



Energy Research and Development Division

FINAL PROJECT REPORT

Smart Ventilation for Advanced California Homes

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Smart Ventilation for Advanced California Homes is the final report for the Smart Ventilation for Advanced California Homes project (Contract Number EPC-15-037) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the <u>CEC's research website</u> (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This project investigated the potential of using smart ventilation technology to reduce ventilation-related energy use, while maintaining indoor air guality, in new high-performance California homes. Evaluation criteria included annual ventilation-related energy, peak energy and time-of-use savings, and the indoor air guality relative to a minimally code-compliant ventilation system. The project's simulation approach used CONTAM's air flow and contaminant transport model, combined with the EnergyPlus building loads model, to investigate the ventilation, indoor air quality, and energy dynamics in homes. The project investigated house types representing the default California Building Energy Efficiency Standards-compliant homes for four varying California climate zones. Single-zone ventilation approaches showed that controls that vary ventilation depending on outdoor temperatures have the ability to consistently save half of ventilation-related energy without compromising long-term indoor air quality. Because this work included contaminants, such as formaldehyde, from building materials and furnishings, focusing ventilation on occupied times did not save much energy unless additional measures were taken — such as one-hour pre-occupancy ventilation. Multizone ventilation approaches showed little potential for additional energy improvements, with indoor air quality impacts dependent on the particular contaminant of interest. Controls that directly sensed contaminants and controlled them to acceptable levels showed that the very low limit in California for formaldehyde resulted in continuous ventilation operation with no energy savings but substantial reductions in contaminants. In summary, these advanced smart ventilation controls have shown the potential to reduce energy use by at least half for a broad range of both new and existing California homes in varying climates using controls that are simple and inexpensive to implement and that little is to be gained from zoned ventilation or direct contaminant control.

Keywords: Smart ventilation, controls, indoor air quality, multizone, contaminant sensing

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EXECUTIVE SUMMARY

Introduction

New California homes have become more energy efficient due to the increased 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 use only as much energy as they can generate with renewable energy sources. For existing homes to perform like high-performance homes, they need upgrades using many of the same approaches used in new construction: better insulation, windows, appliances and lighting. In addition to energy performance, homes must also be comfortable, durable, and healthy places to live. A key aspect to achieve this is to have good indoor air quality that is provided by mechanical ventilation systems. New home construction in California requires minimum ventilation levels. However, increased air tightness can reduce indoor air quality, and as space conditioning, lighting, and some other energy end uses in homes have been effectively minimized, the fraction of energy required to ventilate for good indoor air guality has been increasing. There is a need to reduce the energy used for ventilation in high-performance homes without compromising the well-being of California citizens. "Smart ventilation" can enhance or even improve indoor air quality while saving energy — a win-win for California ratepayers.

Currently, new homes are ventilated primarily by simple fans that operate continuously. Some homes use more complex balanced ventilation systems that include a heat exchanger, but these systems are expensive and difficult to install and maintain correctly. The idea behind smart ventilation is to introduce controls for ventilation systems that can be applied to simpler, lower cost systems as well as to more advanced systems. The key concept behind smart ventilation is to continually adjust the ventilation system in time, and optionally by location, to provide the desired indoor air quality benefits while minimizing energy consumption, utility bills, and other non-indoor air quality costs such as thermal discomfort or noise. For example, smart ventilation allows ventilation to occur at different times of day, depending on outdoor temperatures or whether the home is occupied, or to account for operation of other house fans such as kitchen, bathroom, and dryer exhausts so that the occupant's exposure to contaminants is the same, or lower, as that 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 energy use and peak demand without compromising healthy indoor air.

The competitive market has no incentive to develop smart ventilation systems because builders and contractors have no method to quantify the value of the ventilation/energy tradeoff or to get credit for improved indoor air quality 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 the California Energy Commission (CEC) staff and other policy makers need to evaluate options for future standards, particularly those related to zero net energy homes. The results of this study will facilitate private-sector development of compliant technologies and regulated-sector development of programs.

