker). Here we restrict our analysis to controls tested in both configurations, including zoneExposure, occExposure, occupantVenter, occupantTracker, zoneASHQexposure, and occASHQexposure.

Overall, we observe that the treatment of zones in the controls has inconsistent impacts on IAQ, which vary particularly by prototype, but also by control type and other factors. For most contaminants, treating each zone independently worsened personal exposure and increased ventilation energy savings, because whole dwelling ventilation rates were reduced. Given the worsened personal exposure and small increase in energy savings, we recommend that zonal smart ventilation systems use fewer, rather than more zones, which should reduce system costs and complexity. The apartment prototypes clearly behaved distinctly from the 1-story cases, but their behavior in response to zoning assumptions is largely irrelevant, because these control types almost universally increased annual HVAC energy use for apartment dwellings, so we do not recommend using these strategies under either zoning configuration.

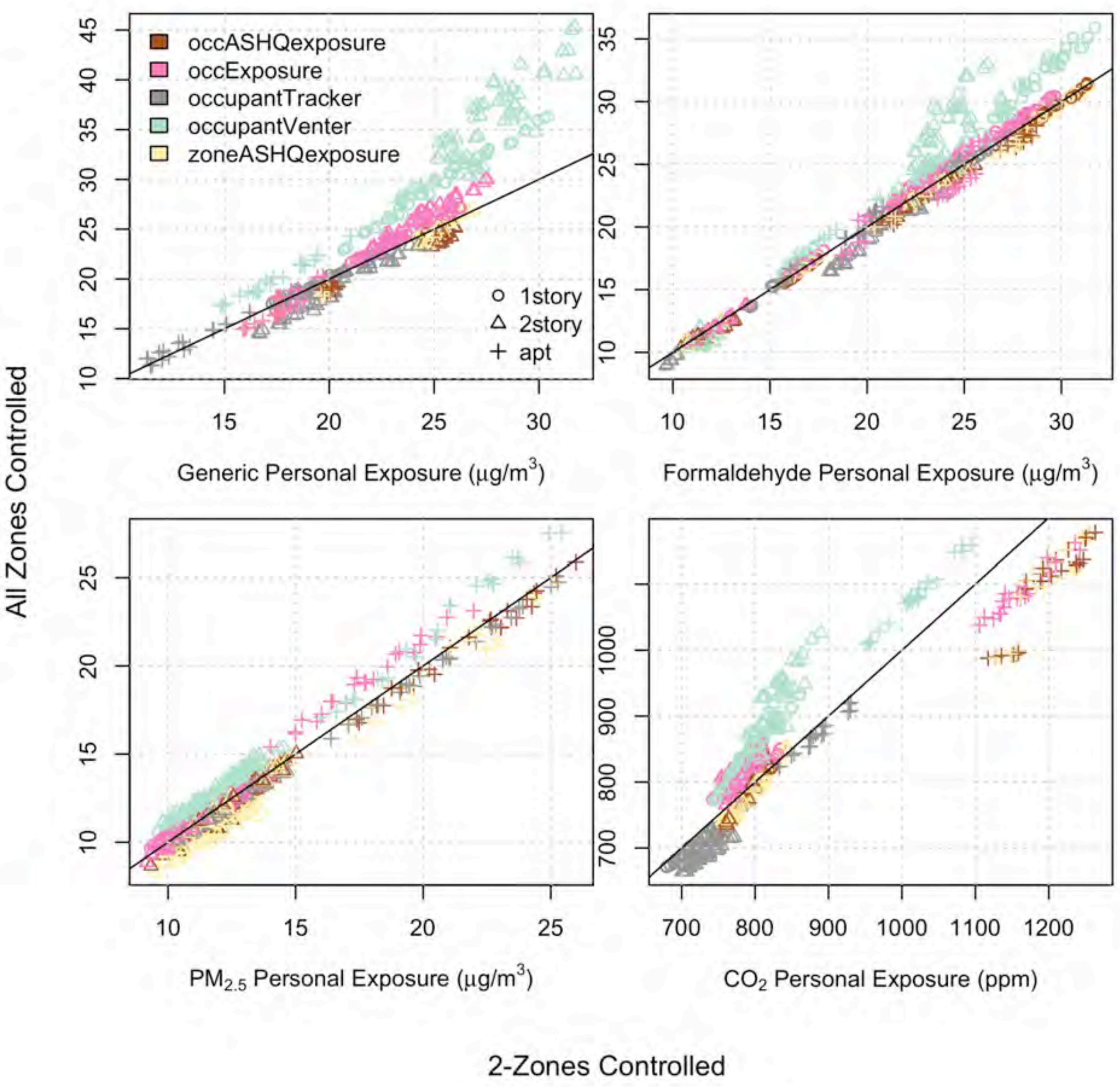
IAQ and Personal Exposures

We compare the personal pollutant exposures for each of these 2- and 4-zone control types in Figure 26, with shapes colored by control type and shapes representing the simulation prototype dwelling (circles are 1-story, triangles 2-story and pluses the apartment). The y-axis represents personal exposure when each zone is treated independently in the dwelling, and the x-axis represents cases where the zones were restricted to only two—either bedrooms or non-bedrooms. Markers to the upper left of the unity line represent cases where treating all zones independently worsened personal exposure for the pollutant shown. Markers to the lower right indicate that treating the dwelling with only two zones worsened personal exposures.

For 1-story dwellings, it appears that personal exposure to most contaminants is worsened when treating each zone independently in these control types. But for particles, the prototype has no clear impacts, while the control strategies clearly vary from one another. We cannot draw any clear, consistent conclusions as to the value of treating each zone independently vs. grouping zones together by typical occupancy patterns. Given the uncertainty and variability in IAQ outcomes, we suggest that a zoned ventilation system and controller that treats only two zones is likely to be lower cost and simpler to design, install and operate, and it does not appear to compromise personal exposure in any predictable way. In addition, for some control types, the exposure is clearly improved when assuming only two control zones (e.g., occVenter and occExposure). The sole control type that targets only improved IAQ and no energy savings (e.g., the occupantTracker) does appear to have some exposure benefit when using all 4-zones in the control scheme. This benefit is possible because the occupantTracker control does not otherwise attempt to save energy by reducing the whole house ventilation rate, it just directs whole dwelling flow to the occupied zone. Unsurprisingly, based on the prior discussions of outdoor particle exposures for zoned ventilation systems, the occupantTracker also marginally worsened particle exposures, because it effectively delivered particles to only occupied zones. .

The occupantVenter controller regularly increases personal exposure by treating the dwelling as four independent zones, which is true for all prototypes. This controller does not attempt to estimate the real-time relative exposure in each zone, instead it simply uses an over-sized fan and then only ventilates a zone (proportional to its floor area) when the zone is occupied. When vacant, a minimum zone flow is delivered to each zone (proportional to zone floor area). This means that the controller simply delivers much less ventilation flow when treating each zone independently. The occExposure controller worsens personal generic and formaldehyde exposures when treating each zone independently in the detached dwellings; apartment results are mixed. This same controller generally increases particle exposure when treating each zone independently, and CO_2 increases in 1-story and decreases in apartment dwellings when treating each zone independently.

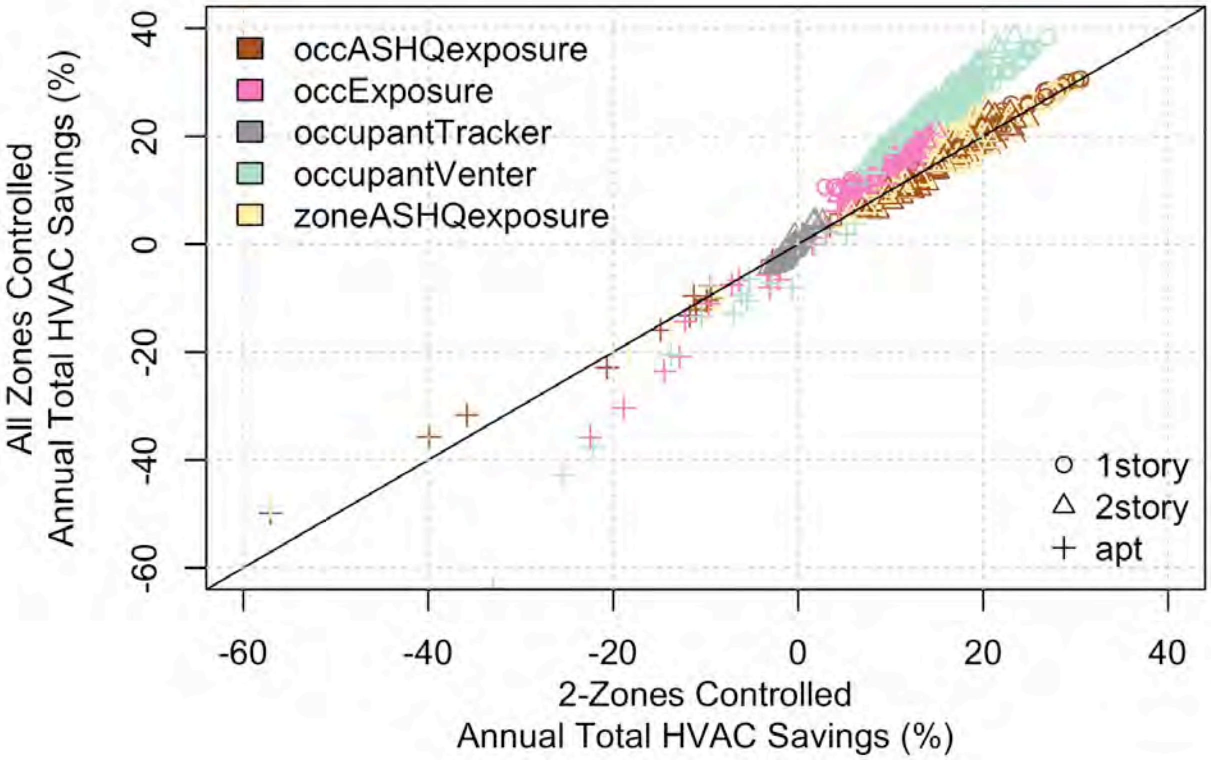
Figure 26: Comparison Of Personal Pollutant Exposure By Number of Control Zones.



Energy Savings

We show the total annual HVAC energy savings for these same controls and zone-control configurations in Figure 27. As expected, the controls that treat each zone independently (y-axis) appear to save more annual HVAC energy use, particularly in the single-family prototypes. The increase in savings appears to be in the range of roughly 0-10% improvement relative to two-zone, bedrooms vs. non-bedrooms control configuration. The occupantVenter controller (teal) had the greatest savings when controlling all zones independently, and it also increased personal exposures most dramatically. While less pronounced, the occExposure controller (pink) also improved energy savings when controlling four independent zones, but again, this was at the expense of generally increased personal exposures. More often than not, the apartment prototypes appear to increase overall annual HVAC energy use, and they behave even worse when using the two-zone configuration. We do not recommend these controls be used in apartment dwellings using either zone configuration.

Figure 27: Total HVAC Energy Savings (%) By Number Of Control Zones.



Summary and Conclusions

We developed and assessed 14 zonal smart ventilation controls using a coupled EnergyPlus/CONTAM framework, in order to determine the potential for zonal ventilation systems paired with smart controls to save energy and either maintain or improve IAQ in new California dwellings. The dwellings represent advanced 1- and 2-story single-family and multi-family apartment units that are constructed to meet Title 24 2019 and have envelopes that are more airtight than typical California construction. Our simulations investigated the impacts of dwelling prototype, ventilation fan type (zonal and non-zonal exhaust, supply and balanced), HVAC system type (forced air and mini-split heat pumps), envelope leakage (0.6, 2 and 3 ACH_{50}), climate zone (CZ1, 3, 10 and 16), and number of control zones (2-zones vs. all zones). A total of 3,527 simulations were executed as part of this zonal simulation work.

Current codes and standards require that dynamically controlled ventilation systems provide equivalent personal exposures to those that would be achieved at a constant whole dwelling target flow rate. We extended this requirement for non-zonal dwellings to our zonal analysis, and also added tracking of specific contaminants—formaldehyde, $PM_{2.5}$ and CO_2—alongside generic contaminants (as is currently codified in ASHRAE 62.2).

Zoned dwellings with zonal ventilation equipment and smart controls form a complex system, which none of the smart controls tested were able to adequately optimize. Overall, the best zonal smart controls offered substantial whole dwelling HVAC energy savings averaging from 15-22% across all cases, with some individual cases reaching whole house HVAC savings up to 40%. These savings in many cases exceeded what was achieved using single-zone ventilation equipment and controls. Yet, cases that saved HVAC energy did so at the expense of worsened personal pollutant exposures for at least one contaminant species. No controls were able to provide equivalent personal contaminant exposures for all species of contaminants assessed, likely because of the diversity of the pollutant sources (indoor continuous or episodic and outdoors) and of the removal mechanisms (outside air ventilation, deposition, filtration). The most common adverse IAQ impact from otherwise effective zonal ventilation equipment and controls was an increase in personal particle exposures. This occurred because outdoor particles were more effectively delivered to the occupants when using zonal ventilation systems. In contrast, many indoor contaminant exposures were reduced by the localized ventilation patterns. Controls that responded directly to measured contaminants in each zone dramatically increased HVAC energy use, because the formaldehyde exposure limit of 9 $\mu g/m^3$ could not be reached, despite a doubling of the annual ventilation rate. Future contaminant control development needs to carefully assess the acceptable exposure limits for contaminants of concern. The aerecoRH controller was developed for heating-dominated climates and is based on increasing ventilation when indoor humidity is high. The scaling of the inlet openings and exhaust flows with zone relative humidity was not optimized for some of the California climates that we assessed. This led to increased ventilation rates compared with the constant fan baseline cases that reduced median non-particle exposures but increased HVAC energy use. CZ16 in the colder dryer mountain regions was the only case where ventilation rates were reduced and energy savings were achieved (median of 19% whole dwelling HVAC savings), but this worsened all personal exposures (from 8 to 78%, depending on the contaminant of interest). Future development of the aerecoRH controls for California will require an optimization effort to identify appropriate methods to scale ventilation with indoor humidity, such that energy savings and adequate IAQ performance are achieved.

The IAQ and energy performance are discussed for each of the factors varied in the simulations below.

HVAC system type had overall marginal impacts on IAQ in most cases due to the use of small capacpity equipment and short runtimes in these energy efficient homes. Particle exposures were substantially reduced in CZ10 and 16 mostly due to the MERV 13 filtration of the forced air systems. The VRF systems used less energy, both in baseline and in smart control modes, because of their low fan energy use and their improved efficiency from variable capacity and thermal zoning. The HPfau systems had higher energy use, but their savings from smart controls were correspondingly higher.

Ventilation system type was a very important factor for the personal contaminant exposures, as well as for the baseline and smart control HVAC energy performance. Balanced fans had the highest ventilation rates and typically the lowest personal pollutant exposures. These were followed by exhaust fans, which tended to have marginally lower exposures than supply fans, with the exception of CO_2, where supply fans outperformed exhaust. When zoned, balanced fans worsened pollutant exposures (from 0.1 to 4%, on average) compared with the non-zonal balanced fan cases. When exhaust fans were zoned, they slightly worsened generic and particle exposures (by 0.6 to 2%, on average), while slightly reducing formaldehyde (0.3%) and slightly reducing CO_2 (3.5%) exposures. For zoned supply fans, the personal exposures dropped for the generic contaminant, formaldehyde and CO_2 (by 1 to 4%, on average), and got worse for particles (9%). Overall, the impacts of zoning were small.

The supply and balanced fan types were most capable of directing outside airflow to the target zone, so they were the most zonally effective. The zonal supply fans clearly reduced exposures for all indoor contaminants, but outdoor particle exposure was increased, because the zoned supplies were very effective at delivering outside air (including particles) to the occupied zones. This occurred despite the filtration of supply airflows using MERV13 filters. The balanced fans actually worsened exposure when zoned, because they shifted the supply and exhaust flows between the zones of the dwelling, and this provided less overall exhaust flow in the zones where it was most beneficial (bathrooms and kitchen), and reduced overall supply airflows in zones with long occupancy periods (bedrooms). Finally, due to their need for recirculated tempering air, the supply and balanced fan types had much higher HVAC energy use. For smart controls that increased total annual outside air flow (e.g., some outside temperature-based controls and the contaminant controls), this higher fan energy almost completely eliminated energy savings. In contrast, for controls that reduced the annual outside air flow (e.g., most zone occupancy controls), the higher energy use of the supply and balanced fan types led to greater savings.

Exhaust fan types generally had much less impact when zoned, because exhaust fans largely distribute outside airflows according to the leakage area in each zone, irrespective of the fan's location in the dwelling. This can be a benefit of this fan type, but it generally makes them a poor candidate for zonal controls. Exhaust fans did provide zonal ventilation benefits when substantial differences in concentrations occurred between zones in the dwelling. These differences occurred in all dwellings due to localized emissions (e.g., cooking, bathing, breathing in closed bedrooms at night), and in the leaky 2-story dwellings where pressure interactions between the ventilation fan and building envelope led to under-ventilated 2nd story zones. In these cases, exhaust fans with zoning provided IAQ benefits. Exhaust fan cases used by far the least annual HVAC energy use, and they performed best for control types that increased annual outside airflows, because the fan energy penalty much smaller than the load reductions achieved through temperature-based shifting of ventilation. Exhaust fan savings were relatively smaller for controls that reduced annual outside airflow. While the absolute energy savings were often smallest for the exhaust fan types, the total annual HVAC energy use was almost always least when using exhaust fans. Due to the marginal IAQ benefits in most cases and to their higher energy use, we cannot recommend that supply and balanced fans receive large incentives relative to exhaust fan equipment.

Dwelling prototype impacted both the IAQ and energy results in the zonal simulations and controls. Due to its adiabatic surfaces and internal heat loads, the apartment dwellings were strongly cooling dominated, and increased ventilation often reduced annual energy use, rather than increasing it. This meant that controls targeting reduced ventilation rates actually used more energy, not less. Outside temperature-based controls also failed to deliver energy savings in the apartment dwellings, again because they are so cooling dominated, and controls were not optimized to account for this interaction with internal loads. The apartment dwellings had the highest air change rates, due to their smaller size and fan sizing calculations in ASHRAE 62.2. Occupants in apartments benefitted from these higher air change rates for contaminants that were emitted constantly throughout the dwelling. But for contaminants with indoor sources that were based on occupant activities, the smaller volume of the apartment dwelling led to increased exposures. This was particularly the case for CO_2 and particles. The single-family dwellings had HVAC loads that resulted in energy savings using the smart controls tested in this work. The 2-story dwellings behaved quite differently than the 1-story when envelope leakage was higher (3 ACH_{50}) and unbalanced fan types were used. In these cases, the fan pressure and envelope pressures interacted, leading to generally low outdoor airflow rates and high contaminant concentrations on the 2nd level zones. Occupants spent lots of time in the 2nd story bedroom zone, so the exposures were notably higher in these cases. These leakier 2-story dwellings had substantial IAQ benefits from using zonal ventilation equipment. The 2-story dwellings also had higher annual HVAC energy use, and often had correspondingly higher energy savings through smart controls.

Envelope leakage was a marginally important factor in the outcomes of the zonal ventilation control performance mostly because the ASHRAE 62.2 fan sizing for single-family homes includes envelope leakage and generally acts to have similar combined natural infiltration and mechanical ventilation across a broad range of envelope leakage. Absolute energy savings (kWh) were greatest in the most airtight dwellings, largely because the fans controlled nearly all of the outside airflow in these cases, so the potential savings were greatest. The relative savings (%) were lowest for these cases. The leakier cases (3 ACH_{50}) had correspondingly the lowest absolute savings and the highest relative savings, because infiltration had greater impacts and the baseline fans were smaller. Envelope leakage also impacted personal exposures, particularly in the leakier homes that used unbalanced ventilation equipment, because the interaction of the fan pressure and envelope pressures led to inconsistent ventilation rates between the zones. This was particularly the case in the 2-story dwellings, where the 2nd level zones were stranded with less outside airflow and higher contaminant concentrations. The very tight 2-story dwellings maintained similar ventilation rates between zones, because they were entirely fan pressure dominated.

Climate zone substantially impacted energy performance, and to a lesser extent personal pollutant exposures. CZ16 showed the highest average personal exposures for the generic contaminant, CO_2 and particles, while having by far the lowest formaldehyde exposures. Low formaldehyde concentrations in CZ16 were driven by the lower emission rate due to lower indoor humidity. CZ16 also had, on average, marginally lower ventilation rates than in the other climate regions, but these differences were not enough to explain the increases in pollutant exposure. Climate zone also dominated the variability in annual HVAC energy use, with the coldest location (CZ16) consistently showing both the highest annual consumption and the greatest absolute energy savings from smart controls. The relative (%) ventilation energy savings were also greatest in CZ16 for controls that used outdoor temperature measurement, but the other control types had much less variability in percent savings between climate regions.

Number of control zones had varying impacts between different control types. A subset of the smart controls were tested with different zoning assumptions, either with two control zones (bedrooms and non-bedrooms) or with each zone controlled independently. The cases with each zone treated independently were able to save more energy, because they further reduced dwelling ventilation rates, but they did this at the expense of increased personal exposures for some contaminants. Given the worsened personal exposure and small increase in energy savings, there is little reason to use more control zones. The apartment prototypes behaved distinctly from the 1-story cases, but their behavior in response to zoning assumptions is largely irrelevant, because these control types almost universally increased annual HVAC energy use for apartment dwellings, so we do not recommend using these strategies under either zoning configuration. The occupantTracker control improved IAQ when all zones were treated independently, but this was because the occupantTracker control did not attempt to save energy, but instead to only improve IAQ. In addition, because the occupantTracker ventilated occupied zones more effectively, it tended to increase personal particle exposures while reducing all other exposures.

Conclusions

Based on this work, two primary questions emerge: (1) Should zonal ventilation equipment be prioritized/encouraged in modern, airtight dwellings; and (2) Do ventilation controls offer substantial energy savings when using zonal equipment and occupancy sensing?

Zonal ventilation equipment typically did not offer evident IAQ improvements when compared against the non-zonal versions of the same fan type (e.g., single-point exhaust vs. multi-point exhaust). Some personal contaminant exposures were reduced when using zonal equipment, but this occurred at the expense of worsened exposures to the other contaminants, generally particles. Given these results, we do not suggest strong support in the building codes to encourage zonal ventilation systems for whole dwelling ventilation. The only exceptions to this might be for 2-story dwellings with 3 or more ACH_{50} envelope leakage that use a single exhaust fan on the lower level, where the 2nd level was substantially under-ventilated.

Zonal smart controls clearly offer a potential source of substantial energy savings in new homes that otherwise provide whole dwelling dilution ventilation without heat recovery. Whole dwelling HVAC savings of 10-20% were common, with individual cases reaching up to 40% savings. But these savings cannot be achieved without worsening personal exposures for at least one contaminant, so these approaches are not yet viable given the current code requirements for equivalent exposure for dynamically controlled ventilation systems. A method must be developed to balance these competing changes in exposure to determine the net-health impacts of a control strategy. On top of this, zonal ventilation systems are expected to be more expensive, complex, and difficult to install and verify correctly for performance and code compliance. Zonal controls add further complexity on top of the zonal equipment.

Future work should include developing a single metric for comparing the personal contaminant exposures resulting from smart controls. New control types will also be developed and tested for existing single-family home retrofits and for multifamily apartment buildings. These controls will be tailored to match the load profiles of these housing types, and we expect them to deliver improved energy performance in those contexts.

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Smart Controls Reference Tables

Tabular summaries of IAQ, site energy and TDV energy performance are provided in the subsections below for each control type tested in this work. These tables aggregate a number of IAQ and energy outcomes by each of the simulation parameters discussed in the prior sections. These results are not discussed here in detail, rather they are provided for the reference.

baseNoFan

Table 16: baseNoFan Aggregated Median IAQ Results.