Project Purpose

To demonstrate the potential of smart ventilation approaches to save energy and maintain indoor air quality and identify the control strategies that offer the best modeled energy savings across a range of California climates and house types, the research had three technical objectives. These objectives are intended to provide the technical material suitable for use by building controls and ventilation manufacturers to produce smart ventilation systems and by codes and standards bodies (specifically Title 24 in California and American Society of Heating Refrigeration and Air Conditioning Engineers [ASHRAE] standard 62.2 for a national audience) to give credit for building with these approaches. The objectives are:

- 1. Revise indoor air quality metrics that go beyond simple fixed continuous ventilation rates and include exposure to key contaminants as well as controls to minimize energy use and reduce peak demand.
- 2. Demonstrate that smart ventilation systems can provide acceptable indoor air quality in zero net energy homes.
- 3. Determine how best to design ventilation systems for California zero net energy homes.

Project Approach

The Lawrence Berkeley National Laboratory project team combines leading residential energy and ventilation researchers with the indoor air quality expertise of the laboratory's Indoor Environment group. The project team has performed several recent research projects for the CEC related to indoor air quality and ventilation of homes. Two key partners that provided additional funding for this study are the U.S. Department of Energy Building America Program and Aereco, a French manufacturer of demand-controlled ventilation systems.

The development of smart ventilation control strategies were based on: a combination of the research team's 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 (for example, from breathing, cooking, and bathing); and studies of measured contaminants in homes The various strategies were assessed analytically using computer simulations combining the CONTAM air flow and pollutant transport with the EnergyPlus building loads model. 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 was analyzed to determine energy use (in both site energy that would appear on a utility bill and time dependent valuation energy that is used to show compliance in the California Building Energy Efficiency Standards. The time dependent valuation assessment assigns weights to energy used depending on time of use, 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 indoor air quality at least as good as a continuously operating ventilation system.

The project had four main technical tasks:

- 1. Review the literature.
- 2. Develop indoor air quality metrics.
- 3. Simulate and evaluate single-zone smart ventilation technology.
- 4. Evaluate multi-zone smart ventilation technology.

The greatest challenges were:

- Developing new metrics for ventilation system control particularly for zonal and direct contaminant control.
- Model development.
- Ensuring that potential smart ventilation controls had some level of practical application at least in the near (less than five year) time horizon.

A project technical advisory committee included representatives from the 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 project partners, the U.S. Department of Energy and Aereco.

A project website was created to track project progress and to allow public access to the project results when the project is complete: <u>svach.lbl.gov</u>.

Project Results

This project successfully demonstrated the potential of smart ventilation to deliver energy savings and identified the control strategies that offer the best modeled energy savings across a range of California climates and house types. The key indoor air quality metric used in this study for evaluating if smart controls provided the same or better indoor air quality 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 weighted average site ventilation energy use by about 40 percent, while time dependent valuation weighted average ventilation energy reductions were higher, up to roughly 60 percent. Because the controls were designed to err on the side of greater ventilation, on average they resulted in better indoor air quality. These same controls led to peak demand reductions during 2:00 p.m. to 6:00 p.m. on the hottest days up to 400 watts. More than 90 percent of site energy savings were for heating end uses, while time dependent valuation energy savings were split fairly 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 (that is,

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 percent.

The multizone results have generally shown that zoning itself is not likely to yield significant improvements over single-zone approaches. The ability to target individual zones for ventilation is offset by the introduction of outdoor particles and the need to account for contaminants generated independently of occupancy (for example, formaldehyde). Furthermore, the ability of homes to be effectively zoned from an indoor air quality perspective is limited by opening of interior doors; operation of heating, ventilation, and air conditioning equipment; and movement of occupants between zones.

Contaminant control approaches are completely dominated by the difficulty in achieving the Office of Environmental Health Hazard Assessment limit for formaldehyde. The project's systems ventilated at their maximum flow rates and still did not achieve the 9 micrograms per cubic meter limit and also doubled energy use.

The results of this research can be used by the State of California to revise the Building Energy Efficiency Standards to allow the use of smart ventilation and provide appropriate energy-saving attributes in code compliance requirements and energy compliance software. The results can also be used by the national home ventilation standard (ASHRAE standard 62.2) to create standard compliance pathways that accommodate smart ventilation approaches. Ventilation equipment manufacturers can use the control strategies and algorithms created in this study to develop new smart ventilation systems.

The next steps, in developing this technology, will be to create prototypes and perform pilot studies to evaluate them in homes and to find ways that these energy savings can be reflected in building codes and standards. This work is being undertaken by Lawrence Berkeley National Laboratory in collaboration with the U.S. Department of Energy Building America Program.

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

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

Part of the U.S. Department of Energy 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.

At industry trade shows, manufacturers of ventilation equipment have expressed interest in the concept of smart ventilation. To be more viable in the marketplace several things are needed:

- 1. A definition of smart ventilation
- 2. Credit in building energy codes and standards, such as Title 24 in California, ASHRAE standard 62.2 and Residential Energy Savings Network ratings

3. Pilot field studies demonstrating smart ventilation systems in homes

Benefits to California

Smart ventilation benefits California ratepayers by its ability to:

- 4. Maintain health, odor, and moisture requirements for indoor air quality.
- 5. Save roughly half of the energy required to mechanically ventilate a home. Enable peak demand reductions of about 400 Watts for a period of two hours that help to ensure grid reliability at peak times. Enable lower-cost approaches to high-performance ventilation.

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, and 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 is 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 (DALYs) lost per 100,000 people in United States residences as a result of exposure to indoor pollutants to be 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 United States, corresponding to about 19 DALYs per 100,000 people.

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 United States climates, the International Energy Conservation Code (IECC) requires an envelope leakage rate of three air changes per hour at 50 pascals (ACH₅₀) (ICC, 2012), and select voluntary programs, such as Passive House, require extreme airtightness at less than 0.6 ACH₅₀. New California homes are typically in the range of four to six ACH₅₀ (Chan et al. 2018). Typical values for new homes even a decade ago were in the range of 6 to 10 ACH₅₀, while older, existing homes range from 10 to 30 ACH₅₀ (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 United States 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 codes and voluntary programs (for example, Washington State 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 more often 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 increase 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 is 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 the exposure from a smart ventilation system is equivalent to or better than a non-smart system, that is, 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, and 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 Residential Integrated Ventilation Controller) was developed and briefly field-tested in California that used occupancy, auxiliary fan sensing, grid signals, and timer-based temperature controls (Walker, Sherman, and Dickerhoff 2012). Less, Walker, and Tang (2014) studied the effects of several temperature-based control strategies that used cut-off temperatures below which indoor air quality (IAQ) fans were turned off (fan airflow was increased during all other hours). Smart controls for humidity control in hot and warm, humid climates were developed for similar homes in Less, Walker, and Ticci (2016). Less and Walker (2017) examined the performance of occupancy and auxiliary fan smart controls in Zero Energy Ready homes across U.S. Department of Energy (U.S. DOE) climate regions. Work at the Florida Solar Energy Center (Martin, Fenaughty, and 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 that 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 of this report, 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 United States climates, this study considers only advanced homes in the State of California, defined as homes that conform to the 2016 Title 24 Building 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 carbon dioxide (CO₂) 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 multizone 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 effects.

Reducing infiltration in existing buildings is a high-payoff state goal that will require installation of smart ventilation systems. The California Energy Commission-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 airtightness without adequate ventilation are harder to estimate, 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 zero net energy 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, 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 greenhouse gas emissions goal, but it 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 Lawrence

Berkeley National Laboratory (LBNL) studies have indicated that simple timer controls to avoid ventilation on summer afternoons or winter nights can save about 40 percent of peak ventilation load, about 15 percent 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, 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, previously mentioned, 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 California Energy Commission (CEC), that is, 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 airtightening measures based on perceived IAQ issues. LBNL is a partner in the U.S. DOE Building America Program, which has several teams, partners, and builders in California as well as builders committed to the U.S. DOE Zero Energy Ready Home Program. They all face the challenge of maintaining IAQ while reducing infiltration to meet their energy-saving goals. Residential Energy Services Network (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: Project Approach

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:

- 1. 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.
- 2. 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.
- 3. 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 ratepayers because it is essential that energy efficient homes are also healthy homes and that the well-being of California citizens is not compromised in our efforts to reduce energy use in the state. Without smart ventilation the options are to either lower health levels or leaving 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 — a win-win for California ratepayers.