Parameter	Personal Generic Exposure ($\mu g/m^3$)	Personal Formaldehyde Exposure ($\mu g/m^3$)	Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)	Personal CO_2 Exposure (ppm)	Personal Generic Exposure, 95th ($\mu g/m^3$)	Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)	Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)	Personal CO_2 Exposure, 95th (ppm)	Personal Generic Relative Exposure	Personal Formaldehyde Relative Exposure	Personal $PM_{2.5}$ Relative Exposure	Personal CO_2 Relative Exposure
VentSysType - None	72	62	15	1481	98	81	72	2083	3.74	2.87	1.08	1.83
CZ - 1	68	69	15	1352	85	81	71	1756	3.52	2.80	1.08	1.73
CZ - 3	70	69	15	1359	86	81	72	1751	3.61	2.92	1.01	1.76
CZ - 10	82	67	15	1600	114	85	73	2106	4.52	3.05	1.04	2.06
CZ - 16	79	40	16	1538	115	63	71	2100	3.88	2.58	1.18	1.91
ACH50 - 0.6	143	134	15	2166	172	198	72	2931	6.78	5.94	1.03	2.66
ACH50 - 2	71	49	14	1355	100	76	71	1888	3.47	2.24	1.12	1.66
ACH50 - 3	53	35	14	1156	77	58	70	1569	2.36	1.48	1.14	1.34
ACH50 – 3, apt	73	68	26	2704	97	80	120	4239	5.57	3.15	0.94	2.56
Prototype - 1story	77	75	14	1452	106	102	66	1941	3.74	2.87	1.04	1.83
Prototype - 2story	68	45	14	1279	101	69	75	1886	2.57	1.64	1.18	1.36
Prototype - apt	73	68	26	2704	97	80	120	4239	5.57	3.15	0.94	2.56
# Control Zones - 2	72	62	15	1481	98	81	72	2083	3.74	2.87	1.08	1.83
HVAC - HPfau	72	63	14	1481	98	80	71	2070	3.74	2.87	1.06	1.83
HVAC - VRF	72	61	15	1483	98	82	75	2093	3.75	2.85	1.15	1.83

Table 17: baseNoFan Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - None	983	614	100	36	69	21	-2	-3
CZ - 1	894	811	100	50	77	53	1	24
CZ - 3	686	473	100	46	19	15	-11	-26
CZ - 10	881	391	100	33	38	10	9	7
CZ - 16	2305	1093	100	31	191	24	-11	-7
ACH50 - 0.6	861	897	100	50	91	33	-5	-5
ACH50 - 2	985	705	100	38	84	25	0	1
ACH50 - 3	1070	575	100	31	72	21	2	7
ACH50 – 3, apt	1165	-501	NA	-77	-256	-95	-10	-16
Prototype - 1story	668	527	100	45	54	19	-4	-4
Prototype - 2story	1199	868	100	37	119	36	3	6
Prototype - apt	1165	-501	NA	-77	-256	-95	-10	-16
# Control Zones - 2	983	614	100	36	69	21	-2	-3
HVAC - HPfau	1168	706	100	36	74	22	-3	-3
HVAC - VRF	881	524	100	36	65	21	-1	-1

Table 18: baseNoFan Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - None	12856	4569	100	29	863	19	-41	-4
CZ - 1	7824	6498	100	51	1050	56	-5	-5
CZ - 3	7260	3268	100	31	88	3	-176	-22
CZ - 10	16135	3766	100	19	761	6	228	8
CZ - 16	22840	9530	100	28	2884	25	-92	-4
ACH50 - 0.6	12780	6600	100	38	967	26	-113	-11
ACH50 - 2	13565	5238	100	32	993	24	-31	-7
ACH50 - 3	14104	4318	100	28	925	20	-8	0
ACH50 – 3, apt	11163	-3737	NA	-56	-2433	-72	-119	-10
Prototype - 1story	9988	4372	100	32	960	18	-34	-3
Prototype - 2story	17670	6600	100	31	1126	21	11	-3
Prototype - apt	11163	-3737	NA	-56	-2433	-72	-119	-10
# Control Zones - 2	12856	4569	100	29	863	19	-41	-4
HVAC - HPfau	14976	5487	100	29	1017	19	-63	-7
HVAC - VRF	11002	4149	100	30	840	20	-25	-2

baseFan

Table 19: baseFan Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure ($\mu g/m^3$)*	*Personal Formaldehyde Exposure ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)*	*Personal CO_2 Exposure (ppm)*	*Personal Generic Exposure, 95th ($\mu g/m^3$)*	*Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)*	*Personal CO_2 Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal $PM_{2.5}$ Relative Exposure*	*Personal CO_2 Relative Exposure*
VentSysType - SPexhaust	20	25	12	832	22	31	64	986	1.00	1.00	1.00	1.00
VentSysType - SPsupply	23	26	12	800	28	37	66	965	1.00	1.00	1.00	1.00
VentSysType - SPbalanced	19	22	12	767	22	29	65	917	1.00	1.00	1.00	1.00
VentSysType - MPexhaust	20	23	13	793	22	31	66	980	1.01	1.00	1.02	0.97
VentSysType - MPsupply	22	23	12	784	23	29	69	943	0.96	0.96	1.09	0.99
VentSysType - MPbalanced	20	23	12	770	22	31	66	935	1.05	1.04	1.00	1.00
CZ - 1	20	24	12	769	22	31	64	923	1.00	1.00	1.00	1.00
CZ - 3	20	26	12	771	22	32	66	940	1.00	1.00	1.00	1.00
CZ - 10	21	25	13	784	23	34	66	965	1.00	1.00	1.00	1.00
CZ - 16	22	16	13	802	25	25	66	975	1.00	1.00	1.00	1.00
ACH50 - 0.6	21	23	12	778	22	30	65	934	1.00	1.00	1.00	1.00
ACH50 - 2	22	24	12	780	24	31	65	930	1.00	1.00	1.00	1.00
ACH50 - 3	22	24	12	775	25	32	65	925	1.00	1.00	1.00	1.00
ACH50 - 3, apt	14	22	21	1054	17	28	110	1356	1.00	1.00	1.00	1.00
Prototype - 1story	20	26	12	764	22	32	62	876	1.00	1.00	1.00	1.00
Prototype - 2story	22	22	12	796	26	30	69	982	1.00	1.00	1.00	1.00
Prototype - apt	14	22	21	1054	17	28	110	1356	1.00	1.00	1.00	1.00
# Control Zones - 2	21	23	12	783	23	31	66	949	1.00	1.00	1.00	1.00
HVAC - HPfau	21	23	11	783	23	31	64	942	1.00	1.00	1.00	1.00
HVAC - VRF	21	23	13	785	23	31	69	961	1.00	1.00	1.00	1.00
Zoned - MP	21	23	12	779	23	30	67	946	1.01	1.00	1.03	0.99

Parameter	***Personal Generic Exposure (µg/m^3)***	***Personal Formaldehyde Exposure (µg/m^3)***	***Personal PM$_{2.5}$ Exposure (µg/m^3)***	***Personal CO$_2$ Exposure (ppm)***	***Personal Generic Exposure, 95th (µg/m^3)***	***Personal Formaldehyde Exposure, 95th (µg/m^3)***	***Personal PM$_{2.5}$ Exposure, 95th (µg/m^3)***	***Personal CO$_2$ Exposure, 95th (ppm)***	***Personal Generic Relative Exposure***	***Personal Formaldehyde Relative Exposure***	***Personal PM$_{2.5}$ Relative Exposure***	***Personal CO$_2$ Relative Exposure***
Zoned - SP	21	23	12	792	24	31	65	952	1.00	1.00	1.00	1.00
FanType - exhaust	20	24	12	813	22	31	65	981	1.00	1.00	1.00	0.99
FanType - supply	22	24	12	794	25	33	67	955	1.00	1.00	1.00	1.00
FanType - balanced	20	22	12	768	22	30	65	926	1.01	1.01	1.00	1.00

Table 20: baseFan Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - SPexhaust	1423	0	0	0	0	0	0	0
VentSysType - SPsupply	1923	0	0	0	0	0	0	0
VentSysType - SPbalanced	2081	0	0	0	0	0	0	0
VentSysType - MPexhaust	1461	-1	0	0	1	0	0	0
VentSysType - MPsupply	1935	-2	0	0	0	0	0	0
VentSysType - MPbalanced	2063	15	1	1	1	0	0	0
CZ - 1	2002	0	0	0	0	0	0	0
CZ - 3	1393	0	0	0	0	0	0	0
CZ - 10	1612	0	0	0	0	0	0	0
CZ - 16	3912	0	0	0	0	0	0	0
ACH50 - 0.6	2151	0	0	0	0	0	0	0
ACH50 - 2	2020	0	0	0	0	0	0	0
ACH50 - 3	1911	0	0	0	0	0	0	0
ACH50 - 3, apt	901	0	0	0	0	0	0	0
Prototype - 1story	1546	0	0	0	0	0	0	0
Prototype - 2story	2471	0	0	0	0	0	0	0
Prototype - apt	901	0	0	0	0	0	0	0
# Control Zones - 2	1889	0	0	0	0	0	0	0
HVAC - HPfau	2007	0	0	0	0	0	0	0
HVAC - VRF	1551	0	0	0	0	0	0	0
Zoned - MP	1891	2	0	0	1	0	0	0
Zoned - SP	1865	0	0	0	0	0	0	0
FanType - exhaust	1444	0	0	0	0	0	0	0
FanType - supply	1928	0	0	0	0	0	0	0
FanType - balanced	2071	0	0	0	0	0	0	0

Table 21: baseFan Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - SPexhaust	16460	0	0	0	0	0	0	0
VentSysType - SPsupply	19940	0	0	0	0	0	0	0
VentSysType - SPbalanced	21794	0	0	0	0	0	0	0
VentSysType - MPexhaust	16442	11	0	0	29	1	1	0
VentSysType - MPsupply	20158	-3	0	0	-5	0	1	0
VentSysType - MPbalanced	21687	110	1	1	10	0	0	0
CZ - 1	16054	0	0	0	0	0	0	0
CZ - 3	13173	0	0	0	0	0	0	0
CZ - 10	21892	0	0	0	0	0	0	0
CZ - 16	36557	0	0	0	0	0	0	0
ACH50 - 0.6	21840	0	0	0	0	0	0	0
ACH50 - 2	21051	0	0	0	0	0	0	0
ACH50 - 3	20911	0	0	0	0	0	0	0
ACH50 - 3, apt	8766	0	0	0	0	0	0	0
Prototype - 1story	16466	0	0	0	0	0	0	0
Prototype - 2story	25943	0	0	0	0	0	0	0
Prototype - apt	8766	0	0	0	0	0	0	0
# Control Zones - 2	19792	0	0	0	0	0	0	0
HVAC - HPfau	22266	0	0	0	0	0	0	0
HVAC - VRF	18144	0	0	0	0	0	0	0
Zoned - MP	19792	25	0	0	8	0	0	0
Zoned - SP	19755	0	0	0	0	0	0	0
FanType - exhaust	16460	0	0	0	0	0	0	0
FanType - supply	19940	0	0	0	0	0	0	0
FanType - balanced	21712	0	0	0	0	0	0	0

supplyTracker

Table 22: supplyTracker Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure ($\mu g/m^3$)*	*Personal Formaldehyde Exposure ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)*	*Personal CO_2 Exposure (ppm)*	*Personal Generic Exposure, 95th ($\mu g/m^3$)*	*Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)*	*Personal CO_2 Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal $PM_{2.5}$ Relative Exposure*	*Personal CO_2 Relative Exposure*
VentSysType - SPbalanced	16	18	12	706	22	29	66	836	0.83	0.86	1.02	0.92
CZ - 1	16	18	12	688	20	29	64	798	0.86	0.89	1.02	0.92
CZ - 3	15	19	12	689	20	30	66	799	0.85	0.87	1.02	0.92
CZ - 10	16	18	12	699	22	32	66	821	0.81	0.84	1.03	0.92
CZ - 16	17	13	13	710	23	22	65	841	0.85	0.89	1.00	0.93
ACH50 - 0.6	15	16	11	681	22	29	64	805	0.79	0.85	1.08	0.91
ACH50 - 2	16	18	12	705	22	29	65	835	0.82	0.87	1.02	0.93
ACH50 - 3	17	19	12	715	22	28	65	840	0.86	0.88	0.99	0.94
ACH50 - 3, apt	10	18	20	845	15	26	105	1011	0.78	0.81	1.02	0.85
Prototype - 1story	16	22	11	689	20	30	60	800	0.86	0.88	1.02	0.92
Prototype - 2story	16	17	12	707	25	28	69	839	0.80	0.84	0.99	0.93
Prototype - apt	10	18	20	845	15	26	105	1011	0.78	0.81	1.02	0.85
# Control Zones - 2	16	18	12	706	22	29	66	836	0.83	0.86	1.02	0.92
HVAC - HPfau	16	18	11	704	22	28	65	835	0.83	0.86	1.03	0.92
HVAC - VRF	16	18	13	707	22	29	70	837	0.83	0.86	1.00	0.92
Zoned - SP	16	18	12	706	22	29	66	836	0.83	0.86	1.02	0.92
FanType - balanced	16	18	12	706	22	29	66	836	0.83	0.86	1.02	0.92

Table 23: supplyTracker Aggregated Site Energy Summary.

Parameter	***Total HVAC Energy Use (kWh)***	***Total HVAC Energy Savings (kWh)***	***Total Vent Energy Savings (%)***	***Total HVAC Energy Savings (%)***	***Total HVAC On-Peak Energy Savings (kWh)***	***Total HVAC On-Peak Energy Savings (%)***	***Total HVAC Super On-Peak Energy Savings (kWh)***	***Total HVAC Super On-Peak Energy Savings (%)***
VentSysType - SPbalanced	2097	-2	0	0	3	1	0	0
CZ - 1	2155	-2	-2	0	4	2	0	0
CZ - 3	1523	-2	-1	0	3	1	0	1
CZ - 10	1780	-1	0	0	4	1	1	0
CZ - 16	4414	-4	0	0	2	0	0	0
ACH50 - 0.6	2394	-5	0	0	5	1	0	0
ACH50 - 2	2250	-4	0	0	4	1	0	0
ACH50 - 3	2176	-8	0	0	4	1	0	0
ACH50 – 3, apt	1007	6	NA	1	3	1	0	0
Prototype - 1story	1687	-1	0	0	0	0	0	0
Prototype - 2story	2803	-29	-2	-1	16	3	0	1
Prototype - apt	1007	6	NA	1	3	1	0	0
# Control Zones - 2	2097	-2	0	0	3	1	0	0
HVAC - HPfau	2344	-3	0	0	4	1	0	0
HVAC - VRF	1933	-2	0	0	3	1	0	0
Zoned - SP	2097	-2	0	0	3	1	0	0
FanType - balanced	2097	-2	0	0	3	1	0	0

Table 24: supplyTracker Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - SPbalanced	21972	-5	0	0	38	1	4	0
CZ - 1	17307	-26	-1	0	40	2	0	0
CZ - 3	14680	-26	-1	0	26	1	5	0
CZ - 10	23739	6	0	0	47	0	27	1
CZ - 16	41382	-15	0	0	41	0	5	0
ACH50 - 0.6	24922	-20	0	0	71	1	4	0
ACH50 - 2	23782	-26	0	0	67	1	4	0
ACH50 - 3	23032	-7	0	0	65	1	4	0
ACH50 – 3, apt	9983	51	NA	1	26	1	8	0
Prototype - 1story	18870	-4	0	0	1	0	2	0
Prototype - 2story	28727	-207	-1	-1	269	3	10	1
Prototype - apt	9983	51	NA	1	26	1	8	0
# Control Zones - 2	21972	-5	0	0	38	1	4	0
HVAC - HPfau	23208	-14	0	0	41	1	5	0
HVAC - VRF	20335	-5	0	0	38	1	3	0
Zoned - SP	21972	-5	0	0	38	1	4	0
FanType - balanced	21972	-5	0	0	38	1	4	0

occupantTracker

Table 25: occupantTracker Aggregated Median IAQ Results.

Parameter	***Personal Generic Exposure ($\mu g/m^3$)***	***Personal Formaldehyde Exposure ($\mu g/m^3$)***	***Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)***	***Personal CO_2 Exposure (ppm)***	***Personal Generic Exposure, 95th ($\mu g/m^3$)***	***Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)***	***Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)***	***Personal CO_2 Exposure, 95th (ppm)***	***Personal Generic Relative Exposure***	***Personal Formaldehyde Relative Exposure***	***Personal $PM_{2.5}$ Relative Exposure***	***Personal CO_2 Relative Exposure***
VentSysType - MPexhaust	21	23	13	713	22	31	65	856	1.01	0.99	0.99	0.92
VentSysType - MPsupply	18	19	12	718	24	31	68	855	0.81	0.85	1.11	0.92
VentSysType - MPbalanced	19	21	12	694	24	32	64	828	0.93	0.94	1.03	0.92
CZ - 1	18	23	12	701	22	31	63	827	0.93	0.93	1.04	0.92
CZ - 3	18	23	12	700	22	32	65	829	0.93	0.93	1.04	0.92
CZ - 10	19	22	12	709	23	34	65	846	0.92	0.93	1.04	0.92
CZ - 16	20	14	13	729	25	24	66	874	0.93	0.95	1.01	0.92
ACH50 - 0.6	19	21	12	702	23	31	64	831	0.94	0.95	1.05	0.92
ACH50 - 2	19	21	12	703	24	31	64	834	0.93	0.93	1.02	0.92
ACH50 - 3	19	22	12	711	25	32	64	845	0.92	0.93	1.01	0.93
ACH50 – 3, apt	13	20	21	873	18	30	107	1021	0.88	0.88	1.03	0.87
Prototype - 1story	19	24	12	701	22	32	61	822	0.94	0.95	1.00	0.93
Prototype - 2story	19	20	12	710	27	30	68	904	0.92	0.93	1.05	0.91
Prototype - apt	13	20	21	873	18	30	107	1021	0.88	0.88	1.03	0.87
# Control Zones - 2	19	21	12	721	23	31	66	941	0.93	0.93	1.03	0.93
# Control Zones - 4	19	21	12	697	24	31	65	832	0.92	0.92	1.03	0.91
HVAC - HPfau	19	21	11	709	23	31	63	846	0.92	0.93	1.04	0.92
HVAC - VRF	19	21	13	711	23	31	69	849	0.93	0.93	1.02	0.92
Zoned - MP	19	21	12	710	23	31	65	847	0.93	0.93	1.03	0.92
FanType - exhaust	21	23	13	713	22	31	65	856	1.01	0.99	0.99	0.92
FanType - supply	18	19	12	718	24	31	68	855	0.81	0.85	1.11	0.92
FanType - balanced	19	21	12	694	24	32	64	828	0.93	0.94	1.03	0.92

Table 26: occupantTracker Aggregated Site Energy Summary.

Parameter	***Total HVAC Energy Use (kWh)***	***Total HVAC Energy Savings (kWh)***	***Total Vent Energy Savings (%)***	***Total HVAC Energy Savings (%)***	***Total HVAC On-Peak Energy Savings (kWh)***	***Total HVAC On-Peak Energy Savings (%)***	***Total HVAC Super On-Peak Energy Savings (kWh)***	***Total HVAC Super On-Peak Energy Savings (%)***
VentSysType - MPexhaust	1499	-9	-2	-1	1	0	1	1
VentSysType - MPsupply	1922	-3	0	0	0	0	0	0
VentSysType - MPbalanced	2068	2	0	0	1	0	0	0
CZ - 1	1948	-9	-2	-1	-1	0	0	0
CZ - 3	1390	-9	-2	-1	0	0	0	1
CZ - 10	1607	-1	0	0	4	1	1	1
CZ - 16	3934	1	0	0	1	0	1	0
ACH50 - 0.6	2141	-6	0	0	1	0	0	1
ACH50 - 2	2007	-7	-1	0	1	0	0	0
ACH50 - 3	1935	-6	-1	0	1	0	0	0
ACH50 – 3, apt	906	0	NA	0	-1	0	0	0
Prototype - 1story	1544	3	0	0	0	0	0	0
Prototype - 2story	2481	-28	-2	-1	8	1	1	1
Prototype - apt	906	0	NA	0	-1	0	0	0
# Control Zones - 2	1911	-4	-1	0	0	0	0	0
# Control Zones - 4	1914	-6	-1	0	1	0	0	0
HVAC - HPfau	2017	-5	-1	0	0	0	0	0
HVAC - VRF	1534	-5	-1	0	1	0	0	0
Zoned - MP	1912	-5	-1	0	1	0	0	0
FanType - exhaust	1499	-9	-2	-1	1	0	1	1
FanType - supply	1922	-3	0	0	0	0	0	0
FanType - balanced	2068	2	0	0	1	0	0	0

Table 27: occupantTracker Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - MPexhaust	16465	-44	-1	0	14	0	10	1
VentSysType - MPsupply	20153	-18	0	0	11	0	3	0
VentSysType - MPbalanced	21761	38	1	0	10	0	6	0
CZ - 1	15638	-92	-2	-1	-7	0	0	0
CZ - 3	13096	-54	-1	-1	13	0	8	1
CZ - 10	21788	29	0	0	44	0	17	0
CZ - 16	36717	-14	0	0	11	0	13	1
ACH50 - 0.6	21809	-6	0	0	14	0	12	1
ACH50 - 2	21010	-29	0	0	18	0	7	0
ACH50 - 3	20871	-20	0	0	23	0	7	0
ACH50 – 3, apt	8783	-14	NA	0	-11	0	1	0
Prototype - 1story	16414	24	0	0	-6	0	2	0
Prototype - 2story	25952	-172	-2	-1	110	1	18	1
Prototype - apt	8783	-14	NA	0	-11	0	1	0
# Control Zones - 2	19824	-19	0	0	11	0	3	0
# Control Zones - 4	19872	-28	0	0	14	0	9	1
HVAC - HPfau	22318	-20	0	0	9	0	5	0
HVAC - VRF	18452	-20	0	0	15	0	8	0
Zoned - MP	19824	-20	0	0	12	0	7	0
FanType - exhaust	16465	-44	-1	0	14	0	10	1
FanType - supply	20153	-18	0	0	11	0	3	0
FanType - balanced	21761	38	1	0	10	0	6	0

varQ

Table 28: varQ aggregated Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure (µg/m^3)*	*Personal Formaldehyde Exposure (µg/m^3)*	*Personal PM$_{2.5}$ Exposure (µg/m^3)*	*Personal CO$_2$ Exposure (ppm)*	*Personal Generic Exposure, 95th (µg/m^3)*	*Personal Formaldehyde Exposure, 95th (µg/m^3)*	*Personal PM$_{2.5}$ Exposure, 95th (µg/m^3)*	*Personal CO$_2$ Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal PM$_{2.5}$ Relative Exposure*	*Personal CO$_2$ Relative Exposure*
VentSysType - SPexhaust	21	25	12	822	42	33	63	1192	0.99	0.99	1.02	0.99
VentSysType - SPsupply	23	26	12	791	44	35	65	1086	0.98	0.99	1.02	0.99
VentSysType - SPbalanced	19	21	12	766	41	27	64	1074	1.00	0.98	0.97	1.00
CZ - 1	20	25	12	771	33	29	63	1002	0.98	0.99	0.97	1.00
CZ - 3	20	25	11	767	41	33	63	1107	0.98	0.99	0.99	1.00
CZ - 10	22	25	12	770	47	41	64	1094	0.99	0.98	1.04	0.98
CZ - 16	23	14	13	815	45	23	65	1172	1.01	0.96	1.06	1.00
ACH50 - 0.6	21	23	11	771	42	30	63	1097	0.99	0.99	0.99	1.00
ACH50 - 2	22	24	11	785	45	33	64	1092	0.99	0.99	1.00	0.99
ACH50 - 3	21	24	11	767	42	33	64	1063	0.97	0.98	1.03	0.99
ACH50 – 3, apt	18	24	21	1174	39	32	111	2370	1.20	1.09	1.02	1.10
Prototype - 1story	20	25	11	761	44	33	62	1091	0.99	0.98	1.01	0.99
Prototype - 2story	23	22	12	811	41	32	66	1089	0.99	0.99	1.00	0.99
Prototype - apt	18	24	21	1174	39	32	111	2370	1.20	1.09	1.02	1.10
# Control Zones - 2	21	24	12	788	42	33	64	1097	0.99	0.99	1.00	1.00
HVAC - HPfau	21	24	11	788	42	33	62	1096	0.99	0.99	1.02	1.00
HVAC - VRF	21	24	13	788	42	33	68	1099	0.99	0.99	1.00	0.99
Zoned - SP	21	24	12	788	42	33	64	1097	0.99	0.99	1.00	1.00
FanType - exhaust	21	25	12	822	42	33	63	1192	0.99	0.99	1.02	0.99
FanType - supply	23	26	12	791	44	35	65	1086	0.98	0.99	1.02	0.99
FanType - balanced	19	21	12	766	41	27	64	1074	1.00	0.98	0.97	1.00

Table 29: varQ Aggregated Site Energy Summary.

Parameter	***Total HVAC Energy Use (kWh)***	***Total HVAC Energy Savings (kWh)***	***Total Vent Energy Savings (%)***	***Total HVAC Energy Savings (%)***	***Total HVAC On-Peak Energy Savings (kWh)***	***Total HVAC On-Peak Energy Savings (%)***	***Total HVAC Super On-Peak Energy Savings (kWh)***	***Total HVAC Super On-Peak Energy Savings (%)***
VentSysType - SPexhaust	1262	204	36	14	26	14	9	11
VentSysType - SPsupply	1855	78	7	4	9	3	2	1
VentSysType - SPbalanced	1984	76	7	4	10	3	-3	-2
CZ - 1	1796	101	10	6	-30	-7	-7	-39
CZ - 3	1326	50	7	4	-24	-8	-5	-19
CZ - 10	1553	38	7	2	50	10	43	21
CZ - 16	3346	485	37	13	130	15	9	6
ACH50 - 0.6	1939	157	12	7	27	7	0	0
ACH50 - 2	1866	156	15	8	28	9	5	4
ACH50 - 3	1862	123	14	7	21	9	0	0
ACH50 – 3, apt	846	31	NA	6	9	3	14	18
Prototype - 1story	1494	155	14	9	26	8	2	1
Prototype - 2story	2389	151	12	6	29	8	4	2
Prototype - apt	846	31	NA	6	9	3	14	18
# Control Zones - 2	1760	125	14	7	17	6	6	5
HVAC - HPfau	1821	193	18	8	20	8	7	6
HVAC - VRF	1582	77	10	5	12	5	4	5
Zoned - SP	1760	125	14	7	17	6	6	5
FanType - exhaust	1262	204	36	14	26	14	9	11
FanType - supply	1855	78	7	4	9	3	2	1
FanType - balanced	1984	76	7	4	10	3	-3	-2

Table 30: varQ Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - SPexhaust	13753	2298	53	15	479	15	153	11
VentSysType - SPsupply	18564	1244	19	8	224	6	67	2
VentSysType - SPbalanced	20262	1526	20	8	235	7	-6	0
CZ - 1	14383	871	11	7	-97	-3	-100	-37
CZ - 3	12656	571	10	5	-11	0	58	5
CZ - 10	19693	2425	33	10	1678	14	600	18
CZ - 16	30779	4982	44	14	2292	18	129	5
ACH50 - 0.6	19830	2210	23	10	963	13	91	4
ACH50 - 2	19467	2218	27	10	1032	13	112	6
ACH50 - 3	19035	2010	31	10	958	13	85	5
ACH50 – 3, apt	8487	674	NA	8	235	6	198	13
Prototype - 1story	14383	2011	27	11	965	15	67	3
Prototype - 2story	23886	2210	27	9	898	12	120	6
Prototype - apt	8487	674	NA	8	235	6	198	13
# Control Zones - 2	18023	1746	27	10	378	11	120	6
HVAC - HPfau	19926	2268	31	11	378	12	143	6
HVAC - VRF	16960	1291	24	9	341	11	110	5
Zoned - SP	18023	1746	27	10	378	11	120	6
FanType - exhaust	13753	2298	53	15	479	15	153	11
FanType - supply	18564	1244	19	8	224	6	67	2
FanType - balanced	20262	1526	20	8	235	7	-6	0

varQmzSingleZoneOpt

Table 31: varQmzSingleZoneOpt Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure (µg/m^3)*	*Personal Formaldehyde Exposure (µg/m^3)*	*Personal $PM_{2.5}$ Exposure (µg/m^3)*	*Personal CO_2 Exposure (ppm)*	*Personal Generic Exposure, 95th (µg/m^3)*	*Personal Formaldehyde Exposure, 95th (µg/m^3)*	*Personal $PM_{2.5}$ Exposure, 95th (µg/m^3)*	*Personal CO_2 Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal $PM_{2.5}$ Relative Exposure*	*Personal CO_2 Relative Exposure*
VentSysType - MPexhaust	21	22	12	737	40	29	65	1047	0.99	0.98	1.01	0.93
VentSysType - MPsupply	18	19	12	728	37	29	68	1023	0.85	0.86	1.12	0.94
VentSysType - MPbalanced	19	21	12	717	41	29	65	1067	0.94	0.92	1.03	0.95
CZ - 1	18	22	12	721	30	28	63	934	0.92	0.93	1.01	0.94
CZ - 3	18	23	12	722	39	32	65	1060	0.94	0.92	1.01	0.95
CZ - 10	20	22	12	715	47	40	66	1063	0.94	0.92	1.08	0.93
CZ - 16	21	13	13	753	41	22	66	1120	1.00	0.91	1.09	0.95
ACH50 - 0.6	19	21	12	716	40	29	64	1003	0.92	0.92	1.06	0.93
ACH50 - 2	20	21	12	727	42	29	65	1050	0.94	0.92	1.06	0.94
ACH50 - 3	20	21	12	722	39	29	65	1027	0.92	0.91	1.06	0.94
ACH50 – 3, apt	16	22	21	1038	39	32	110	1978	1.08	1.02	1.05	1.00
Prototype - 1story	19	24	12	715	42	31	62	1074	0.96	0.94	1.04	0.95
Prototype - 2story	20	20	12	728	37	27	69	1002	0.91	0.91	1.07	0.93
Prototype - apt	16	22	21	1038	39	32	110	1978	1.08	1.02	1.05	1.00
# Control Zones - 2	19	21	12	726	40	29	65	1050	0.94	0.92	1.06	0.94
HVAC - HPfau	19	21	11	726	39	29	63	1038	0.94	0.93	1.08	0.94
HVAC - VRF	19	21	13	727	40	29	70	1059	0.94	0.92	1.04	0.94
Zoned - MP	19	21	12	726	40	29	65	1050	0.94	0.92	1.06	0.94
FanType - exhaust	21	22	12	737	40	29	65	1047	0.99	0.98	1.01	0.93
FanType - supply	18	19	12	728	37	29	68	1023	0.85	0.86	1.12	0.94
FanType - balanced	19	21	12	717	41	29	65	1067	0.94	0.92	1.03	0.95

Table 32: varQmz SingleZoneOpt Aggregated Site Energy Summary.