The results of this research can be used directly by the State of California in revisions to the State Building Energy Code that would allow the use of smart ventilation and provide appropriate energy-saving attributes in code compliance requirements and energy compliance software. The results can also be used by the National home ventilation standard (ASHRAE Standard 62.2) to create standard compliance pathways that accommodate smart ventilation

approaches. Ventilation equipment manufacturers can use the control strategies and algorithms created in this study to develop new smart ventilation systems.

Project Team

The LBNL project team combines leading residential energy and ventilation researchers (Dr. Iain Walker and Mr. Brennan Less) with the IAQ expertise of LBNL's Indoor Environment group (Dr. Rengie Chan and Dr. Brett Singer Dr. Spencer Dutton, Dr. Michael Sohn and Mr. David Lorenzetti). The LBNL team has performed several recent research projects for the Energy Commission related to IAQ and ventilation of homes: the RESAVE ventilation energy savings study (resave.lbl.gov), and the HENGH study with a focus on field measurements (hengh.lbl.gov), whose results were used directly in the smart ventilation for advanced California homes (SVACH) study. Two key partners who provided additional funding for this study are: U.S. DOE's Building America program, which is performing ongoing research on air guality and durability of high-performance homes, and Aereco, a French manufacturer of demand-controlled ventilation systems. Other stakeholders include the ASHRAE 62.2 committee (Dr. Walker is the current chair), the Energy Commission (specifically with regards to potential future changes to the State Energy Code), and the international ventilation research community via participation in the International Energy Agency Annex 5: the Air Infiltration and Ventilation Center who LBNL collaborated with in the creation of an international definition of smart ventilation as part of this project.

Project Overview

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 air flow 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 was 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. 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:

- Literature review. This task investigated previous research on smart ventilation-related topics to form a basis for the development of metrics and control strategies.
- Development of IAQ Metrics. This task examined different methods for evaluating indoor air quality including the CO₂ 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.
- Single zone technology evaluation. This task performed simulation to assess the energy use and IAQ of single-zone smart ventilation approaches.
- 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:

- 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 control to: the maximum allowed by health community standards, or what is typically found in California homes as measured in the HENGH study?
- 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.
- 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. 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 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 (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 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: <u>svach.lbl.gov</u>.

CHAPTER 3: Review of Residential Ventilation Controls and Indoor Air Quality 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, CO₂, 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 — that is, 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 it includes all contaminants. This is particularly important, because field studies of contaminants in homes (the CEC-sponsored Healthy, Efficient New Gas Homes [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 CO₂ 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 cubic meters per hour (m^3/h), a maximum airflow between 50 m^3/h and 75 m^3/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 of 30 - 35 percent to 70 - 80 percent, as shown in Figure 1.

Figure 1: Relationship Between Airflow and Relative Humidity for Air Outlets Used in Nine Current Humidity Demand-Controlled Ventilation Systems in Belgium



Source: 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.

We also assessed the regulatory context in which smart ventilation strategies might be implemented most effectively. 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. We searched the literature for studies examining both energy savings and IAQ impacts of smart ventilation approaches. This meta-analysis of 38 studies of various smart ventilation systems with controls (on either CO_2 , humidity, combined CO_2 and TVOC, occupancy, or outdoor temperature) shows 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 multizone modeling in residential buildings, indicating that multizone 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 Indoor Air Quality in the Marketplace: Metrics and Appraisals

The literature review was combined with other related U.S. 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. Many of these lists focus on reducing emissions of contaminants into homes, primarily from building materials, which 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 U.S. Environmental Protection Agency's (U.S. EPA's) IndoorAirPLUS program, also for new construction, includes specifications for addressing moisture and radon control, pest control, and combustion appliance inspections, as well as for 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 particulate matter with a diameter of 2.5 microns of less (PM2.5), PM10, ozone, carbon monoxide (CO), TVOC and targeted volatile organic compounds (VOCs).