Parameter	***Total HVAC Energy Use (kWh)***	***Total HVAC Energy Savings (kWh)***	***Total Vent Energy Savings (%)***	***Total HVAC Energy Savings (%)***	***Total HVAC On-Peak Energy Savings (kWh)***	***Total HVAC On-Peak Energy Savings (%)***	***Total HVAC Super On-Peak Energy Savings (kWh)***	***Total HVAC Super On-Peak Energy Savings (%)***
VentSysType - MPexhaust	1291	194	35	14	26	14	10	12
VentSysType - MPsupply	1867	68	7	3	5	1	2	1
VentSysType - MPbalanced	1981	64	5	3	4	1	-3	-2
CZ - 1	1787	90	9	5	-30	-8	-7	-39
CZ - 3	1335	47	6	3	-24	-8	-5	-17
CZ - 10	1555	45	9	3	60	12	45	22
CZ - 16	3367	497	36	13	131	15	11	7
ACH50 - 0.6	1957	131	11	7	24	7	0	0
ACH50 - 2	1883	143	13	8	25	8	5	3
ACH50 - 3	1868	122	15	7	19	8	0	0
ACH50 – 3, ACH50	865	24	NA	5	4	1	12	16
Prototype - 1story	1488	156	14	9	24	7	2	1
Prototype - 2story	2393	126	11	5	36	9	5	3
Prototype - apt	865	24	NA	5	4	1	12	16
# Control Zones - 2	1754	117	13	6	15	5	5	6
HVAC - HPfau	1815	169	15	8	17	7	7	6
HVAC - VRF	1577	59	10	4	10	5	4	5
Zoned - MP	1754	117	13	6	15	5	5	6
FanType - exhaust	1291	194	35	14	26	14	10	12
FanType - supply	1867	68	7	3	5	1	2	1
FanType - balanced	1981	64	5	3	4	1	-3	-2

Table 33: varQmz SingleZoneOpt Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - MPexhaust	13853	2263	53	15	486	16	169	14
VentSysType - MPsupply	18968	1158	19	8	236	6	59	3
VentSysType - MPbalanced	20257	1386	19	8	182	6	1	0
CZ - 1	14325	771	9	6	-100	-3	-100	-37
CZ - 3	12656	570	10	5	31	1	46	4
CZ - 10	19728	2550	36	11	1833	16	641	19
CZ - 16	30769	5187	45	14	2371	18	142	5
ACH50 - 0.6	19840	2123	23	10	934	15	117	5
ACH50 - 2	19497	2344	29	10	1027	14	120	6
ACH50 - 3	19062	1979	32	11	957	14	98	5
ACH50 – 3, apt	8585	550	NA	7	182	6	172	11
Prototype - 1story	14325	2023	27	11	944	15	59	2
Prototype - 2story	23644	2355	29	9	986	14	144	6
Prototype - apt	8585	550	NA	7	182	6	172	11
# Control Zones - 2	18100	1708	28	9	381	12	132	6
HVAC - HPfau	19941	2167	31	11	390	12	150	6
HVAC - VRF	16942	1305	23	9	344	11	125	6
Zoned - MP	18100	1708	28	9	381	12	132	6
FanType - exhaust	13853	2263	53	15	486	16	169	14
FanType - supply	18968	1158	19	8	236	6	59	3
FanType - balanced	20257	1386	19	8	182	6	1	0

varQmz

Table 34: varQmz Aggregated Median IAQ Results.

Parameter	Personal Generic Exposure (μg/m^3)	Personal Formaldehyde Exposure (μg/m^3)	Personal PM$_{2.5}$ Exposure (μg/m^3)	Personal CO$_2$ Exposure (ppm)	Personal Generic Exposure, 95th (μg/m^3)	Personal Formaldehyde Exposure, 95th (μg/m^3)	Personal PM$_{2.5}$ Exposure, 95th (μg/m^3)	Personal CO$_2$ Exposure, 95th (ppm)	Personal Generic Relative Exposure	Personal Formaldehyde Relative Exposure	Personal PM$_{2.5}$ Relative Exposure	Personal CO$_2$ Relative Exposure
VentSysType - MPexhaust	26	24	13	805	44	32	67	1149	1.25	1.06	0.99	1.02
VentSysType - MPsupply	23	21	12	800	41	31	69	1135	1.07	0.93	1.15	1.02
VentSysType - MPbalanced	23	22	12	776	43	32	66	1131	1.14	0.98	1.07	1.00
CZ - 1	23	24	12	795	36	32	65	1042	1.13	1.02	1.05	1.03
CZ - 3	23	25	12	790	42	32	66	1121	1.12	1.02	1.04	1.01
CZ - 10	25	24	13	776	51	41	67	1147	1.12	0.98	1.07	1.00
CZ - 16	27	14	14	836	46	23	68	1254	1.17	0.89	1.13	1.03
ACH50 - 0.6	24	23	12	791	48	32	66	1134	1.15	0.99	1.07	1.02
ACH50 - 2	25	23	12	803	51	32	66	1147	1.17	0.99	1.08	1.02
ACH50 - 3	24	23	12	780	41	33	66	1081	1.11	0.97	1.07	1.01
ACH50 – 3, apt	16	22	22	1028	27	30	111	1439	1.14	1.03	1.06	0.99
Prototype - 1story	23	27	12	787	49	35	63	1138	1.18	1.02	1.07	1.04
Prototype - 2story	25	21	12	796	41	30	70	1105	1.12	0.96	1.08	1.01
Prototype - apt	16	22	22	1028	27	30	111	1439	1.14	1.03	1.06	0.99
# Control Zones - 2	24	22	13	799	43	32	67	1135	1.14	0.98	1.07	1.02
HVAC - HPfau	24	22	12	797	42	31	65	1131	1.14	0.98	1.08	1.02
HVAC - VRF	24	22	14	800	44	32	71	1140	1.13	0.98	1.06	1.02
Zoned - MP	24	22	13	799	43	32	67	1135	1.14	0.98	1.07	1.02
FanType - exhaust	26	24	13	805	44	32	67	1149	1.25	1.06	0.99	1.02
FanType - supply	23	21	12	800	41	31	69	1135	1.07	0.93	1.15	1.02
FanType - balanced	23	22	12	776	43	32	66	1131	1.14	0.98	1.07	1.00

Table 35: varQmz Aggregated Site Energy Summary.

Parameter	***Total HVAC Energy Use (kWh)***	***Total HVAC Energy Savings (kWh)***	***Total Vent Energy Savings (%)***	***Total HVAC Energy Savings (%)***	***Total HVAC On-Peak Energy Savings (kWh)***	***Total HVAC On-Peak Energy Savings (%)***	***Total HVAC Super On-Peak Energy Savings (kWh)***	***Total HVAC Super On-Peak Energy Savings (%)***
VentSysType - MPexhaust	1118	335	59	22	45	19	6	7
VentSysType - MPsupply	1556	369	33	18	49	13	1	2
VentSysType - MPbalanced	1680	404	34	18	42	12	1	0
CZ - 1	1450	446	35	18	30	12	-3	-14
CZ - 3	1126	298	31	19	24	10	-1	-4
CZ - 10	1362	266	37	18	72	19	38	19
CZ - 16	3008	880	59	21	206	22	10	6
ACH50 - 0.6	1636	470	35	20	60	18	5	4
ACH50 - 2	1582	437	43	22	62	19	7	5
ACH50 - 3	1579	356	43	19	55	17	3	3
ACH50 – 3, apt	879	-9	NA	-1	-36	-11	2	2
Prototype - 1story	1228	328	43	24	46	17	5	4
Prototype - 2story	2047	453	38	18	67	19	4	5
Prototype - apt	879	-9	NA	-1	-36	-11	2	2
# Control Zones - 2	1497	368	40	19	47	15	4	4
HVAC - HPfau	1561	447	43	19	50	15	4	4
HVAC - VRF	1333	308	37	18	42	15	3	4
Zoned - MP	1497	368	40	19	47	15	4	4
FanType - exhaust	1118	335	59	22	45	19	6	7
FanType - supply	1556	369	33	18	49	13	1	2
FanType - balanced	1680	404	34	18	42	12	1	0

Table 36: varQmz Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - MPexhaust	13959	3400	71	19	673	18	133	7
VentSysType - MPsupply	16838	3718	41	17	750	15	70	5
VentSysType - MPbalanced	17709	3993	47	18	811	16	56	4
CZ - 1	11577	3636	35	18	592	17	-39	-12
CZ - 3	10766	2534	36	18	443	12	53	5
CZ - 10	18297	3810	56	17	1868	15	570	17
CZ - 16	28382	8367	64	21	3115	24	147	6
ACH50 - 0.6	17937	4170	44	19	1180	18	116	6
ACH50 - 2	17393	3952	53	19	1157	18	127	6
ACH50 - 3	17565	3687	53	18	1168	17	90	6
ACH50 – 3, apt	8397	-44	NA	-1	-183	-4	20	1
Prototype - 1story	13026	3597	49	23	1046	19	115	5
Prototype - 2story	21474	4466	49	17	1188	16	134	6
Prototype - apt	8397	-44	NA	-1	-183	-4	20	1
# Control Zones - 2	16331	3709	49	18	716	16	90	5
HVAC - HPfau	18265	4089	53	19	781	17	104	5
HVAC - VRF	15254	3055	47	17	662	16	83	5
Zoned - MP	16331	3709	49	18	716	16	90	5
FanType - exhaust	13959	3400	71	19	673	18	133	7
FanType - supply	16838	3718	41	17	750	15	70	5
FanType - balanced	17709	3993	47	18	811	16	56	4

zoneExposure

Table 37: zoneExposure Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure (μg/m^3)*	*Personal Formaldehyde Exposure (μg/m^3)*	*Personal PM$_{2.5}$ Exposure (μg/m^3)*	*Personal CO$_2$ Exposure (ppm)*	*Personal Generic Exposure, 95th (μg/m^3)*	*Personal Formaldehyde Exposure, 95th (μg/m^3)*	*Personal PM$_{2.5}$ Exposure, 95th (μg/m^3)*	*Personal CO$_2$ Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal PM$_{2.5}$ Relative Exposure*	*Personal CO$_2$ Relative Exposure*
VentSysType - MPexhaust	25	25	11	802	36	35	62	1032	1.21	1.10	0.82	1.03
VentSysType - MPsupply	23	23	11	811	33	33	65	1021	1.10	1.02	0.94	1.05
VentSysType - MPbalanced	23	23	11	791	32	33	61	989	1.15	1.05	0.89	1.03
CZ - 1	23	25	11	788	32	34	61	986	1.13	1.03	0.84	1.03
CZ - 3	23	26	11	789	32	35	63	994	1.14	1.04	0.85	1.03
CZ - 10	24	25	11	803	35	37	63	1020	1.16	1.04	0.85	1.04
CZ - 16	26	16	12	826	36	26	64	1046	1.16	1.08	0.85	1.04
ACH50 - 0.6	25	24	10	802	37	35	61	1032	1.21	1.10	0.83	1.03
ACH50 - 2	25	24	11	799	34	34	62	1000	1.15	1.05	0.89	1.03
ACH50 - 3	24	24	11	792	33	34	62	971	1.11	1.01	0.94	1.03
ACH50 – 3, apt	18	24	19	1140	27	32	105	1713	1.17	1.03	0.82	1.06
Prototype - 1story	24	28	11	793	33	36	59	979	1.15	1.07	0.84	1.05
Prototype - 2story	25	23	11	801	36	33	66	1031	1.13	1.02	0.87	1.02
Prototype - apt	18	24	19	1140	27	32	105	1713	1.17	1.03	0.82	1.06
# Control Zones - 2	23	24	11	794	33	33	63	1010	1.13	1.03	0.85	1.03
# Control Zones - 4	25	24	11	811	34	35	62	1023	1.19	1.06	0.85	1.05
HVAC - HPfau	24	24	10	801	34	34	61	1014	1.15	1.05	0.85	1.04
HVAC - VRF	24	24	12	802	34	34	66	1019	1.14	1.04	0.85	1.03
Zoned - MP	24	24	11	802	34	34	63	1016	1.15	1.04	0.85	1.04
FanType - exhaust	25	25	11	802	36	35	62	1032	1.21	1.10	0.82	1.03
FanType - supply	23	23	11	811	33	33	65	1021	1.10	1.02	0.94	1.05
FanType - balanced	23	23	11	791	32	33	61	989	1.15	1.05	0.89	1.03

Table 38: zoneExposure Aggregated Site Energy Summary.

Parameter	***Total HVAC Energy Use (kWh)***	***Total HVAC Energy Savings (kWh)***	***Total Vent Energy Savings (%)***	***Total HVAC Energy Savings (%)***	***Total HVAC On-Peak Energy Savings (kWh)***	***Total HVAC On-Peak Energy Savings (%)***	***Total HVAC Super On-Peak Energy Savings (kWh)***	***Total HVAC Super On-Peak Energy Savings (%)***
VentSysType - MPexhaust	1343	105	19	6	-17	-5	0	0
VentSysType - MPsupply	1678	257	24	12	-6	-2	-4	-3
VentSysType - MPbalanced	1779	276	26	13	1	0	-4	-4
CZ - 1	1727	240	20	11	-26	-11	-2	-13
CZ - 3	1217	180	22	11	-15	-7	0	0
CZ - 10	1467	159	23	10	6	1	-1	-1
CZ - 16	3506	407	31	10	-9	-2	-7	-4
ACH50 - 0.6	1817	253	20	11	-9	-2	-2	-2
ACH50 - 2	1772	254	24	11	-1	0	-3	-3
ACH50 - 3	1695	247	27	11	3	1	-1	-3
ACH50 – 3, apt	866	-31	NA	-3	-36	-9	-1	-1
Prototype - 1story	1343	197	20	11	-16	-6	-4	-3
Prototype - 2story	2145	335	26	12	7	2	-1	-1
Prototype - apt	866	-31	NA	-3	-36	-9	-1	-1
# Control Zones - 2	1682	187	19	9	-15	-4	-2	-3
# Control Zones - 4	1579	269	29	13	2	1	-1	-2
HVAC - HPfau	1770	243	23	10	-7	-2	-2	-2
HVAC - VRF	1350	212	24	11	-4	-1	-2	-3
Zoned - MP	1593	226	23	11	-5	-1	-2	-2
FanType - exhaust	1343	105	19	6	-17	-5	0	0
FanType - supply	1678	257	24	12	-6	-2	-4	-3
FanType - balanced	1779	276	26	13	1	0	-4	-4

Table 39: zoneExposure Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - MPexhaust	15759	675	17	4	-341	-7	-19	-4
VentSysType - MPsupply	18630	1546	20	7	-354	-6	-133	-8
VentSysType - MPbalanced	19808	1771	21	8	-204	-5	-164	-8
CZ - 1	14992	877	10	5	-874	-29	-65	-21
CZ - 3	12010	926	15	6	-356	-11	-67	-10
CZ - 10	20477	1486	24	6	353	3	-162	-5
CZ - 16	34452	2354	21	7	-361	-6	-159	-6
ACH50 - 0.6	20368	1499	16	6	-492	-9	-146	-7
ACH50 - 2	19920	1469	20	7	-332	-5	-135	-8
ACH50 - 3	19742	1585	23	7	-176	-3	-110	-7
ACH50 – 3, apt	8908	-236	NA	-3	-337	-8	-65	-5
Prototype - 1story	15709	1016	16	6	-486	-11	-155	-8
Prototype - 2story	24108	2167	23	8	-63	-2	-103	-7
Prototype - apt	8908	-236	NA	-3	-337	-8	-65	-5
# Control Zones - 2	18476	950	14	4	-378	-9	-128	-7
# Control Zones - 4	17971	1687	24	8	-202	-3	-106	-7
HVAC - HPfau	20240	1507	21	6	-336	-6	-129	-6
HVAC - VRF	16662	1132	19	6	-298	-7	-112	-7
Zoned - MP	18315	1305	20	6	-319	-6	-122	-7
FanType - exhaust	15759	675	17	4	-341	-7	-19	-4
FanType - supply	18630	1546	20	7	-354	-6	-133	-8
FanType - balanced	19808	1771	21	8	-204	-5	-164	-8

occExposure

Table 40: occExposure Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure ($\mu g/m^3$)*	*Personal Formaldehyde Exposure ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)*	*Personal CO_2 Exposure (ppm)*	*Personal Generic Exposure, 95th ($\mu g/m^3$)*	*Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)*	*Personal CO_2 Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal $PM_{2.5}$ Relative Exposure*	*Personal CO_2 Relative Exposure*
VentSysType - MPexhaust	25	25	12	797	36	35	62	1030	1.21	1.10	0.83	1.03
VentSysType - MPsupply	23	23	11	803	33	33	66	1024	1.08	1.01	0.96	1.04
VentSysType - MPbalanced	23	23	11	789	32	33	61	993	1.15	1.04	0.89	1.04
CZ - 1	23	24	11	783	32	33	61	988	1.12	1.02	0.87	1.03
CZ - 3	23	26	11	784	32	35	62	993	1.13	1.03	0.87	1.03
CZ - 10	24	25	11	797	35	37	63	1023	1.15	1.04	0.88	1.04
CZ - 16	26	16	12	822	36	26	64	1048	1.15	1.07	0.88	1.04
ACH50 - 0.6	24	24	11	793	36	35	62	1036	1.19	1.10	0.84	1.03
ACH50 - 2	24	24	11	795	34	35	62	1001	1.14	1.04	0.90	1.04
ACH50 - 3	24	24	11	790	33	34	62	975	1.11	1.01	0.94	1.03
ACH50 – 3, apt	18	24	19	1132	27	32	106	1697	1.15	1.02	0.81	1.05
Prototype - 1story	24	28	11	790	33	36	60	980	1.17	1.08	0.85	1.05
Prototype - 2story	25	22	11	796	35	33	65	1037	1.12	1.02	0.91	1.01
Prototype - apt	18	24	19	1132	27	32	106	1697	1.15	1.02	0.81	1.05
# Control Zones - 2	23	24	11	786	34	33	63	1008	1.13	1.03	0.89	1.02
# Control Zones - 4	24	24	11	810	34	34	64	1033	1.16	1.05	0.85	1.04
HVAC - HPfau	24	24	10	797	34	34	61	1016	1.14	1.05	0.88	1.04
HVAC - VRF	24	24	12	798	34	33	66	1022	1.14	1.04	0.87	1.03
Zoned - MP	24	24	11	798	34	34	63	1018	1.14	1.04	0.87	1.04
FanType - exhaust	25	25	12	797	36	35	62	1030	1.21	1.10	0.83	1.03
FanType - supply	23	23	11	803	33	33	66	1024	1.08	1.01	0.96	1.04
FanType - balanced	23	23	11	789	32	33	61	993	1.15	1.04	0.89	1.04

Table 41: occExposure Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - MPexhaust	1320	116	22	8	-17	-5	0	-1
VentSysType - MPsupply	1626	271	26	13	-2	0	-5	-3
VentSysType - MPbalanced	1757	289	27	13	3	1	-4	-4
CZ - 1	1697	256	21	12	-31	-13	-2	-14
CZ - 3	1188	184	23	13	-17	-8	0	2
CZ - 10	1435	177	25	11	3	1	-2	-1
CZ - 16	3505	444	30	11	-9	-2	-5	-3
ACH50 - 0.6	1804	274	22	12	-2	0	-3	-2
ACH50 - 2	1720	264	26	12	-4	-1	-4	-3
ACH50 - 3	1692	256	28	12	4	1	-2	-2
ACH50 – 3, apt	864	-23	NA	-2	-30	-8	-2	-2
Prototype - 1story	1363	211	22	12	-23	-9	-5	-4
Prototype - 2story	2124	355	28	12	20	4	0	-1
Prototype - apt	864	-23	NA	-2	-30	-8	-2	-2
# Control Zones - 2	1661	189	20	10	2	0	-1	-2
# Control Zones - 4	1575	267	28	14	-10	-3	-3	-4
HVAC - HPfau	1776	260	25	11	-4	-1	-2	-2
HVAC - VRF	1353	219	25	12	-5	-1	-2	-3
Zoned - MP	1598	241	25	11	-5	-1	-2	-2
FanType - exhaust	1320	116	22	8	-17	-5	0	-1
FanType - supply	1626	271	26	13	-2	0	-5	-3
FanType - balanced	1757	289	27	13	3	1	-4	-4

Table 42: occExposure Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - MPexhaust	15671	876	17	5	-353	-7	-20	-3
VentSysType - MPsupply	18311	1772	22	8	-194	-5	-130	-8
VentSysType - MPbalanced	19401	1976	22	9	-205	-3	-164	-9
CZ - 1	14962	1054	14	6	-690	-30	-55	-22
CZ - 3	12095	1030	18	8	-336	-10	-49	-7
CZ - 10	20290	1663	27	7	372	3	-178	-6
CZ - 16	34434	2483	22	7	-372	-5	-144	-6
ACH50 - 0.6	20140	1760	18	8	-327	-4	-128	-6
ACH50 - 2	20035	1663	21	7	-278	-4	-135	-8
ACH50 - 3	19813	1690	23	8	-91	-3	-110	-8
ACH50 – 3, apt	8886	-239	NA	-3	-336	-9	-48	-5
Prototype - 1story	15664	1063	14	6	-571	-13	-165	-9
Prototype - 2story	23859	2454	23	9	16	0	-83	-5
Prototype - apt	8886	-239	NA	-3	-336	-9	-48	-5
# Control Zones - 2	18238	1217	17	6	-126	-2	-94	-6
# Control Zones - 4	17989	1653	23	8	-346	-8	-134	-8
HVAC - HPfau	19984	1653	21	7	-284	-4	-123	-6
HVAC - VRF	16669	1181	20	7	-254	-5	-110	-8
Zoned - MP	18115	1407	20	7	-267	-5	-117	-7
FanType - exhaust	15671	876	17	5	-353	-7	-20	-3
FanType - supply	18311	1772	22	8	-194	-5	-130	-8
FanType - balanced	19401	1976	22	9	-205	-3	-164	-9

zoneASHQexposure

Table 43: zoneASHQexposure Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure ($\mu g/m^3$)*	*Personal Formaldehyde Exposure ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)*	*Personal CO_2 Exposure (ppm)*	*Personal Generic Exposure, 95th ($\mu g/m^3$)*	*Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)*	*Personal CO_2 Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal $PM_{2.5}$ Relative Exposure*	*Personal CO_2 Relative Exposure*
VentSysType - MPexhaust	25	24	12	770	29	33	66	937	1.21	1.11	0.97	0.99
VentSysType - MPsupply	25	24	12	818	30	33	65	961	1.14	1.05	1.06	1.06
VentSysType - MPbalanced	24	24	12	796	27	33	64	944	1.23	1.09	1.04	1.04
CZ - 1	24	27	12	798	27	33	64	943	1.22	1.08	1.05	1.05
CZ - 3	24	28	12	798	28	34	64	947	1.22	1.09	1.04	1.05
CZ - 10	24	27	12	799	30	35	65	960	1.18	1.05	1.00	1.03
CZ - 16	25	16	12	797	30	25	65	948	1.12	1.05	1.03	1.02
ACH50 - 0.6	25	24	11	794	32	33	62	951	1.21	1.09	0.97	1.03
ACH50 - 2	25	24	12	792	29	32	64	944	1.15	1.04	1.05	1.03
ACH50 - 3	24	23	12	788	27	32	66	941	1.15	1.02	1.08	1.03
ACH50 – 3, apt	19	27	21	1152	22	33	111	1539	1.35	1.15	0.97	1.10
Prototype - 1story	24	29	11	796	28	37	61	917	1.19	1.11	0.99	1.05
Prototype - 2story	25	23	12	784	31	31	68	989	1.14	1.02	1.06	1.01
Prototype - apt	19	27	21	1152	22	33	111	1539	1.35	1.15	0.97	1.10
# Control Zones - 2	25	24	12	801	30	33	67	985	1.19	1.08	1.03	1.04
# Control Zones - 4	24	24	12	796	28	32	63	944	1.18	1.07	1.03	1.03
HVAC - HPfau	24	24	11	797	29	33	62	946	1.18	1.08	1.03	1.03
HVAC - VRF	24	24	13	800	29	33	67	951	1.18	1.08	1.02	1.03
Zoned - MP	24	24	12	798	29	33	65	949	1.18	1.08	1.03	1.03
FanType - exhaust	25	24	12	770	29	33	66	937	1.21	1.11	0.97	0.99
FanType - supply	25	24	12	818	30	33	65	961	1.14	1.05	1.06	1.06
FanType - balanced	24	24	12	796	27	33	64	944	1.23	1.09	1.04	1.04

Table 44: zoneASHQexposure Aggregated Site Energy Summary.

Parameter	Total HVAC Energy Use (kWh)	Total HVAC Energy Savings (kWh)	Total Vent Energy Savings (%)	Total HVAC Energy Savings (%)	Total HVAC On-Peak Energy Savings (kWh)	Total HVAC On-Peak Energy Savings (%)	Total HVAC Super On-Peak Energy Savings (kWh)	Total HVAC Super On-Peak Energy Savings (%)
VentSysType - MPexhaust	1273	177	29	10	-6	-3	0	1
VentSysType - MPsupply	1554	359	33	16	1	0	-3	-2
VentSysType - MPbalanced	1588	443	37	19	28	5	-3	-3
CZ - 1	1496	402	34	18	3	1	0	4
CZ - 3	1059	315	36	20	2	1	1	2
CZ - 10	1375	230	34	15	8	2	-1	0
CZ - 16	3530	373	30	11	-19	-3	-4	-3
ACH50 - 0.6	1725	348	27	15	-8	-2	-2	-2
ACH50 - 2	1598	370	35	17	13	3	0	0
ACH50 - 3	1537	365	39	18	34	9	1	1
ACH50 – 3, apt	878	-52	NA	-6	-65	-16	-3	-3
Prototype - 1story	1232	299	34	18	-6	-1	-2	-2
Prototype - 2story	2024	438	34	15	33	7	1	1
Prototype - apt	878	-52	NA	-6	-65	-16	-3	-3
# Control Zones - 2	1522	321	33	15	3	1	-1	-1
# Control Zones - 4	1511	330	34	16	6	2	0	0
HVAC - HPfau	1651	354	33	15	3	1	-1	-1
HVAC - VRF	1307	298	34	16	4	1	-1	-1
Zoned - MP	1515	323	34	15	4	1	-1	-1
FanType - exhaust	1273	177	29	10	-6	-3	0	1
FanType - supply	1554	359	33	16	1	0	-3	-2
FanType - balanced	1588	443	37	19	28	5	-3	-3

Table 45: zoneASHQexposure Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - MPexhaust	15387	1184	27	7	-241	-6	-14	-1
VentSysType - MPsupply	17906	2296	28	10	-241	-4	-120	-7
VentSysType - MPbalanced	18403	3160	35	14	232	3	-138	-7
CZ - 1	12827	2260	25	14	-429	-14	-14	-8
CZ - 3	11126	1785	32	14	-237	-7	-40	-4
CZ - 10	19988	2113	33	9	461	4	-156	-5
CZ - 16	34324	2320	21	7	-297	-5	-148	-6
ACH50 - 0.6	19878	2028	22	9	-399	-10	-125	-7
ACH50 - 2	18739	2456	30	11	51	1	-87	-6
ACH50 - 3	17916	2638	37	11	401	5	-52	-4
ACH50 – 3, apt	8879	-358	NA	-4	-495	-13	-72	-5
Prototype - 1story	15045	1873	28	11	-268	-6	-136	-7
Prototype - 2story	23512	3190	34	11	416	4	-48	-3
Prototype - apt	8879	-358	NA	-4	-495	-13	-72	-5
# Control Zones - 2	17806	2153	29	10	-140	-2	-99	-6
# Control Zones - 4	17722	2176	31	10	-60	-1	-84	-5
HVAC - HPfau	19497	2238	31	10	-144	-2	-104	-5
HVAC - VRF	15861	1889	30	10	-61	-1	-85	-6
Zoned - MP	17782	2155	30	10	-103	-2	-97	-5
FanType - exhaust	15387	1184	27	7	-241	-6	-14	-1
FanType - supply	17906	2296	28	10	-241	-4	-120	-7
FanType - balanced	18403	3160	35	14	232	3	-138	-7

occASHQexposure

Table 46: occASHQexposure Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure ($\mu g/m^3$)*	*Personal Formaldehyde Exposure ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)*	*Personal CO_2 Exposure (ppm)*	*Personal Generic Exposure, 95^{th} ($\mu g/m^3$)*	*Personal Formaldehyde Exposure, 95^{th} ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure, 95^{th} ($\mu g/m^3$)*	*Personal CO_2 Exposure, 95^{th} (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal $PM_{2.5}$ Relative Exposure*	*Personal CO_2 Relative Exposure*
VentSysType - MPexhaust	25	24	13	771	31	33	67	931	1.22	1.13	0.98	0.99
VentSysType - MPsupply	25	24	12	820	31	34	66	963	1.14	1.05	1.03	1.05
VentSysType - MPbalanced	25	24	12	795	27	34	65	944	1.24	1.09	1.04	1.04
CZ - 1	25	28	12	798	27	34	64	941	1.23	1.09	1.05	1.05
CZ - 3	25	28	12	797	28	35	66	944	1.23	1.10	1.04	1.04
CZ - 10	25	27	12	797	31	36	66	950	1.20	1.06	1.01	1.03
CZ - 16	25	16	13	796	31	25	67	947	1.12	1.07	1.02	1.01
ACH50 - 0.6	25	24	11	793	34	34	64	945	1.20	1.10	0.97	1.03
ACH50 - 2	25	24	12	791	30	33	65	943	1.16	1.05	1.05	1.03
ACH50 - 3	25	23	12	788	27	32	67	941	1.15	1.02	1.08	1.03
ACH50 – 3, apt	19	27	22	1152	23	34	113	1540	1.36	1.15	0.98	1.10
Prototype - 1story	25	29	12	797	29	37	62	917	1.21	1.11	1.01	1.05
Prototype - 2story	25	23	12	782	33	32	68	1012	1.14	1.02	1.05	1.01
Prototype - apt	19	27	22	1152	23	34	113	1540	1.36	1.15	0.98	1.10
# Control Zones - 2	25	24	12	799	32	34	67	1027	1.19	1.10	1.02	1.04
# Control Zones - 4	25	24	12	796	28	33	66	942	1.19	1.08	1.03	1.03
HVAC - HPfau	25	24	11	796	29	33	64	944	1.19	1.09	1.02	1.03
HVAC - VRF	25	24	13	798	29	34	68	949	1.19	1.08	1.03	1.03
Zoned - MP	25	24	12	797	29	33	66	947	1.19	1.08	1.02	1.03
FanType - exhaust	25	24	13	771	31	33	67	931	1.22	1.13	0.98	0.99
FanType - supply	25	24	12	820	31	34	66	963	1.14	1.05	1.03	1.05
FanType - balanced	25	24	12	795	27	34	65	944	1.24	1.09	1.04	1.04

Table 47: occASHQexposure Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - MPexhaust	1262	198	32	11	-2	-1	0	0
VentSysType - MPsupply	1538	377	35	17	14	3	-3	-2
VentSysType - MPbalanced	1586	453	38	19	29	7	-2	-2
CZ - 1	1483	457	35	19	20	6	1	11
CZ - 3	1060	334	38	21	12	5	0	1
CZ - 10	1354	257	36	16	13	3	-1	-1
CZ - 16	3501	432	31	12	1	0	-4	-3
ACH50 - 0.6	1694	376	31	17	0	0	-2	-2
ACH50 - 2	1591	384	36	18	21	4	-1	-1
ACH50 - 3	1526	382	40	18	39	9	0	0
ACH50 – 3, apt	872	-55	NA	-6	-70	-17	-3	-3
Prototype - 1story	1204	334	36	19	-1	0	-3	-2
Prototype - 2story	2017	448	34	16	45	9	1	4
Prototype - apt	872	-55	NA	-6	-70	-17	-3	-3
# Control Zones - 2	1507	344	35	16	23	6	-1	-1
# Control Zones - 4	1507	350	36	17	8	2	-2	-1
HVAC - HPfau	1634	370	35	16	13	2	-1	-1
HVAC - VRF	1288	316	36	17	13	3	-1	-1
Zoned - MP	1507	347	35	17	13	3	-1	-1
FanType - exhaust	1262	198	32	11	-2	-1	0	0
FanType - supply	1538	377	35	17	14	3	-3	-2
FanType - balanced	1586	453	38	19	29	7	-2	-2

Table 48: occASHQexposure Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - MPexhaust	15330	1295	30	8	-163	-3	-15	-1
VentSysType - MPsupply	17852	2583	31	11	0	0	-116	-6
VentSysType - MPbalanced	18218	3308	35	14	305	4	-125	-6
CZ - 1	12706	2721	28	15	-209	-8	-14	-7
CZ - 3	11088	2079	35	16	-106	-4	-33	-3
CZ - 10	19937	2238	34	10	480	4	-163	-5
CZ - 16	33951	2647	23	8	-180	-2	-129	-5
ACH50 - 0.6	19415	2392	26	11	-258	-4	-128	-6
ACH50 - 2	18565	2660	33	12	235	3	-83	-5
ACH50 - 3	17854	2725	38	12	442	5	-44	-3
ACH50 – 3, apt	8903	-360	NA	-4	-517	-13	-56	-4
Prototype - 1story	14758	2139	31	12	-127	-4	-147	-7
Prototype - 2story	23485	3330	34	12	452	5	-25	-2
Prototype - apt	8903	-360	NA	-4	-517	-13	-56	-4
# Control Zones - 2	17502	2327	32	11	209	3	-49	-5
# Control Zones - 4	17677	2396	33	11	-33	0	-102	-5
HVAC - HPfau	19088	2528	33	11	49	1	-73	-5
HVAC - VRF	15660	2139	32	11	80	1	-72	-5
Zoned - MP	17650	2354	33	11	55	1	-73	-5
FanType - exhaust	15330	1295	30	8	-163	-3	-15	-1
FanType - supply	17852	2583	31	11	0	0	-116	-6
FanType - balanced	18218	3308	35	14	305	4	-125	-6

occupantVenter

Table 49: occupantVenter Aggregated Median IAQ Results.

Parameter	***Personal Generic Exposure (µg/m³)***	***Personal Formaldehyde Exposure (µg/m³)***	***Personal PM$_{2.5}$ Exposure (µg/m³)***	***Personal CO$_2$ Exposure (ppm)***	***Personal Generic Exposure, 95th (µg/m³)***	***Personal Formaldehyde Exposure, 95th (µg/m³)***	***Personal PM$_{2.5}$ Exposure, 95th (µg/m³)***	***Personal CO$_2$ Exposure, 95th (ppm)***	***Personal Generic Relative Exposure***	***Personal Formaldehyde Relative Exposure***	***Personal PM$_{2.5}$ Relative Exposure***	***Personal CO$_2$ Relative Exposure***
VentSysType - MPexhaust	30	27	13	841	39	38	66	1015	1.44	1.15	0.91	1.06
VentSysType - MPsupply	27	25	13	863	42	38	69	986	1.26	1.05	1.08	1.08
VentSysType - MPbalanced	25	24	12	800	35	34	65	962	1.27	1.04	1.01	1.03
CZ - 1	26	27	12	817	36	37	65	957	1.26	1.08	0.99	1.05
CZ - 3	26	29	12	823	36	38	66	958	1.28	1.10	0.99	1.05
CZ - 10	28	27	13	848	41	41	68	987	1.36	1.09	0.99	1.07
CZ - 16	29	16	13	863	42	27	67	1011	1.32	1.01	1.00	1.06
ACH50 - 0.6	30	28	12	839	44	40	65	970	1.43	1.13	0.99	1.10
ACH50 - 2	29	26	12	831	39	38	65	971	1.34	1.07	0.99	1.07
ACH50 - 3	27	25	12	811	36	36	65	963	1.24	1.03	1.01	1.04
ACH50 – 3, apt	19	24	21	1038	33	35	111	1262	1.30	1.03	1.00	1.01
Prototype - 1story	27	29	12	821	39	39	63	934	1.32	1.10	0.98	1.07
Prototype - 2story	29	24	12	836	41	35	69	1053	1.29	1.05	1.02	1.05
Prototype - apt	19	24	21	1038	33	35	111	1262	1.30	1.03	1.00	1.01
# Control Zones - 2	26	24	12	811	36	35	65	965	1.23	1.04	0.98	1.03
# Control Zones - 4	31	27	13	879	43	39	68	1078	1.47	1.12	1.06	1.11
HVAC - HPfau	27	25	11	835	38	37	65	978	1.31	1.07	0.99	1.06
HVAC - VRF	27	25	13	837	38	37	69	1000	1.30	1.07	1.00	1.06
Zoned - MP	27	25	12	836	38	37	67	989	1.31	1.07	0.99	1.06
FanType - exhaust	30	27	13	841	39	38	66	1015	1.44	1.15	0.91	1.06
FanType - supply	27	25	13	863	42	38	69	986	1.26	1.05	1.08	1.08
FanType - balanced	25	24	12	800	35	34	65	962	1.27	1.04	1.01	1.03

Table 50: occupantVenter Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - MPexhaust	1217	261	42	16	18	6	1	1
VentSysType - MPsupply	1524	448	43	21	41	12	4	5
VentSysType - MPbalanced	1658	436	41	19	43	11	3	5
CZ - 1	1474	434	38	20	34	13	3	22
CZ - 3	1039	322	39	22	25	11	0	-1
CZ - 10	1302	289	45	18	31	7	10	5
CZ - 16	3260	579	43	16	44	5	-2	-2
ACH50 - 0.6	1563	505	41	23	45	13	2	6
ACH50 - 2	1592	433	41	20	36	11	2	5
ACH50 - 3	1614	363	39	17	32	10	2	5
ACH50 – 3, apt	841	-11	NA	-1	-61	-18	-2	-3
Prototype - 1story	1167	370	40	21	34	11	1	4
Prototype - 2story	1976	535	38	18	47	11	3	9
Prototype - apt	841	-11	NA	-1	-61	-18	-2	-3
# Control Zones - 2	1548	309	32	15	23	5	1	3
# Control Zones - 4	1341	499	51	25	74	19	2	6
HVAC - HPfau	1555	435	39	18	34	9	2	3
HVAC - VRF	1252	356	42	19	31	9	2	4
Zoned - MP	1432	388	41	18	33	9	2	3
FanType - exhaust	1217	261	42	16	18	6	1	1
FanType - supply	1524	448	43	21	41	12	4	5
FanType - balanced	1658	436	41	19	43	11	3	5

Table 51: occupantVenter Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - MPexhaust	14654	1976	45	11	122	3	-10	-1
VentSysType - MPsupply	16838	3352	44	16	346	6	13	1
VentSysType - MPbalanced	17922	3510	39	15	394	6	21	2
CZ - 1	12241	3218	36	18	146	4	10	9
CZ - 3	10738	2194	39	16	110	3	-25	-3
CZ - 10	19122	2727	47	13	808	7	90	3
CZ - 16	31762	3987	39	12	57	1	-23	-1
ACH50 - 0.6	18199	3785	43	18	602	7	5	0
ACH50 - 2	18010	3231	42	16	499	6	6	0
ACH50 - 3	18064	2672	39	13	415	6	6	1
ACH50 – 3, apt	8628	-122	NA	-1	-426	-11	-16	-1
Prototype - 1story	14216	2885	42	16	400	7	0	0
Prototype - 2story	22803	3901	42	15	612	6	10	1
Prototype - apt	8628	-122	NA	-1	-426	-11	-16	-1
# Control Zones - 2	17268	2312	28	11	49	1	-7	-1
# Control Zones - 4	16035	4011	52	19	902	12	36	3
HVAC - HPfau	18326	3300	42	14	310	5	-3	0
HVAC - VRF	14971	2671	42	15	309	4	7	1
Zoned - MP	16673	2972	42	14	310	4	5	0
FanType - exhaust	14654	1976	45	11	122	3	-10	-1
FanType - supply	16838	3352	44	16	346	6	13	1
FanType - balanced	17922	3510	39	15	394	6	21	2

contaminantDwelling

Table 52: contaminantDwelling Aggregated Median IAQ Results.

Parameter	*Personal Generic Exposure ($\mu g/m^3$)*	*Personal Formaldehyde Exposure ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)*	*Personal CO_2 Exposure (ppm)*	*Personal Generic Exposure, 95th ($\mu g/m^3$)*	*Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)*	*Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)*	*Personal CO_2 Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal $PM_{2.5}$ Relative Exposure*	*Personal CO_2 Relative Exposure*
VentSysType - MPexhaust	11	20	11	677	12	25	62	769	0.53	0.87	1.07	0.83
VentSysType - MPsupply	12	20	11	665	13	26	66	774	0.52	0.90	0.92	0.81
VentSysType - MPbalanced	11	21	10	634	11	25	61	724	0.53	0.92	0.87	0.82
CZ - 1	11	21	10	640	11	25	60	732	0.52	0.87	0.93	0.83
CZ - 3	11	22	11	642	11	26	62	746	0.52	0.86	0.94	0.83
CZ - 10	11	22	11	658	12	27	64	770	0.53	0.91	0.96	0.83
CZ - 16	12	17	11	675	13	23	63	800	0.53	1.16	0.90	0.82
ACH50 - 0.6	12	20	11	647	13	25	62	735	0.58	0.91	0.96	0.85
ACH50 - 2	12	21	11	637	13	25	61	718	0.55	0.89	0.93	0.84
ACH50 - 3	11	21	11	631	13	25	61	709	0.53	0.90	0.91	0.83
ACH50 – 3, apt	7	21	16	715	8	26	99	802	0.47	0.93	0.95	0.70
Prototype - 1story	10	22	10	614	11	25	58	666	0.51	0.85	0.93	0.81
Prototype - 2story	14	20	11	677	16	25	67	804	0.63	0.93	0.96	0.86
Prototype - apt	7	21	16	715	8	26	99	802	0.47	0.93	0.95	0.70
# Control Zones - 2	11	20	11	656	12	25	63	760	0.53	0.91	0.94	0.82
HVAC - HPFau	11	20	10	653	12	25	60	757	0.53	0.91	0.96	0.82
HVAC - VRF	11	20	12	658	12	25	67	762	0.53	0.90	0.93	0.83
Zoned - MP	11	20	11	656	12	25	63	760	0.53	0.91	0.94	0.82
FanType - exhaust	11	20	11	677	12	25	62	769	0.53	0.87	1.07	0.83
FanType - supply	12	20	11	665	13	26	66	774	0.52	0.90	0.92	0.81
FanType - balanced	11	21	10	634	11	25	61	724	0.53	0.92	0.87	0.82

Table 53: contaminantDwelling Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - MPexhaust	2053	-694	-116	-46	-93	-40	3	2
VentSysType - MPsupply	2892	-1024	-109	-55	-169	-48	-10	-15
VentSysType - MPbalanced	3460	-1490	-123	-69	-249	-56	-15	-20
CZ - 1	3468	-1334	-114	-79	-221	-78	-14	-74
CZ - 3	2530	-966	-119	-66	-151	-56	-7	-26
CZ - 10	2483	-763	-116	-46	-104	-21	-22	-11
CZ - 16	5536	-1404	-112	-51	-249	-40	4	3
ACH50 - 0.6	3180	-1085	-91	-47	-173	-45	-8	-15
ACH50 - 2	3223	-1217	-116	-56	-187	-51	-10	-15
ACH50 - 3	3238	-1259	-143	-61	-193	-56	-10	-16
ACH50 – 3, apt	1439	-532	NA	-85	6	2	7	14
Prototype - 1story	2760	-1239	-138	-75	-209	-55	-13	-16
Prototype - 2story	3809	-1027	-83	-40	-171	-42	-5	-12
Prototype - apt	1439	-532	NA	-85	6	2	7	14
# Control Zones - 2	3021	-1094	-115	-55	-170	-48	-8	-12
HVAC - HPFau	3276	-1156	-115	-52	-170	-46	-7	-12
HVAC - VRF	2750	-1007	-115	-57	-169	-48	-9	-14
Zoned - MP	3021	-1094	-115	-55	-170	-48	-8	-12
FanType - exhaust	2053	-694	-116	-46	-93	-40	3	2
FanType - supply	2892	-1024	-109	-55	-169	-48	-10	-15
FanType - balanced	3460	-1490	-123	-69	-249	-56	-15	-20

Table 54: contaminantDwelling Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - MPexhaust	22461	-5772	-118	-38	-1446	-25	-20	-1
VentSysType - MPsupply	29093	-8509	-107	-43	-2107	-36	-177	-11
VentSysType - MPbalanced	34487	-12229	-127	-58	-2993	-50	-259	-17
CZ - 1	28306	-11038	-118	-81	-2774	-71	-189	-68
CZ - 3	21757	-7407	-126	-49	-1392	-36	-61	-5
CZ - 10	29866	-6152	-114	-28	-1537	-13	-385	-12
CZ - 16	50815	-12108	-113	-47	-3639	-41	-21	-1
ACH50 - 0.6	30826	-8979	-91	-41	-2102	-35	-144	-8
ACH50 - 2	30946	-9901	-116	-45	-2249	-39	-174	-11
ACH50 - 3	31130	-10389	-141	-49	-2339	-41	-186	-11
ACH50 – 3, apt	13530	-4870	NA	-71	-563	-10	95	7
Prototype - 1story	27230	-10309	-138	-55	-2688	-43	-207	-13
Prototype - 2story	35884	-8365	-84	-36	-2107	-32	-70	-6
Prototype - apt	13530	-4870	NA	-71	-563	-10	95	7
# Control Zones - 2	28861	-8890	-117	-45	-2145	-36	-154	-10
HVAC - HPFau	31646	-9591	-117	-44	-2210	-34	-138	-8
HVAC - VRF	26403	-8175	-115	-46	-1989	-38	-165	-11
Zoned - MP	28861	-8890	-117	-45	-2145	-36	-154	-10
FanType - exhaust	22461	-5772	-118	-38	-1446	-25	-20	-1
FanType - supply	29093	-8509	-107	-43	-2107	-36	-177	-11
FanType - balanced	34487	-12229	-127	-58	-2993	-50	-259	-17

contaminantZone

Table 55: contaminantZone Aggregated Median IAQ Results.

Parameter	Personal Generic Exposure ($\mu g/m^3$)	Personal Formaldehyde Exposure ($\mu g/m^3$)	Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)	Personal CO_2 Exposure (ppm)	Personal Generic Exposure, 95th ($\mu g/m^3$)	Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)	Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)	Personal CO_2 Exposure, 95th (ppm)	Personal Generic Relative Exposure	Personal Formaldehyde Relative Exposure	Personal $PM_{2.5}$ Relative Exposure	Personal CO_2 Relative Exposure
VentSysType - MPexhaust	11	20	11	677	12	25	62	769	0.53	0.87	1.07	0.83
VentSysType - MPsupply	12	20	11	665	13	26	65	774	0.52	0.90	0.92	0.81
VentSysType - MPbalanced	11	21	10	634	11	25	61	724	0.53	0.92	0.87	0.82
CZ - 1	11	21	10	640	11	25	60	732	0.52	0.87	0.93	0.83
CZ - 3	11	22	11	642	11	26	62	746	0.52	0.86	0.94	0.83
CZ - 10	11	22	11	658	12	27	64	770	0.53	0.91	0.96	0.83
CZ - 16	12	17	11	687	13	23	63	814	0.53	1.16	0.92	0.82
ACH50 - 0.6	12	20	11	647	13	25	61	735	0.58	0.91	0.97	0.85
ACH50 - 2	12	21	11	637	13	25	61	718	0.55	0.89	0.93	0.84
ACH50 - 3	11	21	11	631	13	25	61	709	0.53	0.90	0.91	0.83
ACH50 – 3, apt	7	21	16	715	8	26	99	802	0.47	0.93	0.95	0.70
Prototype - 1story	10	22	10	614	11	25	58	666	0.51	0.85	0.93	0.81
Prototype - 2story	14	20	11	677	16	25	67	805	0.63	0.93	0.96	0.87
Prototype - apt	7	21	16	715	8	26	99	802	0.47	0.93	0.95	0.70
# Control Zones - 2	11	20	11	657	12	25	63	761	0.53	0.91	0.94	0.82
HVAC - HPFau	11	20	10	657	12	25	60	757	0.53	0.91	0.96	0.82
HVAC - VRF	11	20	12	660	12	25	67	762	0.53	0.90	0.93	0.83
Zoned - MP	11	20	11	657	12	25	63	761	0.53	0.91	0.94	0.82
FanType - exhaust	11	20	11	677	12	25	62	769	0.53	0.87	1.07	0.83
FanType - supply	12	20	11	665	13	26	65	774	0.52	0.90	0.92	0.81
FanType - balanced	11	21	10	634	11	25	61	724	0.53	0.92	0.87	0.82

Table 56: contaminantZone Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - MPexhaust	2052	-680	-116	-46	-93	-40	3	2
VentSysType - MPsupply	2892	-1010	-109	-55	-170	-48	-10	-15
VentSysType - MPbalanced	3460	-1465	-121	-69	-250	-56	-16	-21
CZ - 1	3467	-1334	-114	-79	-222	-78	-14	-74
CZ - 3	2531	-966	-118	-66	-151	-56	-7	-26
CZ - 10	2486	-763	-117	-46	-104	-21	-22	-11
CZ - 16	5402	-1313	-111	-51	-248	-40	4	3
ACH50 - 0.6	3180	-1085	-91	-47	-168	-45	-8	-15
ACH50 - 2	3225	-1159	-117	-56	-181	-51	-10	-16
ACH50 - 3	3238	-1259	-143	-61	-193	-56	-10	-16
ACH50 – 3, apt	1440	-533	NA	-85	6	2	7	14
Prototype - 1story	2763	-1242	-138	-75	-210	-55	-13	-16
Prototype - 2story	3809	-994	-79	-40	-168	-42	-5	-12
Prototype - apt	1440	-533	NA	-85	6	2	7	14
# Control Zones - 2	3021	-1067	-115	-55	-168	-48	-8	-12
HVAC - HPFau	3275	-1184	-115	-52	-170	-47	-7	-12
HVAC - VRF	2750	-994	-116	-57	-167	-48	-9	-14
Zoned - MP	3021	-1067	-115	-55	-168	-48	-8	-12
FanType - exhaust	2052	-680	-116	-46	-93	-40	3	2
FanType - supply	2892	-1010	-109	-55	-170	-48	-10	-15
FanType - balanced	3460	-1465	-121	-69	-250	-56	-16	-21

Table 57: contaminantZone Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - MPexhaust	22467	-5699	-118	-38	-1445	-25	-20	-1
VentSysType - MPsupply	29084	-8257	-108	-43	-2145	-35	-177	-11
VentSysType - MPbalanced	34483	-11902	-127	-58	-2998	-50	-259	-17
CZ - 1	28306	-11041	-118	-81	-2777	-71	-189	-68
CZ - 3	21756	-7408	-126	-49	-1388	-36	-61	-5
CZ - 10	30026	-6151	-114	-28	-1544	-13	-385	-12
CZ - 16	49724	-11466	-110	-47	-3374	-41	-21	-1
ACH50 - 0.6	30937	-8957	-93	-42	-2078	-35	-144	-8
ACH50 - 2	31115	-9686	-116	-45	-2212	-39	-174	-11
ACH50 - 3	31296	-10201	-141	-49	-2340	-41	-186	-12
ACH50 – 3, apt	13537	-4869	NA	-71	-567	-10	97	7
Prototype - 1story	27552	-10338	-138	-55	-2752	-43	-207	-13
Prototype - 2story	35882	-8066	-79	-36	-2006	-30	-70	-6
Prototype - apt	13537	-4869	NA	-71	-567	-10	97	7
# Control Zones - 2	28858	-8749	-116	-45	-2127	-35	-156	-10
HVAC - HPFau	31644	-9747	-117	-44	-2207	-34	-138	-8
HVAC - VRF	26419	-7944	-115	-46	-2035	-38	-164	-11
Zoned - MP	28858	-8749	-116	-45	-2127	-35	-156	-10
FanType - exhaust	22467	-5699	-118	-38	-1445	-25	-20	-1
FanType - supply	29084	-8257	-108	-43	-2145	-35	-177	-11
FanType - balanced	34483	-11902	-127	-58	-2998	-50	-259	-17

contaminantZoneOcc

Table 58: contaminantZoneOcc Aggregated Median IAQ Results.

Parameter	Personal Generic Exposure ($\mu g/m^3$)	Personal Formaldehyde Exposure ($\mu g/m^3$)	Personal $PM_{2.5}$ Exposure ($\mu g/m^3$)	Personal CO_2 Exposure (ppm)	Personal Generic Exposure, 95th ($\mu g/m^3$)	Personal Formaldehyde Exposure, 95th ($\mu g/m^3$)	Personal $PM_{2.5}$ Exposure, 95th ($\mu g/m^3$)	Personal CO_2 Exposure, 95th (ppm)	Personal Generic Relative Exposure	Personal Formaldehyde Relative Exposure	Personal $PM_{2.5}$ Relative Exposure	Personal CO_2 Relative Exposure
VentSysType - MPexhaust	14	21	11	594	26	27	59	671	0.65	0.91	1.03	0.76
VentSysType - MPsupply	11	16	10	599	27	28	63	673	0.51	0.72	1.08	0.77
VentSysType - MPbalanced	12	19	9	566	22	30	56	635	0.58	0.86	0.92	0.75
CZ - 1	11	19	10	573	21	27	57	640	0.56	0.83	1.03	0.76
CZ - 3	11	20	10	573	22	29	59	645	0.55	0.82	1.04	0.76
CZ - 10	12	20	10	580	27	31	60	662	0.58	0.88	1.05	0.76
CZ - 16	14	14	11	619	30	22	60	704	0.64	1.09	0.97	0.76
ACH50 - 0.6	13	19	10	584	30	29	58	654	0.66	0.88	1.04	0.77
ACH50 - 2	12	19	10	579	24	28	58	644	0.60	0.86	1.02	0.76
ACH50 - 3	12	19	10	574	22	28	58	637	0.55	0.84	1.02	0.75
ACH50 – 3, apt	7	19	16	649	16	29	96	700	0.50	0.84	0.95	0.65
Prototype - 1story	12	20	10	568	25	28	55	622	0.56	0.86	1.00	0.76
Prototype - 2story	15	17	10	600	29	28	62	693	0.68	0.87	1.09	0.79
Prototype - apt	7	19	16	649	16	29	96	700	0.50	0.84	0.95	0.65
# Control Zones - 2	12	19	10	592	25	28	59	660	0.58	0.86	1.03	0.76
HVAC - HPFau	12	19	9	590	25	28	57	658	0.58	0.86	1.04	0.76
HVAC - VRF	12	19	11	592	25	28	63	662	0.58	0.86	1.02	0.76
Zoned - MP	12	19	10	592	25	28	59	660	0.58	0.86	1.03	0.76
FanType - exhaust	14	21	11	594	26	27	59	671	0.65	0.91	1.03	0.76
FanType - supply	11	16	10	599	27	28	63	673	0.51	0.72	1.08	0.77
FanType - balanced	12	19	9	566	22	30	56	635	0.58	0.86	0.92	0.75

Table 59: contaminantZoneOcc Aggregated Site Energy Summary.