For existing homes, U.S. 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 (for example, 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 provides 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

Carbon Dioxide as an Indoor Air Quality Metric: Demand-Controlled Ventilation

Demand-controlled ventilation (DCV) systems have been used for many years in commercial heating, ventilation, and air conditioning (HVAC) systems for controlling comfort and air quality associated with occupancy. For these systems, measured CO₂ is used as an indicator of occupancy and, quantitatively, of human bioeffluents. When the measured CO₂ 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 CO₂ levels as a metric representing occupancy (and bioeffluent emissions) is less applicable to residential applications for the following reasons:

- Occupant densities are much lower and the available CO₂ signal is much harder to discern from background concentrations. This makes CO₂ much harder to use as an occupancy indicator and a control parameter for operating the ventilation system.
- Due to the proportionally lower source strengths, there can also be considerable delays between initiation of occupancy and CO₂ levels reaching the control limit for operation of ventilation system.

- Lower occupancy densities and a larger range of activities mean that occupants are no longer the primary source of pollutants (and thus CO₂ is a less meaningful indicator) that we want to control. A primary example of this is the emissions from building products and materials.
- The nature and degree of air mixing can be quite different in residential buildings.

Despite these drawbacks, CO₂ 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 CO₂ and/or RH. For example, French regulations use a limit of hourly average CO₂ concentrations of 2000 parts per million (ppm). Each hour above this limit is weighted by the CO₂ concentration for that hour. These products are summed for the year and cannot exceed 400,000 parts per million per hour (ppm-h). For RH the limit is set at an hourly average of 75 percent, and the number of allowable hours above this limit is set at 600 hours in kitchens, 1,000 hours in bathrooms, and 100 hours in other rooms Both these requirements must be met. Note that the RH regulation is a multizone 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, that is, 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 to the extent that it is evaluated only during times of occupancy. This equivalency approach can also be used with time-varying emission rates, (for example, 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 allow 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 temperaturecontrolled 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.

International Energy Agency – Energy in Buildings and Communities, 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 these results, 16 target pollutants were selected as potential short-term and longterm exposure risks in low-energy residential buildings: acetaldehyde, acrolein, a-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 16 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 the 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 Indoor Air Quality

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, NO₂, 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 (such as 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 than 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 U.S. (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, and so forth) 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.

Indoor Air Quality Score — Example Metric

One metric this study investigated is the idea of a home IAQ Score that is also being developed by LBNL for the U.S. DOE Building America Program. Home energy scores have provided an important tool in the market-place for assessing a building's energy performance. Energy scores have enabled 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 enable 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 U.S. 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 affect the score in several ways. First, they are evaluated for their potential effectiveness for on each hazard — that is, the level of 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. The strategies are then assessed for their effectiveness. For example, an 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 required 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 it might receive an IAQ score, appraisers from California, Colorado, Florida, and Kentucky were interviewed. 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, U.S. EPA, U.S. DOE 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) use three well-established methods of valuation, often used in tandem or in combination.

- 1. 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.
- 2. 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 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.
- 3. The cost basis method 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 five-year memorandum of understanding, the U.S. DOE has collaborated with The Appraisal Foundation 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.

In recent work for DOE (Mills 2015), the project team 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, "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, signs of moisture damage, and so forth). 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.

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

Getting scores into the multiple listing service (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 (children and individuals with allergies or asthma). 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 to flag certain thresholds (for example, scores 80 and above) as thresholds of acceptability for certain sensitive populations.

CHAPTER 4: Single-Zone Smart Ventilation Controls

The following is a summary of the most important details in Appendix B to this report that discusses the single-zone smart ventilation work.

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 (Sherman, Mortensen, and Walker 2011; Sherman, Walker, and 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 (for example, deposition, filtration, and so forth). The metric compares the concentration of that pollutant under time-varying versus continuous ventilation schemes. Over short time periods (that is, about the time needed to replace all the air in the building), a relative exposure of one means the two ventilation rates are equal. Averaged over longer periods (for example, annually), a value of one 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 five minutes. Annually, the arithmetic mean of the relative exposure during occupied hours must be less than or equal to one 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."