Parameter	***Total HVAC Energy Use (kWh)***	***Total HVAC Energy Savings (kWh)***	***Total Vent Energy Savings (%)***	***Total HVAC Energy Savings (%)***	***Total HVAC On-Peak Energy Savings (kWh)***	***Total HVAC On-Peak Energy Savings (%)***	***Total HVAC Super On-Peak Energy Savings (kWh)***	***Total HVAC Super On-Peak Energy Savings (%)***
VentSysType - MPexhaust	1867	-377	-71	-28	-25	-16	10	9
VentSysType - MPsupply	2473	-521	-58	-30	-46	-13	1	1
VentSysType - MPbalanced	2915	-807	-75	-41	-96	-22	0	-1
CZ – 1	2941	-869	-77	-51	-99	-38	-3	-16
CZ – 3	2012	-546	-70	-42	-51	-22	1	3
CZ – 10	2046	-324	-58	-22	16	4	14	7
CZ – 16	4468	-627	-56	-29	-90	-18	7	5
ACH50 - 0.6	2643	-521	-48	-25	-47	-14	2	4
ACH50 – 2	2677	-644	-69	-31	-66	-19	2	2
ACH50 – 3	2730	-745	-87	-34	-88	-24	1	1
ACH50 – 3, apt	1057	-219	NA	-39	66	18	7	10
Prototype - 1story	2255	-721	-78	-43	-89	-24	1	1
Prototype - 2story	3249	-508	-42	-22	-41	-10	4	6
Prototype - apt	1057	-219	NA	-39	66	18	7	10
# Control Zones - 2	2482	-579	-64	-31	-53	-17	2	3
HVAC - HPFau	2759	-638	-66	-31	-55	-17	2	3
HVAC - VRF	2202	-537	-63	-31	-53	-17	1	2
Zoned – MP	2482	-579	-64	-31	-53	-17	2	3
FanType – exhaust	1867	-377	-71	-28	-25	-16	10	9
FanType – supply	2473	-521	-58	-30	-46	-13	1	1
FanType – balanced	2915	-807	-75	-41	-96	-22	0	-1

Table 60: contaminantZoneOcc Aggregated TDV Energy Summary.

Parameter	*Total HVAC TDV Energy Use (kWh)*	*Total HVAC TDV Energy Savings (kWh)*	*Total Vent TDV Energy Savings (%)*	*Total HVAC TDV Energy Savings (%)*	*Total HVAC On-Peak TDV Energy Savings (kWh)*	*Total HVAC On-Peak TDV Energy Savings (%)*	*Total HVAC Super On-Peak TDV Energy Savings (kWh)*	*Total HVAC Super On-Peak TDV Energy Savings (%)*
VentSysType - MPexhaust	20260	-2818	-68	-26	-280	-6	70	7
VentSysType - MPsupply	24841	-4214	-48	-26	-537	-12	-58	-4
VentSysType - MPbalanced	28198	-6694	-70	-35	-1164	-23	-99	-5
CZ – 1	24339	-7364	-82	-54	-1656	-44	-87	-32
CZ – 3	18455	-4152	-73	-29	-474	-14	50	6
CZ – 10	25057	-1220	-31	-6	865	7	-25	-1
CZ – 16	42928	-6390	-64	-30	-2145	-32	6	0
ACH50 - 0.6	26085	-4152	-39	-23	-844	-13	6	0
ACH50 – 2	26196	-4714	-68	-29	-603	-16	-4	0
ACH50 – 3	26412	-5451	-87	-33	-942	-19	-20	-2
ACH50 – 3, apt	10640	-1664	NA	-30	452	9	24	2
Prototype - 1story	22351	-5891	-81	-34	-1340	-31	-95	-4
Prototype - 2story	30251	-3824	-38	-19	-481	-10	51	3
Prototype - apt	10640	-1664	NA	-30	452	9	24	2
# Control Zones - 2	24465	-4542	-65	-27	-612	-14	-2	0
HVAC - HPFau	26446	-4708	-66	-28	-544	-11	4	0
HVAC - VRF	22351	-4286	-64	-27	-645	-16	-22	-2
Zoned – MP	24465	-4542	-65	-27	-612	-14	-2	0
FanType – exhaust	20260	-2818	-68	-26	-280	-6	70	7
FanType – supply	24841	-4214	-48	-26	-537	-12	-58	-4
FanType – balanced	28198	-6694	-70	-35	-1164	-23	-99	-5

aerecoRH

Table 61: aerecoRH Aggregated Median IAQ Results

Parameter	*Personal Generic Exposure (μg/m^3)*	*Personal Formaldehyde Exposure (μg/m^3)*	*Personal PM$_{2.5}$ Exposure (μg/m^3)*	*Personal CO$_2$ Exposure (ppm)*	*Personal Generic Exposure, 95th (μg/m^3)*	*Personal Formaldehyde Exposure, 95th (μg/m^3)*	*Personal PM$_{2.5}$ Exposure, 95th (μg/m^3)*	*Personal CO$_2$ Exposure, 95th (ppm)*	*Personal Generic Relative Exposure*	*Personal Formaldehyde Relative Exposure*	*Personal PM$_{2.5}$ Relative Exposure*	*Personal CO$_2$ Relative Exposure*
VentSysType - MPexhaust	17	22	12	759	28	27	66	992	0.84	0.93	1.19	0.95
CZ - 1	12	21	12	734	18	25	61	923	0.76	0.91	1.23	0.92
CZ - 3	13	22	12	738	19	26	64	954	0.77	0.92	1.22	0.92
CZ - 10	16	23	13	843	28	27	66	1187	1.05	0.98	1.18	1.03
CZ - 16	38	17	15	1016	57	28	70	1473	1.78	1.10	1.08	1.27
ACH50 - 0.6	17	21	12	738	27	26	64	948	0.84	0.94	1.36	0.95
ACH50 – 2	18	22	12	756	28	27	64	992	0.80	0.92	1.20	0.93
ACH50 – 3	18	22	12	756	28	27	63	972	0.77	0.90	1.18	0.92
ACH50 – 3, apt	14	22	23	1079	22	26	109	1622	1.08	1.03	1.20	1.06
Prototype - 1story	13	21	12	660	22	27	60	807	0.65	0.86	1.20	0.88
Prototype - 2story	21	21	13	801	37	28	68	1097	0.94	0.93	1.19	0.99
Prototype - apt	14	22	23	1079	22	26	109	1622	1.08	1.03	1.20	1.06
# Control Zones - 2	17	22	12	759	28	27	66	992	0.84	0.93	1.19	0.95
HVAC - HPFau	17	22	12	755	27	27	62	988	0.84	0.93	1.19	0.95
HVAC - VRF	17	22	13	760	28	27	69	1000	0.84	0.93	1.19	0.95
Zoned - MP	17	22	12	759	28	27	66	992	0.84	0.93	1.19	0.95
FanType - exhaust	17	22	12	759	28	27	66	992	0.84	0.93	1.19	0.95

Table 62: aerecoRH Aggregated Site Energy Summary.

Parameter	*Total HVAC Energy Use (kWh)*	*Total HVAC Energy Savings (kWh)*	*Total Vent Energy Savings (%)*	*Total HVAC Energy Savings (%)*	*Total HVAC On-Peak Energy Savings (kWh)*	*Total HVAC On-Peak Energy Savings (%)*	*Total HVAC Super On-Peak Energy Savings (kWh)*	*Total HVAC Super On-Peak Energy Savings (%)*
VentSysType - MPexhaust	1649	-209	-34	-11	-15	-5	-3	-5
CZ - 1	2347	-503	-61	-17	-41	-13	-3	-47
CZ - 3	1455	-344	-88	-20	-26	-14	5	10
CZ - 10	1317	-68	-25	-6	-13	-3	-4	-3
CZ - 16	2934	684	60	19	147	18	-3	-2
ACH50 - 0.6	1710	-229	-19	-11	-9	-2	-3	-5
ACH50 – 2	1714	-242	-34	-15	-17	-6	-3	-7
ACH50 – 3	1735	-269	-50	-18	-21	-9	-3	-11
ACH50 – 3, apt	649	-21	NA	-5	-31	-8	2	4
Prototype - 1story	1522	-321	-71	-35	-23	-11	-3	-3
Prototype - 2story	2404	20	5	1	24	7	-3	-15
Prototype - apt	649	-21	NA	-5	-31	-8	2	4
# Control Zones - 2	1649	-209	-34	-11	-15	-5	-3	-5
HVAC - HPFau	2207	-231	-33	-11	-15	-4	-2	-4
HVAC - VRF	1588	-195	-35	-11	-15	-5	-3	-5
Zoned - MP	1649	-209	-34	-11	-15	-5	-3	-5
FanType - exhaust	1649	-209	-34	-11	-15	-5	-3	-5

Table 63: aerecoRH Aggregated TDV Energy Summary.

Parameter	***Total HVAC TDV Energy Use (kWh)***	***Total HVAC TDV Energy Savings (kWh)***	***Total Vent TDV Energy Savings (%)***	***Total HVAC TDV Energy Savings (%)***	***Total HVAC On-Peak TDV Energy Savings (kWh)***	***Total HVAC On-Peak TDV Energy Savings (%)***	***Total HVAC Super On-Peak TDV Energy Savings (kWh)***	***Total HVAC Super On-Peak TDV Energy Savings (%)***
VentSysType - MPexhaust	18179	-782	-54	-6	-544	-9	-8	-1
CZ - 1	16694	-138	-66	-1	31	3	-37	-43
CZ - 3	12658	-1196	-244	-8	-47	-1	110	18
CZ - 10	20797	-770	-152	-6	-690	-9	-62	-3
CZ - 16	27269	-78	9	-1	-601	-20	-10	-1
ACH50 - 0.6	18191	-3254	-54	-19	-772	-58	-9	-8
ACH50 – 2	18221	-2076	-42	-13	-319	-28	16	-4
ACH50 – 3	18409	-2421	-60	-15	-387	-30	-3	-3
ACH50 – 3, apt	6956	12	NA	0	-295	-5	25	2
Prototype - 1story	17464	-6365	-220	-89	-2861	-128	12	-1
Prototype - 2story	22824	443	9	2	1393	20	-36	-9
Prototype - apt	6956	12	NA	0	-295	-5	25	2
# Control Zones - 2	18179	-782	-54	-6	-544	-9	-8	-1
HVAC - HPFau	21824	-809	-39	-5	-341	-5	12	1
HVAC - VRF	18155	-703	-70	-6	-544	-9	-8	-1
Zoned - MP	18179	-782	-54	-6	-544	-9	-8	-1
FanType - exhaust	18179	-782	-54	-6	-544	-9	-8	-1

Supplementary Appendix: Creating CONTAM models for SVACH multi-zone study

This appendix details the process of setting up CONTAM models for the multi-zone phase of the SVACH project.

Model overview

This section describes the model scope, and how the models relate to each other.

File names

As described above, the study uses three floor plans, or *CEC prototypes*:

- 1-story residence.
- 2-story residence.
- Multifamily apartment.

Files for CONTAM models have names like `ppp_ddd.xxx`, where:

- `ppp` names the CEC prototype (floor plan):
    - `1sr`, 1-story residence.
    - `2sr`, 2-story residence.
    - `apt`, multifamily apartment.
- `ddd` indicates details about the particular model.
- `xxx` is the file extension.
    - `prj` for CONTAM input (project) files.

Model genesis

Creating the CONTAM models involves several steps. Files associated with some of these intermediate steps are saved, both to show the provenance of the final models, and to make revisions easier.

Models derived for each prototype may include:

- *Common* model, `ppp_common.prj`.
    - Contains all modeling elements that do not differ between final models for this prototype.
- *Pressure test* model, `ppp_pressure.prj`.
    - Derived from the common model.
    - Used to tune the common model's air change rate during a pressurization test.

Common model – Overview

The common model, `ppp_common.prj`, contains as much information as possible, without requiring any model element to be removed in order to form a final model.

The common model includes:

- The physical geometry (wall placement, zone heights).
- All flow elements (even those that are not used by a flor path).
- Envelope paths that represent adventitious leaks.
- All common interior paths.
- Wind profiles.
- Pollutant definitions.
- Fans, including central air handlers.
- Control elements needed to enable co-simulation with EnergyPlus.
- Airflow and pollutant transport solver parameters (e.g., tolerances).

The common model does not include:

- Schedules.
  - All schedules are defined in EnergyPlus.

Initialization

This section describes starting model `ppp_common.prj`.

Using CONTAM v3.2, open a new project file.

Under `View`->`Project Options`->`Units`, set the `System of Units` to `IP`. However, leave the `Units of Flow` as `kg/s`.

Turn on CONTAM's *pseudo-geometry* mode. This will make the sizing look right, and will also help when generating an EnergyPlus IDF file. To do so:

- Open `View`->`Project Options`->`Sketchpad Dimensions`.
- Set the `Scaling Factor` to 1 ft for the `1sr` and `2sr` prototypes, and to 0.5 ft for `apt` (whose smaller zones need more pixels to accommodate all icons).
- Check `Show Pseudo-Geometry`.

- Increase the sketchpad `Width` and `Height`, if necessary, so that the calculated width and height are at least equal to the corresponding model dimension. The sketchpad dimensions can always be changed later, if necessary.

CONTAM tips:

- Copy an existing common model, if one exists, and delete the flow paths and walls. Use `Tools`->`Delete by box` to select and delete all icons on all levels. Compared to starting a new PRJ file, this will pre-populate the model with the shared element information.
- Pseudo-geometry mode makes the status bar of the CONTAM user interface show coordinates in the selected scaling factor. This will help the CONTAM plan look right. However, pseudo-geometry mode doesn't give full control over the size of each zone. For example, the sketchpad may only let you adjust the length of a wall in two-cell increments.

Common model – Contaminants

In CONTAM, it can save work to define contaminants before creating zones and flow paths, since this allows copy-pasting certain GUI elements. For example, attaching a filter to a flow path, then copy-pasting that path to duplicate it throughout the model, is easier than later adding the filter to many paths.

Contaminant species

In the common model, enter the contaminant data shown in the table below. Open the `Data`->`Species` menu, and for each contaminant, select `New` under `Local Project elements`.

Species definitions for all models. Give a zero value to any entries not defined in the table.

Species Name	Mol Wt [kg/kmol]	Default Conc	Non-trace	Use in sim	Comments
ashq	28.9645	0 μg/kg		✓	ASHRAE equivalence metric (fixed source rate / floor area).
co2	44.0090	400 ppm		✓	Ambient conc (~ 607.8 mg/kg).
form	30.0260	3 ppb		✓	Formaldehyde, CH2O (~ 3.11 μg/kg).
pm	0.0000	10 μg/m3		✓	PM2.5

Note we ignore (i.e., set to zero) the following CONTAM species properties:

- Diffusion coefficient and specific heat (used only for the 1D duct model).

- Mean diameter and effective density (used only for particles, to convert between particle count and mass/volume concentrations).
- Decay rate (used only for radioactive contaminants, to do unit conversions).
- UVGI susceptibility constant (used only for UV filter effectiveness).

CONTAM tips:

- When changing a default concentration, set the units (via the pull-down menu to the right of the input area) *before* setting the value. Otherwise, you may have to enter the value again, since the GUI updates the value when you change the units.
- The default concentration of a species serves as both:
  - The initial concentration in each zone (unless the zone definition overrides the default).
  - The ambient concentration (unless the simulation provides the value via a CTM or WPC file).
- CONTAM distinguishes between *species*, which are substances that can be transported, and *contaminants*, which are species that actually get used in a simulation. Since we use all defined species, the distinction is not important here.
- CONTAM distinguishes between *trace* and *non-trace* contaminants. Trace contaminants are idealized as not affecting the density of air, while non-trace contaminants do.
  - This project does not define any non-trace contaminants.
  - If you define any non-trace contaminants, you must define at least two of them, and their default concentrations must add up to 1 kg/kg.
- CONTAM treats the species name “H2O” as special. In particular, it uses the humidity ratio from the weather file, if any, to define the outdoor water concentration.
  - This project does not define water as a contaminant in the PRJ file. Instead, we model water transport in EnergyPlus, since it provides a two-layer surface sorption model, and since its equipment operation models use its internal estimates.

Constant-coefficient source/sink elements

This step defines the contaminant source/sink elements that model emissions in the zones.

Source/sink elements represent the emission models that underlie actual contaminant sources. Contaminant sources get defined in the zones, and elaborate the source elements in a number of ways:

- The actual source has a multiplier, which multiplies the emission rate found by the source element model.
- The actual source can have a control element input. If provided, the control value further multiplies the emission rate set by the source element model and the source multiplier. This allows EnergyPlus to specify the actual source rates.

In the common model, enter the constant-coefficient source/sink element data shown in the table below. Open the `Data`->`Source/Sinks` menu, and for each source/sink in the table, select `New` under `Local Project elements`, then select the `Constant Coefficient` model.

Constant-coefficient source/sink elements.

Source element name	Generation Rate	Removal Rate	Species	Comments
ashq_s	20 $\mu g/hr$	0 kg/s	ashq	Source rate μg/m2/hr. Source mult gives floor area. *No* control signal.
co2_s	1 mg/s	0 kg/s	co2	Control signal sets actual rate.
form_s	1 $\mu g/hr$	0 kg/s	form	Source rate μg/m2/hr. Source mult gives floor area. Control signal sets actual rate.
pm_s	1 mg/s	0 kg/s	pm	Control signal sets actual rate.

CONTAM tips:

- When changing a contaminant generation or removal rate, set the units (via the pull-down menu to the right of the input area) *before* setting the value. Otherwise, you may have to enter the value again, since the GUI updates the value when you change the units.

Deposition source/sink elements

This step defines the contaminant source/sink elements that model deposition in the zones.

In the common model, enter the deposition rate source/sink element data shown in the table below. Open the `Data`->`Source/Sinks` menu, and for each source/sink in the table, select `New` under `Local Project elements`, then select the `Deposition Rate` model.

Deposition rate source/sink elements.

Source element name	Deposition Rate	Species
pm_dep	0.6 /hr	pm

CONTAM tips:

- Particle deposition *cannot* be modeled via the “decay rate” property in the contaminant definitions. That property only affects reporting – it does not define a decay model.
- When changing a contaminant deposition rate, set the units (via the pull-down menu to the right of the input area) *before* setting the value. Otherwise, you may have to enter the value again, since the GUI updates the value when you change the units.

Filters

In the common model, enter the filter data shown in the table below. Open the `Data->Filters` menu, and for each filter in the table, select `New` under `Local Project elements`. Enter the data, either in the initial input panel, or under its `Edit Element Data` link.

Constant-efficiency filter definitions for all models.

Filter name	Species	Efficiency	Comments
ahu_f	pm	0.9	Filter, air handling unit.
env_fn_f	pm	0.9	Filter, ducted supply/exhaust fans.
env_lk_f	pm	0.5	Pen losses, envelope leakage paths.

If the table does not list an input parameter, leave it set to the default value. If the table does not list a contaminant, do not add it to the filter.

CONTAM tips:

- When adding element data, be sure to tap `Add` or `Replace` to enter the data in the filter.
- The area, depth, and density parameters are used only for the Simple Gaseous Filter model. They can be ignored here.

Common model – Simulation parameters

On the `Run Control` tab of the `Simulation->Set Simulation Parameters` dialog:

- Select `Transient` Airflow Simulation Method.
- Select `Transient` Contaminants.
- Select `Default solver (Implicit Euler)` Transient Integration Method.

- Set the `Transient Simulation, Start` date and time to 00:00:00 on 7-July.
- Set the `Transient Simulation, Stop` date and time to 24:00:00 on 14-July.
- Under `Simulation Time Steps`:
  - Set both `Calculation` and `Output` to one-minute steps (00:01:00).
  - Set `Status` to 24:00:00.

On the `Weather` tab of the `Simulation`->`Set Simulation Parameters` dialog:

- Under `Transient Weather Data`, verify that the weather file defaults to "None". EnergyPlus will supply the weather data.
- Under `Transient Contaminant Data`, verify that the CTM file defaults to "None". During co-simulation with EnergyPlus, a CTM file will supply the outdoor concentrations. However, the CTM file path will be filled in automatically, at the time the FMUs get generated.
- Under `Wind Pressure and Contaminant (WPC) Data`, verify that the WPC file defaults to "None".

On the `Weather` tab of the `Simulation`->`Set Simulation Parameters` dialog, under `Steady State Weather Data`, choose `Edit Weather Data`. Note that this same dialog can be accessed from the `Weather`->`Edit Weather Data` menu item. In the resulting dialog:

- On the `Weather` tab, set the following:
  - Ambient temperature, 67 F. Note this differs, intentionally, from the zone temperatures that will be set later. This avoids getting zero airflows everywhere during stand-alone test runs.
  - Absolute pressure, 101325 Pa.
  - Relative humidity, 0.
  - Wind speed, 0.
- For details on the `Wind` tab, see the section below on wind.

On the `Output` tab of the `Simulation`->`Set Simulation Parameters` dialog:

- Under `Airflow` Simulation Results:
  - Select `Detailed` airflow rates.

  - Select `Detailed` ages of air.
- Under `Contaminant` Simulation Results:
  - Select `Detailed` contaminant concentrations.
- Under `Controls` Results:
  - De-select the `Log File` item.
- Under `Display and logging`:
  - Choose `Console window` display mode.
  - Choose `Minimum ouput (list=0)` log mode.
- Note that some of the output selections made here will be overwritten when the PRJ is conditioned for use in an FMU. The selections here are to aid in checking runs while the PRJ file is under development.

On the `Airflow Numerics` tab of the `Simulation`->`Set Simulation Parameters` dialog:

- Select the `Simple Trust Region` solver.
- Set `Maximum iterations` to 30.
- Set `Relative Convergence Factor` to 1e-5.
- Set `Absolute Convergence Factor` to 1e-6 /s.
- Choose the `Skyline` linear equation solver.
- Select `Resequence Linear Equations`.
- Select `Linear Airflow Initialization`.
- Select `Run steady state initialization to convergence`.
- Make sure `Vary density during time step` is *not* checked.

On the `Contaminant Numerics` tab of the `Simulation`->`Set Simulation Parameters` dialog (note these should all be the default values):

- Select the `Skyline` Linear Contaminant solver.
- Set `Maximum Iterations` to 100.
- Set `Relaxation Coefficient` to 1.1.

- Set `Relative Convergence Factor` to 1e-6.
- Set `Absolute Convergence Factor` to 1e-15 kg/kg.
- Set `Trapezoidal Integration Factor` to 1.
- Choose to `Resequence Linear Equations`.

Common model – Levels

This section describes creating the levels for `ppp_common.prj`.

Set the level data according to the tables below. Note in the tables that `roof` is not a level, but rather is included for configuring weather/wind.

To calculate the attic height:

- Assume a 5/12 pitch roof.
- Let W give the width of the attic (i.e., the exterior wall-to-wall distance in the narrowest direction).
  - 1sr, $W = 46$ ft.
  - 2sr, $W = 29$ ft.
  - apt, not applicable.
- Attic height is $(W/2)(5/12) = 5W/24$.
- Note the attic height lets the model predict temperature-induced exchange between attic and outdoors, via stack effect.

Prototype-specific notes:

- The multifamily apartment has no attic.

CONTAM tips:

- Access the level data via `Level`->`Edit Level Data`.
- After editing a level, remember to click `<< Replace <<` in order to save the new level information.
- To add a new level, choose `Level`->`Insert Blank Level`->`Above current level`.
- Note that CONTAM calculates the `Elevation` for all levels above the first.
- Use `Page Up` and `Page Down` to change the level displayed on the sketchpad.

Level data for one-story residence.

Level	Elevation [ft]	Distance to level above [ft]
gnd_lvl	1	9
atc_lvl	10	9.6
Roof	19.6	N/A

Level data for two-story residence.

Level	Elevation [ft]	Distance to level above [ft]
gnd_lvl	1	9
upr_lvl	10	9
atc_lvl	19	6.0
Roof	25.0	N/A

Level data for multifamily apartment.

Level	Elevation [ft]	Distance to level above [ft]
gnd_lvl	10	8
Roof	18	N/A

Common model – Zones

This section describes drawing the zones for `ppp_common.prj`.

Sketch in the walls, using either `Tools`->`Draw Walls` or `Tools`->`Draw Boxes`, and then click-dragging with the mouse.

Align the zones on upper levels at least somewhat realistically with those below, to allow placing flow paths between them.

CONTAM tips:

- When drawing walls with the sketchpad in pseudo-geometry mode, the GUI shows the length of the current wall (in the lower-left corner). This makes it easy to give zones the right approximate dimensions.
- After using the first mouse click to "anchor" a wall or box, you can use the arrow keys (rather than the mouse) to sketch the wall, and press `Return` (rather than a second click) to finish the wall.
- When drawing walls, note it is OK to overlap an existing wall. The GUI will simply merge the new wall into the old one. This facilitates drawing walls using the "boxes" approach.

- When sketching the walls on upper levels, select `Level`->`Reveal Level Below` to show the level below in gray. This may make it easier to get the outline right as you fill in the walls.
- To exit wall- or box-drawing mode, press `Escape`.
- To stop drawing a wall before completing it, press `Escape`.
- To remove an incorrect wall after it is drawn, select the unwanted wall segment and press `Delete`.

Zone parameters
After sketching the walls, add zone icons and fill in the zone parameters:

- Enter the zone volume from the tables below.
- Set the zone temperature to 68 F.
- Check whether the zone is included in the building volume:
    - All occupied zones should be included.
    - The attic zone (`atc`), if the building has one, should *not* be included in the building volume. Un-check `Include in building volume` from the `Zone Data` panel of the `Zone Properties` input dialog.

CONTAM tips:

- The CONTAM GUI lets you fill in either the zone's floor area or its volume. Whichever you enter, CONTAM will calculate the other value, using the specified level height.
- For most zones, it's OK to enter the floor area. However you must enter the volume for the attic zone. For the attic, entering the floor area will give the zone too great a volume (since CONTAM cannot account for the sloping roof). It's more important for the model to have the right volume, than the right floor area. Thus there's no need to be alarmed if you notice that the GUI claims the attic zone has a much smaller floor area than that entered in the table.
- Note with CONTAM in pseudo-geometry mode, the GUI will estimate the zone floor area and volume when you first create the zone. In addition, if you select a zone icon, a tool tip will show both the entered area and the apparent area on the sketchpad (the latter will be in braces). This is a good way to check that everything is on track.

Zone data for one-story residence.

Zone	Area [ft2]	Fraction of living area [-]	Vol [ft3]	Vol [m3]	Comments
Atc	2100.0	N/A	10080.0	285.43	Attic.
Brm	604.9	28.8%	5443.9	154.15	Bedrooms.
Com	915.6	43.6%	8240.6	233.35	Common area. Marked “Other” on drawing.
Kit	243.5	11.6%	2191.3	62.05	Kitchen.
Wet	336.0	16.0%	3024.2	85.64	Bathrooms and laundry.

Zone data for two-story residence.

Zone	Area [ft2]	Fraction of living area [-]	Vol [ft3]	Vol [m3]	Comments
Atc	1450.0	N/A	4350.0	123.18	Attic.
Brm	777.5	28.8%	6997.2	198.14	Bedrooms.
Com	936.7	34.7%	8430.7	238.73	Downstairs common area. Marked “Other” on drawing.
Fam	240.5	8.9%	2164.2	61.28	Upstairs family area. Marked “Other” on drawing.
Kit	313.3	11.6%	2819.3	79.83	Kitchen.
Wet	432.1	16.0%	3888.6	110.11	Bathrooms and laundry.

Zone data for multifamily apartment.

Zone	Area [ft2]	Fraction of living area [-]	Vol [ft3]	Vol [m3]	Comments
Brc	88.6	10.2%	708.8	20.07	Child’s bedroom.
Brm	231.6	26.6%	1852.7	52.46	Master bedroom.
Com	379.2	43.6%	3033.3	85.89	Common area. Marked “Other” on drawing.
Kit	101.0	11.6%	807.9	22.88	Kitchen.
Wet	69.7	8.0%	557.3	15.78	Bathrooms and laundry.

Common model – Zone contaminants

This section describes contaminant-related entries that get specified in each zone.

Zone sources

This step defines the common model contaminant sources.

Place sources in each occupied zone. Parameterize the sources as shown in the tables below. In each zone:

- The multiplier for `co2` and `pm` is 1. This, along with the zone source control element described below, lets EnergyPlus specify the source rate directly.
- The multiplier for `ashq` and `form` is the floor area of the zone [m2]. This reflects the fact that the emission rates for these contaminants depend on the size of the zone.

Prototype-specific notes:

- For the family zone in the two-story residence, do not subtract the area of the stairway cutout to the floor below, when finding the zone's floor area.

CONTAM tips:

- Place source icons using the `Tools`->`Draw Icon`->`Source/Sink` menu item. The cursor may have to be inside a zone to enable selecting this menu item.
- Most sources will have an additional control input, to allow EnergyPlus to set the actual source rates. Leave at least 4 pixels (and preferably 5) free to one side of the sources, to allow sufficient space to later draw the controls.
- Like most CONTAM graphical elements, source/sink icons can be copied and pasted around the model. This can reduce the time needed to duplicate sources across zones.

Source/sinks, for one-story residence.

Zone	Source/sink element	Multiplier
Brm	ashq_s	56.2
	co2_s	1
	form_s	56.2
	pm_s	1
com	ashq_s	85.1
	co2_s	1
	form_s	85.1
	pm_s	1
kit	ashq_s	22.6
	co2_s	1
	form_s	22.6
	pm_s	1
wet	ashq_s	31.2
	co2_s	1
	form_s	31.2
	pm_s	1

Source/sinks, for two-story residence.

Zone	Source/sink element	Multiplier
brm	ashq_s	72.2
	co2_s	1
	form_s	72.2
	pm_s	1
com	ashq_s	87.0
	co2_s	1
	form_s	87.0
	pm_s	1
fam	ashq_s	22.3
	co2_s	1
	form_s	22.3
	pm_s	1
kit	ashq_s	29.1
	co2_s	1
	form_s	29.1
	pm_s	1
wet	ashq_s	40.1
	co2_s	1
	form_s	40.1
	pm_s	1

Source/sinks, for multifamily apartment.

Zone	Source/sink element	Multiplier
brc	ashq_s	8.2
	co2_s	1
	form_s	8.2
	pm_s	1
brm	ashq_s	21.5
	co2_s	1
	form_s	21.5
	pm_s	1
com	ashq_s	35.2
	co2_s	1
	form_s	35.2
	pm_s	1
kit	ashq_s	9.4
	co2_s	1
	form_s	9.4
	pm_s	1

wet	ashq_s	6.5
	co2_s	1
	form_s	6.5
	pm_s	1

Zone source controls

Set up control elements so that EnergyPlus can set the source strengths during a simulation.

For all zone contaminant sources except `ashq`, draw a control element with a link that ends in (i.e., points to) the source. Use `Tools`->`Draw Links` to draw these links. Then open and configure each control element:

- Choose control element type `Constant`.
- Name the control element like `zzz_ccc_set`, where:
  - `zzz` is the name of the zone in which the source appears.
  - `ccc` is the name of the contaminant associated with the source.
- Set the control value to 0.
  - EnergyPlus will set the desired value during simulation.

Zone deposition

This step defines the deposition of particles, by placing an appropriate source/sink element in each zone.

Place a deposition source/sink in every zone (including `atc`):

- Each source/sink uses element `pm_dep`.
- Leave its multiplier at the default value of 1.
- Do not attach a control element.

Zone concentration sensors

Each occupied zone (i.e., not the attic) gets sensors that communicate the estimated contaminant concentrations to EnergyPlus.

In each occupied zone, for each contaminant:

- Using `Tools`->`Draw Links`, draw a link from a new origin control element to a new destination control element.

CONTAM tips:

- Unlike other controls, which either originate at, or terminate in, existing icons (for example, contaminant sources, or flow paths), the controls here get drawn from scratch. To do so, click on a blank area of the sketchpad, and draw the link by dragging or using the arrow keys.
- After the initial click anchors the origin control element, you can use the arrow keys and `Return` key, rather than the mouse, to draw the link and the destination control element.
- It may be necessary to press `Escape` after drawing each destination link. This will leave the link-drawing cursor (pink box) activated, but allow you to begin a new link at a new origin.
- Press `Escape` a second time to exit link-drawing mode.

Configure the origin control element (from which the control link arrow originates), to make it measure the concentration:

- Choose control element type `Sensor`.
- Select `Mass fraction of contaminant [kg/kg]`.
- Choose the appropriate contaminant from the pull-down input field.
- Enter the sensor `Gain` from the table below.
- Leave the sensor `Offset` set to 0.
- Leave the sensor `Time Constant` set to 0 sec.

Configure the destination control element (at which the control link arrow terminates), to make it expose the concentration for use in EnergyPlus:

- Choose control element type `Signal split`.
  - Signal splitters normally allow re-use of a control signal, but serve dual purpose when the model is embedded in an FMU.
- Name the control element like `zzz_ccc_get`, where:
  - `zzz` is the name of the zone containing the sensor.
  - `ccc` is the name of the contaminant associated with the sensor.
- Fill in the control element’s `Description` field with the pollutant and units (for example, “co2 [ppmv]”). See the table below.

Zone contaminant sensors.

Species	Sensor gain	Split element name	Comments
ashq	1e+09	zzz_ashq_get	*zzz* gives zone name. Sensor output [$\mu g/kg$].
co2	658149	zzz_co2_get	[ppmv].
form	1.20408e+09	zzz_form_get	Assumes air density 1.20408 kg/m3. [$\mu g/m^3$].
pm	1.20408e+09	zzz_pm_get	[$\mu g/m^3$].

Common model – Flow elements

This section describes flow elements for the common model.

Background – Flow elements versus flow paths

The models follow CONTAM's distinction between flow paths and flow elements.

A *flow path* represents a physical path that carries airflow, while a *flow element* specifies the mathematical model for the airflow through a path. Each flow path has a link to its underlying flow element (along with other path-specific information, such as the path height, filtration characteristics, wind pressure profile, and so on).

The flow element defines the underlying pressure-flow characteristic of the path. For example, a flow element might represent a particular type of window. Then multiple flow paths can link to that same window element. Each path provides its own window height, orientation, opening schedule, and so on.

A flow path also has a *multiplier*, a parameter that scales the flow calculated by the underlying flow element. This is mainly a modeling convenience. Suppose, for example, that a particular wall has five identical windows. Then the model could represent all of them using a single flow path, linked to the appropriate window flow element, and with a multiplier of 5.

In addition to using the multiplier to count the number of paths, the multiplier can also supply the total area of a path. With this modeling idiom, the flow element represents the pressure-flow relationship for a unit area of some class of leak (for example, interior wall construction), in units like [cm^2 leak / m^2 wall]. Then the multiplier gives the total area of the actual path. Under this approach, multiple walls of similar construction can all link to the same flow element, with each wall supplying its own area as the flow path multiplier. Similarly, one can specify leakage normalized by the length of an interface, for example to represent cracks between walls and floors. In this case, the multiplier gives the length of the interface.

CONTAM tips:

- When specifying a flow element using the "leakage area powerlaw" model, the GUI helps support the idiom of letting flow elements define normalized leakage parameters. In particular, the input panel for the flow element allows the selection of per-item, per-unit-length, and per-unit-area leaks. Then the input panel for the flow path echoes this selection in its choice of units for the multiplier.

- The input panels accept mixed units, and CONTAM converts values as needed. Thus it does not cause problems, for example, to specify the flow element leakage area in cm^2/m^2, and to specify the flow path total area in ft^2.
- A PRJ file can define flow elements that it does not instantiate with any flow path.

Flow element definitions

The table below gives the flow element models. Parameters marked "tuned" vary not just between floor plans, but also among models for a given floor plan. Specifically, for a given prototype, the parameters may be tuned to yield multiple desired air change rates. This tuning, of course, differs from prototype to prototype.

CONTAM tips:

- CONTAM lets you edit and create new flow elements either en masse, through the `Data`->`Airflow Elements...` menu item, or as needed, via the flow path input panel.
- It is possible to export flow elements from one model as a library, and to then import that library into another model.

Flow elements.

Name	Model	Comments
atc_flr	Leakage area powerlaw Unit area basis Area 1 cm2 / m2 *(tuned)* Discharge coeff 1 Exponent 0.67 Reference pressure 4 Pa	Leakage from attic to room below. Tuned to give the common model the desired air change rate. Path mult gives area of interface [ft2].
atc_roof	Leakage area powerlaw Unit area basis Area 0.003 m2 / m2 Discharge coeff 1 Exponent 0.67 Reference pressure 4 Pa	Distributed roof leakage. Path mult gives area of attic floor under the roof (not roof area) [ft2].
atc_vent	Orifice area powerlaw Area 1 ft2 Exponent 0.5 Discharge coeff 0.6 Reynolds number 30	Builder-installed attic vent. Path mult gives area of vent [ft2]. Accept calculated Hydraulic Diameter
env_slab	Leakage area powerlaw	Envelope leakage at floor slab.

	Unit length basis Area 1 cm2 / m *(tuned)* Discharge coeff 1 Exponent 0.67 Reference pressure 4 Pa	Tuned to give the common model the desired air change rate. Path mult gives length of crack [ft].
env_wall	Leakage area powerlaw Unit area basis Area 1 cm2 / m2 *(tuned)* Discharge coeff 1 Exponent 0.67 Reference pressure 4 Pa	Distributed envelope wall leakage. Includes leaks around doors & windows. Tuned to give the common model the desired air change rate. Path mult gives area of wall [ft2].
fan_1kgs	Constant mass flow fan Flow rate 1 kg/s	Fan. Path mult gives mass flow rate [kg/s].
idr_main	Two-way two-opening Height 80 in Width 32 in Discharge coeff 0.78	Main part of interior doorway. 32 in wide by 80 in high. Path mult gives count.
idr_ucut	Orifice area powerlaw Area 25.3 in2 Exponent 0.5 Discharge coeff 0.6 Reynolds number 30	Interior door undercut. 32 in wide by 2 cm high. Path mult gives count.
int_flr	Leakage area powerlaw Unit area basis Area 2 cm2 / m2 Discharge coeff 1 Exponent 0.67 Reference pressure 4 Pa	Distributed interior floor leakage. Path mult gives area of floor [ft2].
int_wall	Leakage area powerlaw Unit area basis Area 2 cm2 / m2 Discharge coeff 1 Exponent 0.67 Reference pressure 4 Pa	Distributed interior wall leakage. Path mult gives area of wall [ft2].
orf_1cm2	Orifice area powerlaw Area 1 cm2 Exponent 0.5 Discharge coeff 0.6 Reynolds number 30	Discrete hole (e.g., for stairway or trickle vent). Path mult gives area of hole [cm2] (or mult gives hole ct, ctrl gives area).

Common model – Flow paths

This section describes and parameterizes the flow paths for the common model.

Ambient to attic flow paths

Flow paths from the outdoors into the attic fall into two categories: (1) attic vents; and (2) adventitious leaks. Attic vents are intentional, builder-installed paths, installed according to code requirements.

Parameterize the attic vents by the following rules:

- Find the total opening area as $S/300$, where S gives the area of the attic floor.
- Distribution:
  - Place 50% of the total opening area at the soffit.
  - Place 50% of the total opening area at the ridge.
- Plan distribution:
  - Place all flow paths on the walls on opposite sides of the ridge (i.e., on the long walls).
  - Divide leaks evenly between the two sides. Note for the paths at the ridge, it doesn't really matter which wall gets the leak. However, for consistency, group the ridge path icons with the soffit path icons.
- Orient each path's `Positive Flow Direction` from outdoors into the attic.
  - Note the flow path tables indicate the positive flow direction via the `From` and `To` zone entries.
- Do not add a filter element.

Parameterize the adventitious leaks by the following rules:

- Find the total leakage area as $0.003S$, where S gives the area of the attic floor.
  - Note use the floor area – not the roof area, as one might expect.
  - For comparison to the vent area, this is equivalent to $S/333$.
- Place 90% of the total leakage area at soffit-height.
  - On every attic envelope wall.
  - Distributed proportional to the length of the wall segment.
- Place 5% of the total leakage area halfway between the soffit and ridge.
  - On the sides opposite the ridge (i.e., on the long walls).

  - Divided evenly between the two sides.
- Place 5% of the total leakage area at ridge-height.
  - Using same rules as for the paths halfway between soffit and ridge.
- Filter `env_lk_f`.

Prototype-specific notes:

- For the single-story residence, all the attic leaks on the north and east sides may be placed on a single wall segment, even though that zone has two wall segments facing those directions. This is permissible because nothing in the model distinguishes between those wall segments (i.e., they have the same wind pressures, and same internal pressures at each height).
- The multifamily apartment has no attic.

CONTAM tips:

- Create the filter under the `Filter` tab of the `Airflow Path Properties` dialog. Select `New Filter` and choose the filter element in the resulting dialog.
- You can copy-paste flow paths. This speeds up the process of defining a number of parameters that flow paths share, for example, the same flow element, relative elevation, and filter. Note, however, that not all properties get copied. For example, the user interface may reset the flow direction (i.e., the from-zone and to-zone). Thus it is wise to check all copy-pasted paths.
- CONTAM labels the outdoor node as ambient, or `Ambt`. The tables follow this convention.
- Envelope flow paths default to labeling inward flows as positive (i.e., so that flow from outside to the interior zone gets reported as a positive value). This is the convention used in the tables here. Other (interior-to-interior) flow paths will require editing to make sure they have the right flow direction.

Flow paths between outdoors and attic, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filter	Comments
Ambt	atc N wall atc S wall	atc_vent	0.0	1.75		Soffit vents (2).
Ambt	atc N wall atc S wall	atc_vent	9.6	1.75		Ridge vents (2).

Ambt	atc N wall atc S wall	atc_roof	0.0	1.477 ft2	env_lk_f	Soffit leaks (2).
Ambt	atc E wall atc W wall	atc_roof	0.0	1.358 ft2	env_lk_f	Soffit leaks (2).
Ambt	atc N wall atc S wall	atc_roof	4.8	0.1575 ft2	env_lk_f	Roof leaks (2).
Ambt	atc N wall atc S wall	atc_roof	9.6	0.1575 ft2	env_lk_f	Roof leaks (2).

Flow paths between outdoors and attic, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filter	Comments
Ambt	atc N wall atc S wall	atc_vent	0.0	1.208		Soffit vents (2).
Ambt	atc N wall atc S wall	atc_vent	6.0	1.208		Ridge vents (2).
Ambt	atc N wall atc S wall	atc_roof	0.0	1.239 ft2	env_lk_f	Soffit leaks (2).
Ambt	atc E wall atc W wall	atc_roof	0.0	0.7186 ft2	env_lk_f	Soffit leaks (2).
Ambt	atc N wall atc S wall	atc_roof	3.0	0.1088 ft2	env_lk_f	Roof leaks (2).
Ambt	atc N wall atc S wall	atc_roof	6.0	0.1088 ft2	env_lk_f	Roof leaks (2).

Attic to occupied zone flow paths

Connect the attic to every occupied zone below it, using an `atc_flr` flow element. The multiplier gives the area of the interface between the attic and the zone. See the tables below.

Note the leakage area parameter of the flow element has not yet been set. It will be set during the tuning procedure described below. For now, any reasonable initial value – say, 1 cm^2/m2 – will do.

Prototype-specific notes:

- The multifamily apartment has no attic, and no leaks through the ceiling. We model the apartment as on the second floor of a two-story building, with an impermeable membrane at the roof. The model expresses this by omitting flow paths between the zones and the level above.

CONTAM tips:

- When placing flow path icons in the attic floor, it may be helpful to select `Level->Reveal Level Below`.

Flow paths between attic and occupied zones, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt
atc	Brm	atc_flr	0	604.9 ft2	env_lk_f
atc	Com	atc_flr	0	915.6 ft2	env_lk_f
atc	Kit	atc_flr	0	243.5 ft2	env_lk_f
atc	Wet	atc_flr	0	336.0 ft2	env_lk_f

Flow paths between attic and occupied zones, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt
atc	Brm	atc_flr	0	777.5 ft2	env_lk_f
atc	Fam	atc_flr	0	240.5 ft2	env_lk_f
atc	wet	atc_flr	0	432.1 ft2	env_lk_f

Envelope wall flow paths – Through wall

The occupied zones connect to outdoors through paths representing two types of leaks in the envelope walls: (1) leaks in the envelope wall proper; and (2) leaks at the floor-wall interface.

We characterize leaks in the envelope wall proper using a single flow element, `env_wall`. This flow element accounts for doors and windows, as well as for area-distributed leaks.

Parameterize the leaks through the envelope wall proper by the following rules:

- Use flow element `env_wall`.
- Divide the total area of each wall segment equally among 3 panels (horizontal strips). This area is the multiplier for the flow paths on that wall segment.
- Distribution of N panels over a height H:
  - Each panel has height H/N.
  - Place a flow path's relative elevation halfway up the panel it represents.
  - For panel $0 \leq i < N$, its flow path is at relative elevation $(0.5 + i)(H/N)$.
- Positive flow direction from outdoors to indoors.
  - Note the default flow path direction will sometimes achieve this, but sometimes will not.

- Filter `env_lk_f`.

Prototype-specific notes:

- For the 2-story residence, all the envelope leaks on the east and south sides of the common zone may be placed on a single wall segment, even though that zone has two wall segments facing those directions. This is permissible because nothing in the model distinguishes between those wall segments (i.e., they have the same wind pressures, and the same internal pressures at each height).
- The multifamily apartment shares its north and south walls with other apartments. These apartments are assumed to be at the same pressure as the modeled apartment, so that no air exchange takes place between them. The model expresses this by omitting flow paths between the zones and apartments to the north and south.
- The multifamily apartment shares its west wall with a corridor. The corridor walls are assumed airtight. The model expresses this by omitting flow paths to the west.

CONTAM tips:

- A flow path's relative elevation gives its height compared to some reference level in the zone of interest. The models here follow the convention that the relative elevation is the height above the floor. In particular, this means that the same relative elevations apply to both floors in the two-story residence.

Flow paths representing leaks through the envelope wall, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt	Comments
Ambt	brm E wall	env_wall	1.5 4.5 7.5	108.0 ft2	env_lk_f	Same mult each elev. Defines `env_elevs`.
Ambt	brm N wall	env_wall	env_elevs	60.0 ft2	env_lk_f	
Ambt	brm S wall	env_wall	env_elevs	37.7 ft2	env_lk_f	
Ambt	com E wall	env_wall	env_elevs	30.0 ft2	env_lk_f	
Ambt	com N wall	env_wall	env_elevs	90.0 ft2	env_lk_f	
Ambt	com W wall	env_wall	env_elevs	91.6 ft2	env_lk_f	

Ambt	kit S wall	env_wall	env_elevs	47.2 ft2	env_lk_f
Ambt	kit W wall	env_wall	env_elevs	46.4 ft2	env_lk_f
Ambt	wet S wall	env_wall	env_elevs	65.1 ft2	env_lk_f

Flow paths representing leaks through the envelope wall, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt	Comments
Ambt	brm N wall	env_wall	1.5 4.5 7.5	109.9 ft2	env_lk_f	Same mult each elev. Defines `env_elevs`.
Ambt	brm W wall	env_wall	env_elevs	63.7 ft2	env_lk_f	
Ambt	com E wall	env_wall	env_elevs	87.0 ft2	env_lk_f	
Ambt	com N wall	env_wall	env_elevs	117.6 ft2	env_lk_f	
Ambt	com S wall	env_wall	env_elevs	117.6 ft2	env_lk_f	
Ambt	fam E wall	env_wall	env_elevs	54.0 ft2	env_lk_f	
Ambt	fam N wall	env_wall	env_elevs	40.1 ft2	env_lk_f	
Ambt	kit N wall	env_wall	env_elevs	32.4 ft2	env_lk_f	
Ambt	kit S wall	env_wall	env_elevs	32.4 ft2	env_lk_f	
Ambt	kit W wall	env_wall	env_elevs	87.0 ft2	env_lk_f	
Ambt	wet E wall	env_wall	env_elevs	33.0 ft2	env_lk_f	
Ambt	wet S wall	env_wall	env_elevs	150.0 ft2	env_lk_f	
Ambt	wet W wall	env_wall	env_elevs	23.3 ft2	env_lk_f	

Flow paths representing leaks through the envelope wall, for multifamily apartment.

From	To	Flow	Relative	Mult	Filt	Comments

		Element	Elev [ft]			
Ambt	brc E wall	env_wall	1.3 4 6.7	23.6 ft2	env_lk_f	Same mult each elev. Defines `env_elevs`.
Ambt	brm E wall	env_wall	env_elevs	26.8 ft2	env_lk_f	
Ambt	com E wall	env_wall	env_elevs	26.9 ft2	env_lk_f	

Envelope wall flow paths – Slab-wall interface

These leaks occur at the interface between the ground floor slab and the envelope wall. As a shorthand, we label them as “slab” leaks, even though they do not represent leakage through the slab itself.

Parameterize the slab-to-wall leaks by the following rules:

- Use flow element `env_slab`.
- Multiplier is the length of the wall segment.
- Positive flow direction from outdoors to indoors.
- Filter `env_lk_f`.

Prototype-specific notes:

- For the 2-story residence, only the ground floor has this type of leak.
- For the 2-story residence, all the envelope leaks on the east and south sides of the common zone may be placed on a single wall segment, even though that zone has two wall segments facing those directions.
- The multifamily apartment does not have this type of leak, since it is above the ground floor.

Flow paths representing leaks at the floor-wall interface, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt
Ambt	brm E wall	env_slab	0	36.0 ft	env_lk_f
Ambt	brm N wall	env_slab	0	20.0 ft	env_lk_f
Ambt	brm S wall	env_slab	0	12.6 ft	env_lk_f
Ambt	com E wall	env_slab	0	10.0 ft	env_lk_f
Ambt	com N wall	env_slab	0	30.0 ft	env_lk_f
Ambt	com W wall	env_slab	0	30.5 ft	env_lk_f

Ambt	kit S wall	env_slab	0	15.7 ft	env_lk_f
Ambt	kit W wall	env_slab	0	15.5 ft	env_lk_f
Ambt	wet S wall	env_slab	0	21.7 ft	env_lk_f

Flow paths representing leaks at the floor-wall interface, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt
Ambt	com E wall	env_slab	0	29.0 ft	env_lk_f
Ambt	com N wall	env_slab	0	39.2 ft	env_lk_f
Ambt	com S wall	env_slab	0	39.2 ft	env_lk_f
Ambt	kit N wall	env_slab	0	10.8 ft	env_lk_f
Ambt	kit S wall	env_slab	0	10.8 ft	env_lk_f
Ambt	kit W wall	env_slab	0	29.0 ft	env_lk_f

Ducted supply and exhaust flow paths

Give each occupied zone one supply fan and one exhaust fan, connecting it to the outdoors. See the tables below.

Prototype-specific notes:

- For the multifamily apartment, some zones have no exterior wall (e.g., the wet zone). For these zones, place the fan flow paths directly in the wall shared with an adjacent apartment. This is permissible because the model does not explicitly include adjacent apartments. Therefore CONTAM treats the flow path as connecting to ambient.

CONTAM tips:

- Flow elements that directly specify the airflow rate, such as those used for ducted supply and exhaust paths, do not vary their flow depending on the pressure at their inlet and outlet. Thus they are not sensitive to hydrostatic pressure variations in the zone. For convenience, the flow elements can be modeled with a relative elevation of 0, no matter what their height in the physical building.

- The ducted supply and exhaust paths could also have been defined using the simple air handler airflow model. This approach would allow modeling the ducted flows even in a zone that had no wall separating it from the ambient zone. This also would have simplified the EnergyPlus scripting, by avoiding the need to create control elements (see below).

- It should now be possible to run the model without getting any errors. Run the model using menu item `Simulation`->`Run Simulation`. If the model runs, check the airflow in the ducted supply and exhaust paths (the graphical user interface will show the airflows as green lines, pointing from each flow path in the direction of positive flow). The paths should appear in matching pairs, with equal flows directed inward and outward across the envelope. To go back to editing the model, choose `View`->`Normal Mode`.

Flow paths representing ducted supply and exhaust, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt	Comments
Ambt	brm	fan_1kgs	0	1	env_fn_f	Supply fan.
brm	Ambt					Exhaust fan.
Ambt	com	fan_1kgs	0	1	env_fn_f	
com	Ambt					
Ambt	kit	fan_1kgs	0	1	env_fn_f	
kit	Ambt					
Ambt	wet	fan_1kgs	0	1	env_fn_f	
wet	Ambt					

Flow paths representing ducted supply and exhaust, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt	Comments
Ambt	brm	fan_1kgs	0	1	env_fn_f	Supply fan.
brm	Ambt					Exhaust fan.
Ambt	com	fan_1kgs	0	1	env_fn_f	
com	Ambt					
Ambt	fam	fan_1kgs	0	1	env_fn_f	
fam	Ambt					
Ambt	kit	fan_1kgs	0	1	env_fn_f	
kit	Ambt					
Ambt	wet	fan_1kgs	0	1	env_fn_f	
wet	Ambt					

Flow paths representing ducted supply and exhaust, for multifamily apartment.

From	To	Flow Element	Relative Elev [ft]	Mult	Filt	Comments
Ambt	brc	fan_1kgs	0	1	env_fn_f	Supply fan.
brc	Ambt					Exhaust fan.
Ambt	brm	fan_1kgs	0	1	env_fn_f	
brm	Ambt					
Ambt	com	fan_1kgs	0	1	env_fn_f	
com	Ambt					

Ambt	kit	fan_1kgs	0	1	env_fn_f
kit	Ambt				
Ambt	wet	fan_1kgs	0	1	env_fn_f
wet	Ambt				

Ducted supply and exhaust controls

Each of the flow paths representing ducted supply and exhaust fans needs a control element to allow EnergyPlus to set its mass flow rate.

Draw the control elements:

- Choose `Tools`->`Draw Links`.
- Click three or more pixels away from the icon representing the ducted supply or exhaust fan of interest, and use the mouse or arrow keys to draw a control link that ends at the flow path. The resulting link should look like a red arrow, pointing into the flow path.

CONTAM tips:

- The control icon can be outside the building (i.e., in the ambient zone).
- Hit `Esc` to exit the link-drawing mode.
- After drawing the controls, choose `View`->`Results Mode` to show the flow direction in the ducted fans. This will verify the flow direction when naming the controls.

Configure the control elements that set the mass flows:

- Choose control element type `Constant`.
- Name the control element like `zzz_dsup_set` or `zzz_dexh_set`, where:
    - – `zzz` is the name of the zone that the flow path links to outdoors.
    - – `dsup` indicates a ducted supply, for which the path has positive flow from outdoors into the zone.
    - – `dexh` indicates a ducted exhaust, for which the path has positive flow from the zone to outdoors.
- Set the control value to 0.
    - – EnergyPlus will set the desired value during simulation.

Operable interior door flow paths

All operable interior doors are defined with two flow paths: (1) an undercut; and (2) the main doorway. This allows the door as a whole to be scheduled as open or closed, by scheduling the main door, while leaving the undercut as always active.

Flow paths representing operable interior doors, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult
brm	com	idr_ucut	0	1
		idr_main	2 cm	1
brm	wet	idr_ucut	0	1
		idr_main	2 cm	1
com	wet	idr_ucut	0	1
		idr_main	2 cm	1

Flow paths representing operable interior doors, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult
brm	fam	idr_ucut	0	1
		idr_main	2 cm	1
brm	wet	idr_ucut	0	1
		idr_main	2 cm	1
fam	wet	idr_ucut	0	1
		idr_main	2 cm	1

Flow paths representing operable interior doors, for multifamily apartment.