This study reports two different relative exposure values, which 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 envelope 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 five minutes, which aligns with the overall simulation time step of five minutes. The smart ventilation control 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 project team 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. 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. The team 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.

To allow for time-varying ventilation fan capacities must exceed the minimum code requirements because they must 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."

Smart Control Descriptions

The smart control approaches are summarized in Table 1.

Simulation Approach and 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. The project team created detailed models of two prototype homes: a one-story 2,100 square foot (ft²) prototype home and a two-story 2,700 ft² prototype home, with forced-air space conditioning systems. The HVAC was sized using Air Conditioning Contractors of America Manual J load calculation procedures, with thermostat schedules set to meet those specified in the 2016 alternative calculation manual (ACM) The ventilation systems are compliant with ASHRAE 62.2-2016 that includes infiltration credits and sub-additivity adjustment for unbalanced exhausts. Exhaust systems were used as the reference as they are by far the most popular method of complying with ventilation requirements in the state.

Several deliberate deviations were made from the Title 24 prescriptive path prototypes; the study did not include whole house economizer fans that are present in the prototype homes, and it improved the HVAC equipment efficiencies. The project team did not model any duct leakage because advanced homes were modeled with ducting assumed to be within conditioned space, consistent with Title-24 2016 prescriptive path option C.

Table 1: Summary of Single-Zone Smart Control Strategies

Control	Description
Name	
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 (four, six, and eight hours) are pre-calculated using weather files. Fans are oversized to run continuously outside of lockout hours to ensure daily exposure equal to or less than 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 equal to or less than 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 equal to or less than 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 equal to or less than 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: Fan off when unoccupied Fan at 35 percent flow when unoccupied Pre-ventilate the home one 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 run time and overall ventilation rates. This controller was added onto each of the other control types to assess combined control performance.

Source: Lawrence Berkeley National Laboratory

The study did not include automatic window controls for optimizing ventilation cooling. Equipment efficiency was increased beyond prescriptive minimums to seasonal energy efficiency rating (SEER) 16 A/C and 92 annual fuel utilization efficiency (AFUE) gas furnaces to align with standard new construction practice encountered in HENGH field study and based on Technical Advisory Committee feedback. The project team used three envelope leakage levels — one, three, and five ACH₅₀ — to represent a range of new construction airtightness. For the tight one ACH₅₀ home, the ventilation system that was controlled using the study's smart ventilation strategies was a balanced system; for the other homes a simple exhaust fan was used.

The project team selected climate zones that represent 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.

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. (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 2:00 to 6:00 p.m. 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 statewide estimates of energy savings, nor does it identify which controllers are best optimized for statewide use. Instead, the report provides 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, used parameters pre-calculated using an optimization routine, and reduced weighted average site ventilation energy use by 31 percent – 39 percent (370 – 465 kilowatt-hours per year [kWh/year]; 8 percent – 11 percent of whole house HVAC energy), while TDV weighted average ventilation energy reductions were higher, at 31 percent – 64 percent (1,235 – 2,654 kWh/year; 5 percent – 10 percent 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 (that is, kitchen, bathroom, and dryer exhausts) sensing increased site energy savings in all cases, from roughly 5 percent to 15 percent, with smaller increases in the highest performing control cases. This procedure increased the average non-normalized site ventilation savings for the best control types to a range between 40 percent and 48 percent (TDV ventilation savings between 40 percent and 65 percent). More than 90 percent 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 2:00 to 6:00 p.m. period on the hottest days of the year was reduced through use of the smart controls, with peak load reductions of 0 - 400 watts. The project team believes that specific peak controls could achieve even greater reductions in demand. The vast majority of site energy savings were for heating end uses (greater than 90 percent 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 10 percent (improved IAQ), but they increased peak exposure to the occupants, with some controls having much higher peaks than others.





Source: Lawrence Berkeley National Laboratory

Smart ventilation and baseline constant fan cases did not provide the same IAQ because the project team chose control strategies to be slightly conservative — that is, to provide a reduction in exposure in almost all cases. Figure 3 illustrates the reductions in exposure for each controller showing that typical reductions were about 5 percent – 10 percent.