From	To	Flow Element	Relative Elev [ft]	Mult
brc	com	idr_ucut	0	1
		idr_main	2 cm	1
brm	com	idr_ucut	0	1
		idr_main	2 cm	1
com	wet	idr_ucut	0	1
		idr_main	2 cm	1

Operable interior door controls

After adding interior doors, draw and configure control elements to allow EnergyPlus to set the door opening position. For each operable door (i.e., for interior doors paired with an undercut):

- Draw a link that terminates in the main doorway (i.e., in the `idr_main`, rather than the `idr_ucut`, icon).
- Choose control element type `Constant`.

- Name the control element like `zza_zzb_dr_set`, where:
    - `zza` and `zzb` are the names of the zones that the door connects, in alphabetical order.
- Set the control value to 0.
    - EnergyPlus will set the desired value during simulation.

Large interior opening flow paths

The kitchen connects to the common area via a large opening. Model the large opening as a double-wide door. Since the door is assumed always open, do not model a door undercut.

In addition, we wish to force mixing between the closely-coupled spaces. This reflects the reality that some cooking-generated pollutants are able to escape into the rest of the house, even with kitchen extraction fans running. Note that one could combine the common area and kitchen into a single zone. However in that case, CONTAM would predict that any contaminant released in the kitchen would instantaneously mix into the common area. Thus the tool would not be able to predict any advantage to extracting air from the kitchen over extracting from the common areas. Furthermore, the large volume of the common area would unrealistically dilute the cooking-related pollutants.

To force mixing between the kitchen and common area, add balanced mixing flows. The mixing flows are fan flow elements, with identical mass flow rates. This mixes the air between the two rooms, without disrupting the mass flow balance that CONTAM calculates for the rest of the house.

Adjust the fan mass flow rate to make the two rooms equilibrate at a desired *inter-zonal mixing time*, τ.

We define the mixing time as follows. Suppose two zones form a closed, isothermal, system. Let a volume flow rate, Q, of air transport pollutant from zone 1 to zone 2, and let a balanced flow rate Q transport pollutant from zone 2 to zone 1. The zones have volumes V_1 and V_2, respectively.

Now suppose that at time $t = 0$, zone 1 has zero concentration, $c_1(t = 0) = 0$, while zone 2 has well-mixed concentration $c_2(t = 0) = c_{2,0}$.

The mixing time is the time it takes for the concentration in zone 1 to reach some fraction, α, of that in zone 2:

$$c_1(\tau) = \alpha c_2(\tau)$$

where $c_i(t)$ denotes the concentration in zone i at time t, and where $0 < \alpha < 1$. Note that the mixing time is a function of the mixing fraction, i.e., $\tau = \tau(\alpha)$.

The closed system is governed by the coupled differential system

$$\frac{d}{dt}\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{bmatrix} -\lambda_1 & \lambda_1 \\ \lambda_2 & -\lambda_2 \end{bmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

where $\lambda_i = Q/V_i$ is the *air change rate* for zone i.

Solving and matching to initial conditions $c_1(0) = 0$ and $c_2(0) = c_{2,0}$ yields

$$\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} c_s \\ c_s \end{pmatrix} + \begin{pmatrix} 1 \\ c_{2,0} - c_s \end{pmatrix} e^{-(\lambda_1+\lambda_2)t}$$

where the steady-state concentration in both zones,

$$c_s = \frac{V_2}{V_1 + V_2} c_{2,0}$$

distributes the initial mass, $V_2 c_{2,0}$, uniformly throughout the combined volumes.

Substituting into the mixing-time definition gives

$$\tau = \frac{1}{\lambda_1 + \lambda_2} \ln\left(\frac{V_2 + \alpha V_1}{V_2[1-\alpha]}\right)$$

Note that the mixing time depends on α, but not on the initial concentration $c_{2,0}$.

Solving for $(\lambda_1 + \lambda_2)$, and substituting $\lambda_i = Q/V_i$, gives the volume flow rate Q that establishes the desired mixing time $\tau(\alpha)$ as

$$Q = \frac{V_1 V_2}{V_1 + V_2}\left(\frac{1}{\tau}\right) \ln\left(\frac{V_2 + \alpha V_1}{V_2[1-\alpha]}\right)$$

While CONTAM allows specifying the mixing flows in volumetric units, we wish to parameterize those flow elements using a mass flow rate, in order to make it easier to verify the model in the coupled simulations. For the conversion, we assume air density $\rho = 1.2041$ kg/m3, which corresponds to an air temperature of 20 C at standard atmospheric pressure.

Flow paths representing large interior openings, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments
com	kit	idr_main	0	2	
com	kit	fan_1kgs	0	0.3719	Mixers (2).
kit	com				Mult is for $\tau(0.9) = 10$ min. Use 0.7438 for 5 min. Use 0.1859 for 20 min.

Flow paths representing large interior openings, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments

com	kit	idr_main	0	2	
com kit	kit com	fan_1kgs	0	0.4333	Mixers (2). Mult is for $\tau(0.9) = 10$ min. Use 0.8665 for 5 min. Use 0.2166 for 20 min.

Flow paths representing large interior openings, for multifamily apartment.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments
com	kit	idr_main	0	2	
com kit	kit com	fan_1kgs	0	0.1370	Mixers (2). Mult is for $\tau(0.9) = 10$ min. Use 0.2740 for 5 min. Use 0.0685 for 20 min.

Interior wall flow paths

In addition to doors, interior zones connect via distributed leakage through their shared walls. For these flow paths:

- Use flow element `int_wall`.
- Divide the total available area of each wall segment equally among 3 panels (horizontal strips). This area is the multiplier for the flow paths on that wall segment.
  - Find the total available area of a wall segment as its apparent area (length times width), minus the area of any interior door in that segment.
  - Subtract the door area before dividing the wall area among the panels. That is, don't try to account for the fact that the door impinges less on the upper panel than on the lower ones. One could do so, but it's a small difference, and it would give the similar flow paths different multipliers, making the data entry harder to check.
- Set the height distribution as described for envelope walls.

Flow paths representing distributed leaks in interior walls, for one-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments
brm	Com	int_wall	1.5 4.5	55.6 ft2	Same mult each elev. Defines `iw_elevs`.

			7.5		
brm	Wet	int_wall	iw_elevs	62.8 ft2	
com	Kit	int_wall	iw_elevs	35.3 ft2	
com	Wet	int_wall	iw_elevs	36.9 ft2	
kit	Wet	int_wall	iw_elevs	46.4 ft2	

Flow paths representing distributed leaks in interior walls, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments
brm	Fam	int_wall	1.5 4.5 7.5	48.1 ft2	Same mult each elev. Defines `iw_elevs`.
brm	Wet	int_wall	iw_elevs	113.7 ft2	
com	Kit	int_wall	iw_elevs	75.1 ft2	
fam	wet	int_wall	iw_elevs	40.1 ft2	

Flow paths representing distributed leaks in interior walls, for multifamily apartment.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments
brc	brm	int_wall	1.3 4 6.7	26.7 ft2	Same mult each elev. Defines `iw_elevs`.
brc	com	int_wall	iw_elevs	44.4 ft2	
brm	com	int_wall	iw_elevs	28.9 ft2	
brm	wet	int_wall	iw_elevs	26.8 ft2	
com	kit	int_wall	iw_elevs	41.7 ft2	
com	wet	int_wall	iw_elevs	12.6 ft2	

Interior floor-to-floor flow paths

The two-story residence includes flow paths between occupied zones on different floors. These represent the stairway cutout, and distributed leakage (based on the area of the shared ceiling-floor interface). See the table below.

Flow paths between occupied zones on different floors, for two-story residence.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments
brm	com	int_flr	0	548.3 ft2	
brm	kit	int_flr	0	229.2 ft2	
fam	com	int_flr	0	200.1 ft2	
fam	com	orf_1cm2	0	37539	Stairway cutout area (cm2).
wet	com	int_flr	0	162.7 ft2	
wet	Kit	int_flr	0	84.1 ft2	

Trickle vent flow paths

The apartment model gets flow paths representing trickle vents with controllable leakage areas. This allows EnergyPlus to simulate control systems that modulate the envelope leakage in response to some control signal of interest. For example, the Aereco humidity-sensitive ventilation system sets the cross-sectional area of vents, as well as mechanical exhaust flow rates, based on the humidity in the occupied zones.

In each “dry” zone with an envelope wall, add a flow path representing a trickle vent, as detailed in the table below. Dry zones are occupied zones in which occupants are the primary source of humidity (i.e., not the kitchen or wet zones).

Flow paths representing controlled trickle vents, for multifamily apartment.

From	To	Flow Element	Relative Elev [ft]	Mult	Comments
Ambt	brc	orf_1cm2	7.5	1	Mult gives vent count. Ctrl gives leakage area [cm2].
Ambt	brm	orf_1cm2	7.5	1	
Ambt	com	orf_1cm2	7.5	1	

Trickle vent controls

After adding trickle vents, draw and configure control elements to allow EnergyPlus to set the opening area. For each trickle vent:

- Draw a link that terminates in the flow path icon.
- Choose control element type `Constant`.
- Name the control element like `zzz_trklar_set`, where `zzz` is the name of the zone.
- Set the control value to 0.
    - EnergyPlus will set the desired value during simulation. Note that setting the control value to 0 will keep the trickle vent from participating during pressurization testing.

Common model – Simple air handlers

Use CONTAM's "Simple Air Handling System" model to represent a recirculating central air-handling unit. Simpler Air Handling Systems define flow paths at a higher level of abstraction than the other, flow element-based, flow path models. This set of linked components allows setting up an air handler, without having to define all the fans, ducts, and terminals.

Note that if a particular control scheme does not use a simple air handler, it can simply be switched off, by setting its control inputs to zero.

CONTAM tips:

- The air handlers do not need explicit controls to set their airflow rates, because the EnergyPlus FMU capability provides this automatically.

Air handling system

First, add an "Air Handling System" icon somewhere on the sketchpad. This central hub will coordinate the supply and return terminals associated with the air handler:

- Use `Tools`->`Draw Icon`->`Air Handling System`. Alternately, type `H` with the program in Normal Mode view.
- Set the parameters on the air handler's `AHS` tab:
    - Name "central_ahu".
    - Minimum Outside Air flow 0 kg/s.
- Set the parameters on the air handler's `Filters` tab:
    - Outdoor air filter, `ahu_f`.
    - Return air filter, `ahu_f`.

CONTAM tips:

- Place the air handler system component outside the building, to emphasize its collective nature, and to avoid visual clutter in the zones.

Supply and return terminals
Add "Supply" and "Return" terminals in every occupied zone:

- Use `Tools`->`Draw Icon`->`Supply` and `Tools`->`Draw Icon`->`Return`, respectively.
- Open each terminal, and set the parameters on the `System` tab:
  - Design Flow Rate, 1 kg/s.
  - AHS, select `central_ahu` from the pull-down list.

CONTAM tips:

- After defining the first Supply and Return terminals, you can copy-paste them into the other zones.
- NIST's EnergyPlus export tool requires the Supply and Return terminals to appear in matched pairs. This explains why every zone with a Supply needs a Return, even if the return flow will always be zero.
- NIST's EnergyPlus export tool automatically connects simple air handler systems (on the CONTAM side) to air loop elements (on the EnergyPlus side). This explains why the CONTAM model does not need control elements to allow EnergyPlus to control the simple air handlers.
- Physically, we wish to model a filter on every supply air stream. However, for simplicity we model filters at the central air handler, on its outdoor air and recirculation streams.

To check that the air handling system is defined correctly so far, run a simulation. With the sketchpad in `View`->`Results Mode`, clicking on the air handler system component should show the following:

- O/A, N kg/s, where N is the number of occupied zones. This is the total outside air supplied by the system to the zones.
- R/A, 0 kg/s. This is the total recirculated air, i.e., the total return air supplied by the system to the zones.
- X/A, N kg/s. This is the total exhaust air, i.e., the total return air dumped by the system back to outdoors.

Simple air handler schedules

By default, the simply air handler system supplies 100% outside air. Modeling a pure recirculation system requires attaching a schedule. For this project, EnergyPlus will provide the schedule. However for stand-alone testing we attach a schedule to the air handler, as follows:

- Define a new day schedule:
    - Choose `Data`->`Day Schedules`->`Dimensionless`.
    - Select `New` under `Local Project elements`.
    - Name, `zero_day`.
    - Under `Schedule Data`, select each time, edit the value to be 0, and click `Insert` to change the value in the schedule. There should be only two times defined, `00:00:00` and `24:00:00`.
    - Click on `Display Graphically` to verify that the schedule is zero all day long.
    - Click `OK`, and then exit the Day Schedules Manager dialog box.
- Define a new week schedule:
    - Choose `Data`->`Week Schedules`->`Dimensionless`.
    - Select `New` under `Local Project elements`.
    - Name, `zero_week`.
    - Under `Day Schedules`, select each day type, ensure `zero_day` is selected, and click `Replace` to change the value in the schedule. Note you can use the `shift` key while selecting, and then change all the day types at once.
    - Click on `Display Graphically` to verify that the schedule is zero all day long.
    - Click `OK`, and then exit the Week Schedules Manager dialog box.
- Control the air handler using the new week schedule:
    - Open the air handler system component, and select its `Schedule` tab.
    - Under `Outdoor Air Schedule`, select `zero_week`.

Re-run the simulation, and verify that the system recirculates air only, and provides no outside air. With the sketchpad in `View`->`Results Mode`, clicking on the air handler system component should show the following:

- O/A, 0 kg/s.
- R/A, N kg/s.
- X/A, 0 kg/s.

CONTAM tips:

- Note that the scheduled outside air fraction only controls what fraction of supplied air comes from outside *when the system has the choice between return air or outside air*. If the Supply terminals, in sum, supply more air than the Return terminals provide, then CONTAM makes up the difference using outside air. This means that when using EnergyPlus to set the flow rates in each Supply and Return, the supply and return flows need to balance in EnergyPlus. Otherwise, the simple air handler will either dump air to outside, or bring in outside air, as needed to make up the difference.

Check flow paths

The common model now has all flow paths defined.

As a simple check on the work above, run `Simulation`->`Run Building Check` to verify the model.

Next, prepare to run the model, by verifying the weather drivers are all set to zero:

- Open `Weather`->`Edit Weather Data`.
- Set outdoor temperature to 68 F.
- Set wind speed to 0.

Finally, run the model (`Simulation`->`Run Simulation`). The model should predict zero airflow through all paths except: (1) the forced mixing fans; and (2) the air handler supply and return terminals. Since these are in balanced pairs, they should not induce other zone-to-zone flows. Verify the following:

- The graphical user interface should be in “Results Mode”:
  - You should see green line segments coming from the fan elements.
  - The `View`->`Results Mode` menu item should be selected.

- Ducted supply and exhaust fans:
  - Appear in balanced pairs.
  - Each occupied zone has one pair connecting it to the outdoors.
  - Each has zero flow.
- Forced mixing fans:
  - Appear in balanced pairs.
  - Connect `kit` to `com` zones.
  - Have the desired flows (see the tables above).
- Simple air handler Supply and Return components:
  - Appear in matched pairs.
  - Appear in every occupied zone.
  - Each has a flow 1 kg/s.
- All remaining (passive) flow paths have zero flow.
  - This includes all paths in the attic.
  - Do not expect exactly-zero flows, due to solver tolerances.

CONTAM tips:

- After running a simulation, to remove visual clutter when editing, select `View`->`Normal Mode`.

Common model – Initial concentrations

For most contaminant species, the default concentration (specified in the `Data`->`Species` menu) gives both the outdoor and the initial concentrations.

However, the initial concentration for formaldehyde differs from that outdoors. This reflects the fact that indoor sources account for large fraction of indoor mass for this species.

This change affects:

- Every occupied zone (i.e., not the attic).
- The simple air handler.

In the common model, change the initial concentration to the values noted in the table below. If the table labels the initial concentration as 'Default', then the initial concentration should already be set correctly.

To make this change:

- For occupied zones, open the zone icon, choose the `Contaminant Data` tab, and set the `Initial Concentration` entry.
- For the simple air handler, set the initial concentration on both the air handler's `Supply System` and `Return System` tabs.

Initial concentrations for occupied zones and simple air handlers.

Species	Init Conc	Comments
ashq	0 μg/kg	Default
co2	400 ppm	Default
form	18 ppb	~ 18.66 μg/kg.
pm	10 μg/m3	Default

Common model – Wind

This section defines wind pressure calculations for the common model.

Background – Wind pressure

CONTAM finds the wind pressure on a wall as the product of a *wind pressure coefficient*, C_p, and the stagnation pressure associated with the *approach wind speed*, V_b, at the building:

$$P_w = C_p \frac{\rho}{2} V_b^2$$

The approach wind speed is the local free-stream wind speed at building height or eave height.

In general, $-1 < C_p < 1$. Wind striking the wall head-on generates positive pressure ($C_p > 0$), while wind parallel to or behind the wall causes suction ($C_p < 0$).

This project also accounts for sheltering due to local obstructions, via a *wind shelter coefficient*, S_u, which converts the approach wind speed to the actual wind speed, V_w, at the wall:

$$V_w = S_u V_b$$

In general, $0 < S_u \leq 1$.

Both C_p and S_u depend on the wind angle. However, CONTAM provides just one mechanism for adjusting wind pressure due to wind direction, namely, its C_p tables.

Therefore this project merges both pressure and sheltering effects into a *combined wind pressure coefficient*

$$C_p^* = C_p S_u^2$$

Thus the values entered in the CONTAM tables are combined wind pressure coefficients, even though CONTAM refers to them simply as wind pressure coefficients.

Approach wind speed

The approach wind speed, V_b, differs from the meteorological or *met wind speed*, V_m, measured at a local met station.

CONTAM does not allow the user to specify V_b directly. Instead, it reads V_m from a steady-state input, or from a weather file, and finds V_b as

$$V_b = A_o \left(\frac{H_b}{H_m}\right)^{a_b} V_m$$

where:

- The *local terrain constant*, A_o, and the exponent, a_b, depend on the terrain around the building.
- Heights H_b and H_m give the roof or eave height, and the height of the met station, respectively. CONTAM assumes $H_m = 10$ m.

By contrast, ASHRAE and RegCap use

$$V_b = \left(\frac{\delta_m}{H_m}\right)^{a_m} \left(\frac{H_b}{\delta_b}\right)^{a_b} V_m$$

where:

- δ_m and δ_b give the wind boundary layer thickness at the met station and building, respectively.
- Exponent a_m depends on the terrain around the met station.

To make CONTAM follow the ASHRAE formulation, set

$$A_o = \left(\frac{\delta_m}{H_m}\right)^{a_m} \left(\frac{H_m}{\delta_b}\right)^{a_b}$$

If $H_m \neq 10$ m, this formula would require further adjustment, to compensate for CONTAM's hard-coded assumption.

For this project, we follow RegCap in assuming $H_m = 10$ m, $\delta_m = 270$ m, and $a_m = 0.14$.

The table below converts the RegCap terrain assumptions into CONTAM input parameters.

RegCap terrain assumptions, and corresponding CONTAM inputs. For comparison purposes, the table also shows the values suggested in the CONTAM User Guide.

Terrain Type	RegCap δ_b	RegCap a_b	RegCap-equivalent (A_0, a_b)	CONTAM UG (A_0, a_b)
City center Half buildings > 25 m	460	0.33	(0.45, 0.33)	(0.35, 0.40)
Suburban and wooded areas	370	0.22	(0.72, 0.22)	(0.60, 0.28)
Open terrain Met station	270	0.14	(1.00, 0.14)	(1.00, 0.15)
Open water Completely flat	210	0.10	(1.17, 0.10)	

For this project, we assume a suburban area. To set the conversion from met wind speed to approach wind speed in the PRJ file:

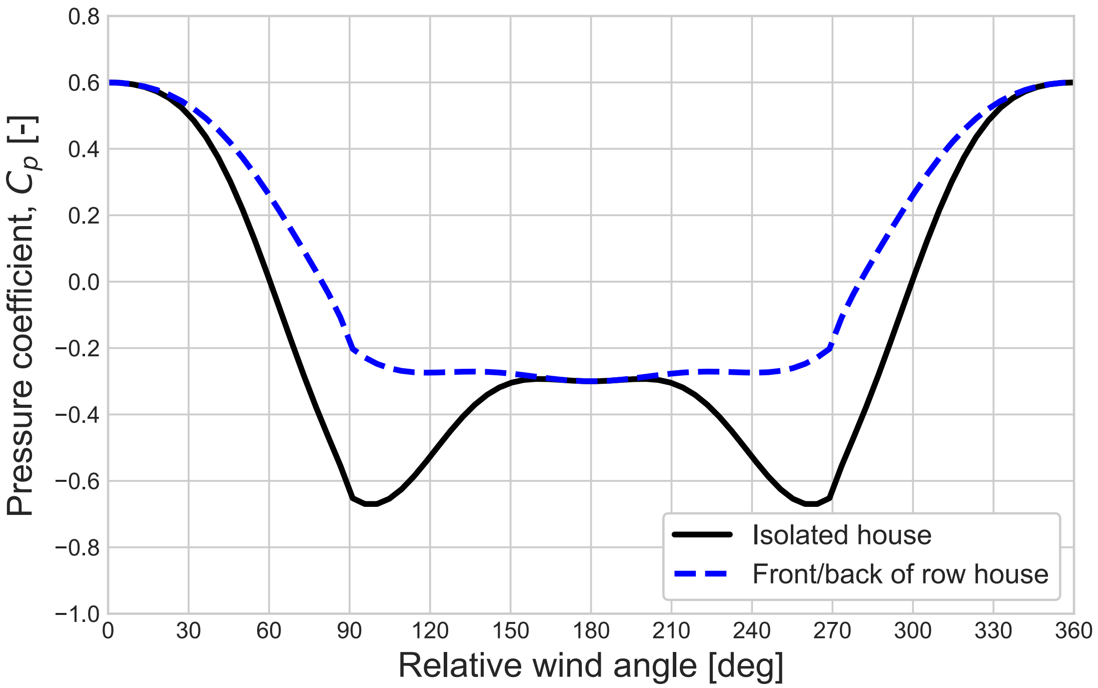
- Choose `Weather`->`Edit Weather Data`.
- On the `Wind` tab, set:
  - Relative North, 0 deg.
  - Roof height, taken from table of level data (above).
  - Local terrain constant, 0.72.
  - Velocity profile exponent, 0.22.

Background – Wall wind pressure

For walls, we find the wind pressure coefficient using Walker’s harmonic trigonometric interpolation function (ASHRAE Handbook of Fundamentals, 2013, Chapter 16).

The figure below shows C_p as a function of wind direction for two cases: (1) an isolated house; and (2) the front and back walls of a row house.

Figure 28: Wind Pressure Coefficient On Walls, Not Accounting For Sheltering Due To Local Obstructions.



Both curves have a maximum $C_p \approx 0.6$ at a wind angle of 0 degrees, i.e., for wind directly impinging on the wall. Furthermore both curves have slight suction, $C_p \approx -0.3$, at an angle 180 degrees, i.e., when the wall faces directly away from the wind.

The curves differ, however, for wind parallel to the wall, i.e., at an angle 90 degrees or 270 degrees. For an isolated house, flow separation along the wall generates large negative pressures, $C_P \approx -0.65$. For the front or back wall of a row house, the obstructing houses along the row prevent this separation, and the wind pressure does not vary much with the wind angle. Note that the side walls of a row house respond in the same way as for an isolated house, because wind parallel to those walls comes from the relatively unobstructed front or back of the house.

Background – Roof wind pressure

For roofs, we find the wind pressure coefficient using Walker's empirical function (Walker, Forest, and Wilson, "An attic-interior infiltration and interzone transport model of a house," Building and Environment, v40 (2005), pp701-718).

The figures below show C_p as a function of wind direction for two cases: (1) an isolated house; and (2) the front and back walls of a row house. The curves differ due to the same row house effect described for walls. Furthermore the wind pressure depends on the roof pitch, with flatter roofs generally experiencing greater suction pressures, at a greater range of wind angles.

Figure 29: Wind Pressure Coefficient On Roofs, For An Isolated House.

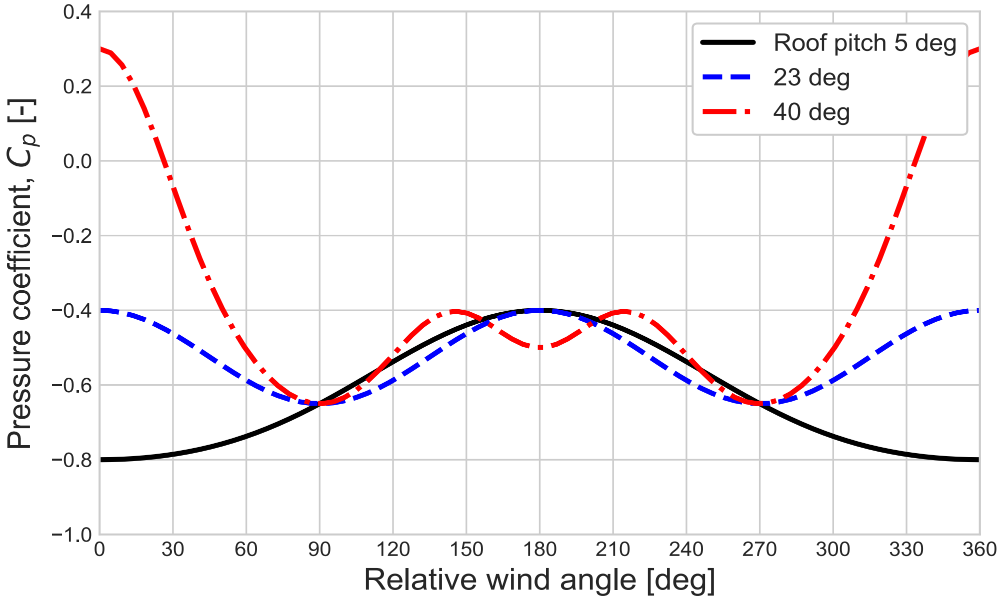
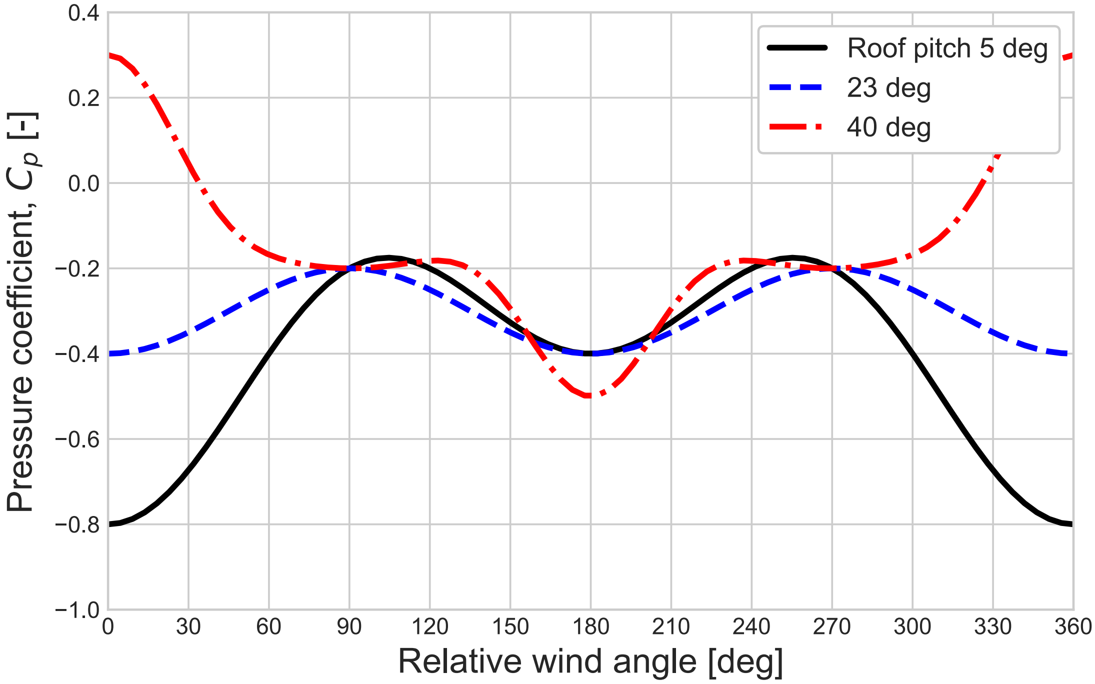


Figure 30: Wind Pressure Coefficient On Roofs, For The Front And Back Walls Of A Row House.

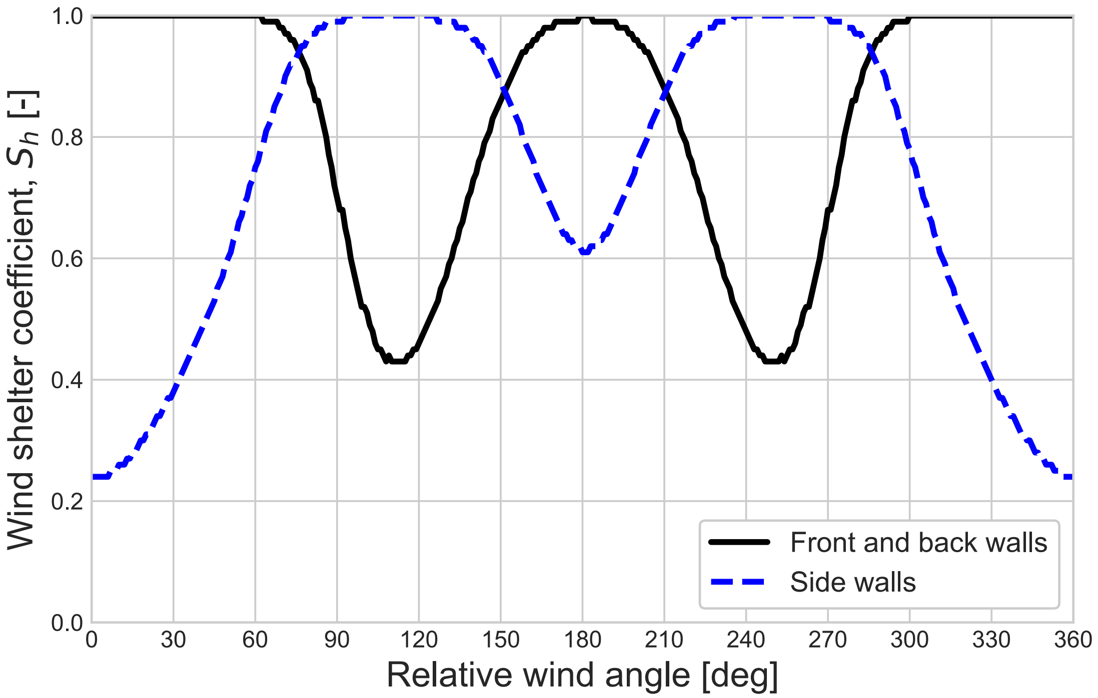


For roofs, this project uses only the C_p curves for the front and back of a row house. The project assumes a gable roof, oriented with the roof sloping toward the front and back, at a 5/12 pitch (22.6 degrees). The attic walls on the sides of the house are given wall C_p coefficients.

Background – Wind shelter coefficient

This project uses tabular wind shelter coefficients, generated using results from I.S. Walker's PhD dissertation. The figure below shows the shelter coefficients applied to the house walls (note that the roof wind pressure coefficients do not have a sheltering adjustment).

Figure 31: Wind Shelter Coefficient For A Row House.



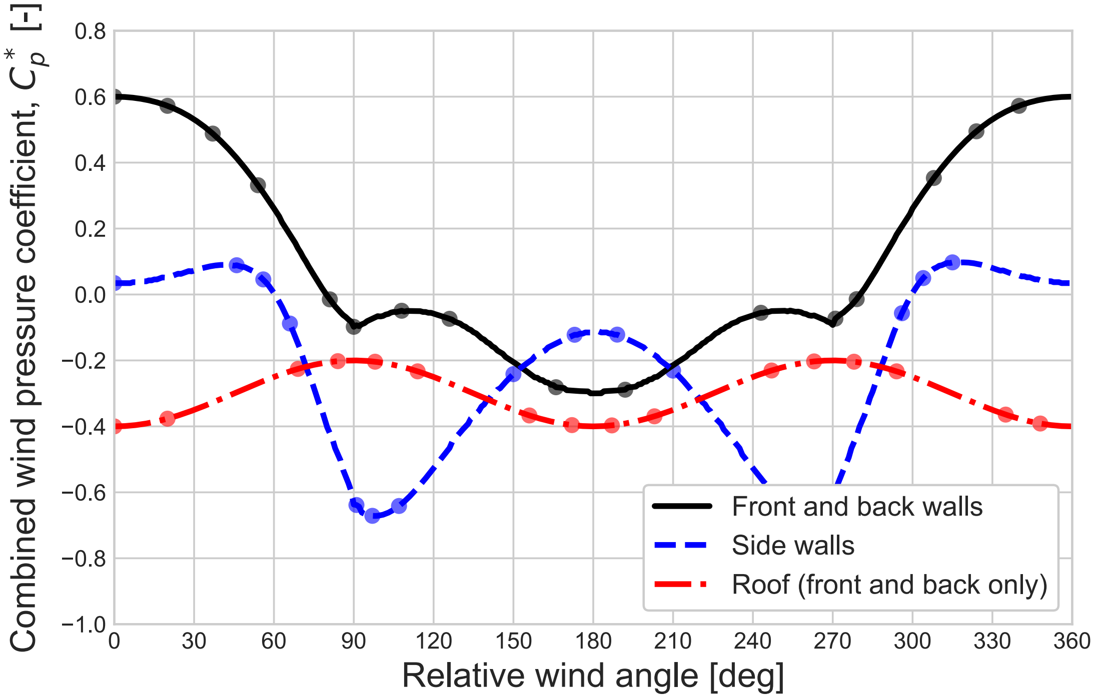
For the front and back walls of the house, winds at 0 and 180 degrees relative angle experience no sheltering. However nearby houses reduce the wind speed significantly for winds blowing along the row of houses.

For the same reason, the side walls of the house experience considerable sheltering for head-on winds, with the actual wind speed reduced to nearly 20% of the approach wind speed. Conversely, the side walls have no sheltering from winds coming from the front and back of the house.

Define wind pressure profiles

The figure below shows the combined wind pressure coefficients used for this project. As noted above, the roof does not have a shelter coefficient, so $C_p^* = C_p$ for the roof.

Figure 32: Combined Wind Pressure Coefficients Used In This Study. The Dots Show The 16 Points That Define The CONTAM Wind Pressure Profiles.



The C_p^* curves were calculated at relative wind angles spaced one degree apart. Entering these points into a CONTAM PRJ file requires further processing.

CONTAM stores wind pressure coefficients in *wind pressure profiles*. These tables specify C_p as a function of wind direction for up to 16 angles. During each run, CONTAM interpolates these data for intermediate angles, as needed.

To convert the continuous C_p^* curves described above into data for CONTAM wind pressure profiles, we chose points from the continuous profile by approximately minimizing the sum of squared errors that would result from linear interpolation in the table.

The minimization algorithm generated initial selections of points using three heuristics:

- Sampling with uniform spacing between angles.

- Taking a greedy approach, by always choosing the next point from the continuous curve in order to minimize the interpolation error.
- Choosing points at minima or maxima of the continuous curve, then finishing the initial selection using the greedy approach.

Starting from these three initial selections, the algorithm randomly removed observations, replacing each removed point with the greedily-selected best point from the continuous curve. The algorithm stops after a sufficiently large number of replacements proceed without improving the error. Because of its random selection approach, this algorithm is not guaranteed to minimize the error. Furthermore, since the error uses a linear interpolation function, while CONTAM uses a cubic spline to interpolate between points, the curves are not guaranteed optimal.

The figure of C_p^* coefficients uses dots to show the final points selected for use in the CONTAM wind profiles. The tables below list the points.

To enter the points in a CONTAM wind pressure profile:

- Select `Data`->`Wind Pressure Profiles...` and click `New` under `Local Project elements`.
- Enter the profile name and data points from the tables below.
- Select `Curve Fit 1`.
- Click `Redraw`, and verify, visually, that the profile matches that in the figure above.

Points used for the CONTAM wind pressure profiles, for the front and back walls. Pressure profile `row_house_front`.

Angle [deg]	Coefficient	Angle [deg]	Coefficient
0	0.6000	166	-0.2813
20	0.5722	192	-0.2888
37	0.4880	243	-0.0555
54	0.3314	271	-0.0733
81	-0.0148	279	-0.0141
90	-0.0980	308	0.3533
108	-0.0493	324	0.4949
126	-0.0738	340	0.5722

Points used for the CONTAM wind pressure profiles, for the side walls. Pressure profile `row_house_side`.

Angle [deg]	Coefficient	Angle [deg]	Coefficient

0	0.0346	173	-0.1221
46	0.0887	189	-0.1217
56	0.0458	210	-0.2309
66	-0.0881	254	-0.6474
91	-0.6384	268	-0.6567
97	-0.6713	296	-0.0568
107	-0.6414	304	0.0498
150	-0.2416	315	0.0974

Points used for the CONTAM wind pressure profiles, for the roof. Pressure profile `row_house_roof`.

Angle [deg]	Coefficient	Angle [deg]	Coefficient
0	-0.4000	187	-0.3970
20	-0.3766	203	-0.3695
69	-0.2257	247	-0.2305
84	-0.2022	263	-0.2030
98	-0.2039	278	-0.2039
114	-0.2331	294	-0.2331
156	-0.3669	335	-0.3643
172	-0.3961	348	-0.3914

Attach wind pressure profiles

After defining the profiles, attach one to every envelope path. Note that, technically, the envelope paths with fans don’t need a wind pressure profile, but it doesn’t hurt to attach one.

To attach a wind profile to a flow path:

- Open the flow path input dialog.
- Select the `Wind Pressure` panel.
- Select the `Variable` wind pressure option.
- Select the appropriate wind pressure profile from the pull-down menu.

Choose the wind pressure profile based on the envelope path location.

For the one-story residence and two-story residence:

- Paths on the front and back walls get profile `row_house_front`.
- Side walls, including gable ends in the attic, get profile `row_house_side`.

- Paths in the roof, including vents placed at soffit height, get profile `row_house_roof`.

For the multifamily apartment:

- Paths on the east wall get profile `row_house_front`.
- Note the model has no other connections to ambient.

CONTAM tips:

- CONTAM accounts for the wall orientation when finding the input wind direction for a wind pressure profile. A wind direction of 0 degrees always represents wind hitting the wall straight on, just as represented in the figures above. This means a single profile can be shared by walls of different orientation.
- CONTAM automatically duplicates the observation at 0 degrees for use at 360 degrees. Therefore the tables do not have to include an observation at 360 degrees, in order to completely define the C_p curve.

Check wind profiles

The common model now has all envelope wind profiles defined.

As a simple check on the work above, run `Simulation`->`Run Building Check` to verify the model.

To check the wind profiles in greater detail, first verify that `View`->`Wind Pressure Type` is on `User Set`. Then select `View`->`Wind Pressure Mode`. The graphical user interface now shows the pressure drop across, and the expected flow direction through, each envelope flow path.

Now select `Weather`->`Edit Weather Data` and, in the resulting dialog box, select the `Wind Pressure Display` panel. Set the temperature to 68 F, and the wind speed to 10 m/s. Then step through the cardinal wind directions, checking that the flow paths show the expected pressure drops:

- For wind direction 0 degrees: (i.e., coming from above/north):
  - North-facing paths should show flow going into the building.
  - South-facing paths should show flow exiting the building.
  - Paths on the sides of the house should have flow exiting the building.
  - The roof should have outflow at all paths.
- For wind direction 90 degrees: (i.e., coming from the right/east):

  - East-facing paths should have inflow.
  - North, South, and West-facing paths should have outflow.
  - The roof should have outflow at all paths.
- Wind at 180 degrees (i.e., coming from below/south) should reverse the flows in the north and south faces, compared to the above/north case.
- Wind at 270 degrees (i.e., coming from left/west) should reverse the flows in the east and west facades, compared to the right/east case.

Remember to de-select `View`->`Wind Pressure Mode` when done.

Pressure test model – Overview

The pressure test model, `ppp_pressure.prj`, is a throw-away intermediate step. It is used to tune the common model's air change rate during a simulated building pressurization test.

Each common model has up to three parameters that set its leakage characteristics:

- α_a, area-normalized leakage in the attic floor [cm^2/m^2] (set in flow element `atc_flr`).
- α_s, length-normalized leakage between the floor slab and the envelope walls [cm^2/m] (`env_slab`).
- α_w, area-normalized leakage in the envelope walls [cm^2/m^2] (`env_wall`).

The pressure test model chooses values for these parameters, in order to achieve some target air change rate (ACR) in a simulated building pressurization test.

For building prototypes with multiple target ACRs, a single common model will have multiple sets of values for the tuning parameters.

Approach

For each prototype and target ACR, find the model parameters as follows:

- Establish the target pressurization air change rates through each type of leakage path.
- Estimate the initial parameter values.
- Iteratively tune the pressure test model, using CONTAM's pressurization test mode.
- Log the tuned parameter values.

The remainder of this section describes general procedures for each step. Later sections fill in details for each prototype.

CONTAM tips:

- CONTAM's built-in pressurization test mode automatically:
  - Pressurizes every interior zone to the desired pressure.
  - Sets wind to zero.
  - Sets all zones, including ambient, to a fixed temperature.
  - Forces all flow through duct and fan elements to zero.
  - Produces a special output file, which lists the total airflow needed to pressurize the building.

Initialization

Copy the common model and save as `ppp_pressure.prj`.

Open and save the model using CONTAM 3.3 (since this is the version that will be used when co-simulating with EnergyPlus). Note that converting to CONTAM 3.3 is probably not necessary, since the airflow capabilities of CONTAM 3.3 match those of 3.2. However, take this precautionary measure anyway.

If the model has an attic, verify, from the `Zone Properties` input dialog, that its volume is *not* included in the building volume.

Set the simulation parameters:

- Choose `Simulation`->`Set Simulation Parameters`.
- On the `Run Control` tab:
  - Choose `Building Pressurization Test`.
  - Set the pressure to 50 Pa.

Set the initial leakage parameters, as described below for each prototype.

Estimating leakage using a single-zone model

Each flow element that needs to be tuned has a normalized leakage area parameter, α, which applies to all paths that use that flow element. As described above, α normalizes the leakage area, either by the total wall area, or by the total crack length.

To estimate α for a flow element, we first find the leakage area that causes CONTAM to calculate the expected airflow at 50 Pa pressurization, for a single-zone model with only one type of leak.

The paths of interest are governed by a compact form of the orifice equation,

$$Q = \frac{C_b}{\sqrt{\rho}} \Delta P^n$$

where ΔP is the pressure drop through the path [Pa], Q is the volumetric airflow rate through the path [m^3/s], ρ is the air density [kg/m^3], C_b is the flow coefficient, and n the flow exponent. While CONTAM supports several forms of powerlaw airflow model, it uses this particular expression for airflow elements defined by the leakage area formulation. See the "Airflow Analysis" section of the CONTAM User Guide for more information.

We seek the C_b that forces this simple model to sustain a total air change rate ϕ air changes per hour at interior pressure $\Delta P_\phi = 50$ Pa (the *ACH50* value of the house). Relate ϕ to Q as

$$\phi = 3600 \frac{Q}{V}$$

where V is the house volume [m^3], and 3600 s/hr converts the air change rate from air changes per second to ACH.

Combining, the desired flow coefficient is

$$C_b = \frac{\phi V \sqrt{\rho}}{3600} \Delta P_\phi^{-n}$$

However, the CONTAM user interface does not specify C_b directly. Therefore we next relate C_b to the input parameters used to specify the airflow elements.

The flow elements of interest use the leakage area formulation

$$Q = C_D A \sqrt{\frac{2\Delta P}{\rho}}$$

where the user specifies a discharge coefficient C_D, leakage area A, and reference pressure ΔP_r.

Matching the volume flow rate from this expression, to that from the compact form, requires

$$C_D A \sqrt{\frac{2\Delta P_r}{\rho}} = \frac{C_b}{\sqrt{\rho}} \Delta P^n$$

from which

$$C_b = C_D A \sqrt{2} \Delta P_r^{0.5-n}$$

CONTAM performs this calculation for the user. Note that this expression differs slightly from the corresponding expression in the ASHRAE Handbook of Fundamentals (2013, p.16.16). The ASHRAE version uses a factor $\sqrt{2/\rho}$, rather than $\sqrt{2}$. This follows since the ASHRAE flow equation is $Q = C\Delta P^n$, rather than $Q = C_b \Delta P^n / \sqrt{\rho}$. ASHRAE also has an additional constant factor to convert units.

In order to parameterize the model, then, we choose A such that CONTAM will calculate the desired C_b:

$$A = \frac{\phi V}{3600 C_D} \sqrt{\frac{\rho}{2\Delta P_r}} \left(\frac{\Delta P_r}{\Delta P_\phi} \right)^n$$

Note that A gives the total leakage area for all flow paths that use the flow element of interest. To find the flow element's normalized leakage parameter, α, requires dividing by the total area associated with the paths of interest.

Leakage parameters for unused flow elements

Some models do not use all flow elements (for example, the apartment model does not use `atc_flr`). In this case, set the normalized leakage to 100 (units [cm^2/m^2] or [cm^2/m]). This will help expose problems in case the model inadvertently uses the element (alternately, the model can omit the flow element; however, this makes it harder to compare PRJ files with text-based tools).

CONTAM tip:

- CONTAM does not allow setting a flow element's normalized leakage to 0. Otherwise, that would be a natural choice for this parameter.

Finding air change rates

As noted above, each model has up to 3 parameters to tune. This section describes one possible approach to tuning the leakage parameters.

Note that, since the pressurization test enforces the desired zone pressure, and reports the airflows that arise as a result, the flow paths do not interact as they do in an ordinary simulation. Therefore the leakage parameters can be changed independently. This may speed up the iterative search for the parameters, since all the parameters can be updated without regard for changes in the other parameter values.

After setting the flow element leakage parameters, run the pressure test model to find the air change rate, using the `Simulation`->`Run Simulation` menu item.

CONTAM's building pressurization test produces a special output VAL file, named like `ppp_pressure.val`. In this file, locate the following information:

- The volume flow rate, Q [m^3/h].

  - Note CONTAM reports this in multiple units – be sure to take the right one.

- The volume, V, of the conditioned zones [m^3].
  - Check that the volume matches the sum of volumes of zones listed as belonging to the occupied zones, in the zone data tables above.

Use these values to find the air change rate, Q/V [ACH] or [1/h].

The VAL file also reports the outbound flows through all paths that connect zones whose volume is included in the conditioned volume, to any zone whose volume is not so included. Among the flow rate units reported are m^3/h. This makes it easy to compare against target flow rates in ACH.

A Python script, `summarize_pressure_test.py`, performs the calculations described above. To run the script, use the runtime help option (switch `-h` or `--help`):

```
$ python summarize_pressure_test.py --help
```

When looking at the script's output, check that only the expected flow element types have non-zero air change rates. In particular, any fan elements, and flow elements representing trickle vents, should carry zero flow.

Tuning the leakage parameters

At this point, for each adjustable parameter α, we know the following values:

- α^c, current value of the normalized leakage parameter α.
- f^t, target value of the sum of flows through the flow element types that α controls.
- f^c, current value of the sum of flows.

To tune the leakage parameters, we iteratively update the model with a new value of α, entering at least six significant figures, then re-run the model. Note that CONTAM rounds inputs, so entering more than six significant figures is generally not necessary. We iterate until each parameter converges to at least five significant figures.

We apply two main numerical procedures to the task of finding a new α at each iteration. Call this new parameter value α^t.

The first procedure for estimating α^t assumes

$$f = c\alpha$$

The unknown parameter c depends on the pressure drop through the paths, the flow exponent, the total area or length associated with the paths, and the internal adjustments CONTAM makes to account for temperature effects on air viscosity and density.

Assume that c does not vary much from one run of the pressure test model to another. Then one may estimate

$$c = \frac{f^c}{\alpha^c}$$

and use it to find the value of α that should produce the target flow. From $f^t = c\alpha^t$ it follows:

$$\alpha^t = \frac{f^t}{c} = \frac{f^t}{f^c}\alpha^c$$

In practice, when close to the final solution one might "damp" this value somewhat, for example by using the average of the old and new values:

$$\alpha^t = \frac{1}{2}\left(1 + \frac{f^t}{f^c}\right)\alpha^c$$

However, close to the final solution, we have observed that the number of significant digits available for specifying α is too granular to hit the target airflow rate exactly. Specifically, changing α in the last digit that the CONTAM user interface accepts, may not change the computed air change rate, or may change it by a large amount relative to the error from the target value f^t.

Therefore in practice we use the first numerical procedure to establish a bracket on the target air change rate, then apply bisection to further refine α^t. This procedure eventually leads to two values of α, call them α_1^t and α_2^t, which the user interface will accept unchanged, but which are close enough that the user interface rounds their average value to one of the bracketing α. We then select, as the final α^t, whichever of α_1^t and α_2^t sets the air change rate closest to its target value f^t.

Logging the tuned parameters

After converging on appropriate values for the leakage parameters, copy the relevant lines out of the PRJ file, into a leakage parameter file.

The scripts that generate Functional Mockup Units (FMUs) can read that file, in order to parameterize the FMU correctly. Details are beyond the scope of this document. See the technical documentation in the leakage parameter directory for details.

Pressure test model – 1sr

The one-story residence uses all three tuning parameters.

Since multiple combinations of values for those three tuning parameters can achieve the same pressurization air change rate, we further constrain the relationship between the parameters, as follows:

- Ceiling flow paths account for 50% of the total pressurized ACR. This follows the default assumption in the Title 24 Alternative Calculation Method (2016).

- Envelope flow paths account for 25% of the total pressurized ACR.
- Slab-to-wall flow paths account for 25% of the total pressurized ACR.

Tune the model to 0.6, 2, and 3 ACH50.

Leakage parameters – 1sr

To estimate the normalized leakage areas in the `1sr` model:

- Apportion the total air change rate in the 50-25-25 ratio desired for the ceiling, slab, and wall leakage paths.
- Estimate the total leakage area for all paths associated with the flow element of interest.
- Normalize by the ceiling area, slab perimeter length, and envelope area, respectively.

The table below shows these initial estimates, for the flow element reference parameters $C_D = 1$, $n = 0.67$, and $\Delta P = 4$ Pa, and for $\rho = 1.204$ kg/m3.

Initial values for normalized leakage areas, for one-story residence.

ACH50 [1/hr @ 50 Pa]	Target ACR (atc_flr, env_slab, env_wall) [1/hr]	α_a (atc_flr) [cm2/m2]	α_s (env_slab) [cm2/m]	α_w (env_wall) [cm2/m2]
0.6	0.3, 0.15, 0.15	0.16327	0.27216	0.099211
2	1, 0.5, 0.5	0.54424	0.90719	0.3307
3	1.5, 0.75, 0.75	0.81637	1.3608	0.49606

Applying the tuning procedure described above to the `1sr` prototype results in the values shown in the table below.

Final values for normalized leakage areas, for one-story residence.

ACH50 [1/hr @ 50 Pa]	α_a (atc_flr) [cm2/m2]	α_s (env_slab) [cm2/m]	α_w (env_wall) [cm2/m2]
0.6	0.163286	0.272199	0.099217
2	0.5449	0.907247	0.330722
3	0.81858	1.36084	0.496054

Pressure test model – 2sr

The two-story residence uses all three tuning parameters, chosen as follows:

- Ceiling flow paths get the same area-normalized leakage as `1sr`.

- Slab-to-wall flow paths get the same length-normalized leakage as `1sr`.
- Envelope flow paths are chosen to make the model give the target ACR.

Tune the model to 0.6, 2, and 3 ACH50.

Leakage parameters – 2sr

For each leakage class, take the initial values for the envelope leaks from the table of final values for the one-story residence.

Tuning the `2sr` prototype results in the values shown in the table below.

Final values for normalized leakage areas, for two-story residence.

ACH50 [1/hr @ 50 Pa]	α_a (atc_flr) [cm2/m2]	α_s (env_slab) [cm2/m]	α_w (env_wall) [cm2/m2]
0.6	0.163286	0.272199	0.177157
2	0.5449	0.907247	0.590768
3	0.81858	1.36084	0.885954

Pressure test model – apt

The multifamily apartment uses only one of the tuning parameters, the area-normalized envelope leakage. As noted above:

- The model assumes equal pressurization in the apartments above, below, and to the sides; and no leakage to the hallway. Hence only the envelope wall has leakage paths from an occupied zone to some other node in the airflow system.
- The model assumes the unit is on the second level, and hence has no special leakage paths between the floor and the envelope wall.

This leaves the envelope paths, to tune the model to the desired leakage.

We assume that the envelope paths account for 30% of the total airflow under pressurization. Thus for a total airflow ϕ air changes at 50 Pa pressurization, the envelope paths are tuned to carry an airflow 0.3ϕ air changes.

Tune the model to a total airflow of 3.5 ACH50.

Leakage parameters – apt

To estimate the normalized leakage areas in the `apt` model:

- Apportion the total air change rate so that 30% exits the envelope wall leaks.
- Estimate the total leakage area for all paths associated with the flow element of interest.

- Normalize by the envelope area.

The table below shows these initial estimates, for the flow element reference parameters $C_D = 1$, $n = 0.67$, and $\Delta P = 4$ Pa, and for $\rho = 1.204$ kg/m3.

Initial values for normalized leakage areas, for multifamily apartment.

ACH50 [1/hr @ 50 Pa]	Target ACR (atc_flr, env_slab, env_wall) [1/hr]	α_a (atc_flr) [cm2/m2]	α_s (env_slab) [cm2/m]	α_w (env_wall) [cm2/m2]
3.5	0, 0, 1.05	100	100	1.9049

Tuning the `apt` prototype results in the values shown in the table below.

Final values for normalized leakage areas, for multifamily apartment.

ACH50 [1/hr @ 50 Pa]	α_a (atc_flr) [cm2/m2]	α_s (env_slab) [cm2/m]	α_w (env_wall) [cm2/m2]
3.5	100	100	1.90579

Supplemental information – EnergyPlus

The table below shows the units that EnergyPlus uses when passing data to a CONTAM model.

Units to use in EnergyPlus, when passing data to a CONTAM model.

Variable type	CONTAM control name	Units	Comments
Airflow, ducted exhaust	zzz_dexh_set	kg/s	Note `zzz` names zone.
Airflow, ducted supply	zzz_dsup_set	kg/s	
Interior door position	zza_zzb_dr_set	-	Note `zza` and `zzb` name connected zones. Set to 0 (closed) or 1 (open).
Leakage area, trickle vents	zzz_trklar_set	cm2	
Source rate, co2	zzz_co2_set	mg/s	
Source rate, formaldehyde	zzz_form_set	$\mu g/m2/hr$	Normalized by floor area. PRJ multiplier gives floor area.
Source rate, particles	zzz_pm_set	mg/s	

The table below shows the units that CONTAM uses when passing data to EnergyPlus.

Units that CONTAM uses when passing data to an EnergyPlus model.

Variable type	CONTAM	Units	Comments

	control name		
Concentration, co2	zzz_co2_get	ppmv	Note **zzz** names zone.
Concentration, formaldehyde	zzz_form_get	$\mu g/m^3$	
Concentration, particles	zzz_pm_get	$\mu g/m^3$	