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 48 percent – 55 percent (561– 651 kWh/year; 13 percent – 15 percent whole house HVAC savings), and TDV ventilation savings from 46 percent – 72 percent (1900 – 2950 kWh/year; 7 percent – 11 percent whole house HVAC TDV savings). More than 90 percent of site energy savings were for heating end uses, while TDV energy savings were split fairly evenly between heating and cooling.



Figure 3: Reduction in Real Relative Exposure

Source: Lawrence Berkeley National Laboratory

The best overall controllers used seasonal shifting of ventilation. To illustrate this, 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.

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 one-hour pre-occupancy flush out period, though savings were still marginal compared to temperature-based controls.

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, and it is not recommended that the state adopt air tightness requirements.

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 none of the currently available products actually ensure compliance with the ASHRAE ventilation standard. More work is required to allow builders and designers to take credit for smart ventilation control strategies in demonstrating compliance with California's Title 24 Building Energy Efficiency Standard. 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.

Figure 4: Controller Relative Exposure for VarQ Controller



Source: Lawrence Berkeley National Laboratory

CHAPTER 5: Multizone and Contaminant-Controlled Smart Ventilation

The following is a summary of Appendix C, a detailed report discussing the multizone and contaminant-controlled smart ventilation work, highlighting 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 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, a ventilation system could be controlled to ventilate only 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 standard (CAN/CSA, 2010) requires a supply of 10 L/s in master bedrooms and 5 L/s in 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).

Method

The 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 one-story CEC single-family prototype dwelling and a single apartment unit from the CEC multi-family prototype buildings were simulated. The assessment looked at relatively tight envelopes of 0.6, 2, and 3 ACH₅₀ 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. Two different heating and cooling approaches were analyzed: central forced-air with a minimum efficiency reporting value (MERV) 13 particle filter (as required by 2019 Title 24) that tends to mix air between zones, and distributed systems with no filtration and much less distribution between zones. The apartment dwellings were simulated only at one envelope leakage level — three ACH₅₀ — 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. This division allowed the project team to account for the major difference in locations for pollutant emissions (moisture mostly in wet rooms — kitchens and bathrooms — 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:

- Central exhaust located in other zone
- 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.
- Balanced system, with exhaust flows from kitchen and bathroom zones, and supply flows (with MERV 13 filtration) to other and bedroom zones

The zoned systems were:

- Exhaust fans located in each zone of the dwelling, controlled independently.
- Supply fans located in each zone of the dwelling, controlled independently.
- Balanced supply/exhaust systems located in each zone of the dwelling. Note, this differs from current ducted systems, which were balanced for the home, but not for each zone in the home. This system was balanced in each zone.
- Central exhaust with controlled inlets in each zone.

Whole-house target and mechanical fan airflows were calculated using the ASHRAE 62.2-2016 ventilation standard, and these whole-house flows were divided among 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 Efficiency Standard. This weighting approach represents the project team's 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 among 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 used the real-time generic contaminant concentration predicted in each zone by CONTAM, and compared 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

reference exposure level is 7 parts per billion (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, the particle removal mechanisms include filters in mechanical systems, interior deposition, and, for outdoor particles, filtration by the building envelope.

Outdoor contaminant levels were assumed to be a constant 400 ppm for CO₂, used weather data for moisture, used U.S. EPA ambient sample data for hourly particle levels, and a fixed 3 ppb for formaldehyde.

Smart Control Descriptions

A key aspect of zonal ventilation control is knowing which zones are occupied. All zonal controllers used the zone occupancy as a key control input. A typical nine-hour workday/school day absence from 8:00 a.m. to 5:00 p.m. Monday through Friday, with continuous weekend occupancy was assumed. A fixed schedule of occupants moving among rooms at different times of day was imposed, together with scripting their activities within the zones (for example, 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 multizone. As with the single zone, 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 air flow. Instead, they change which zone the air is supplied to or exhausted from based on 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 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.
 - o cocupantTracker This is the same as the supply tracker, but also includes exhaust air, to the extent 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. These controls used measured outdoor temperatures to shift ventilation flows to mild weather periods.
 - 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 twozone dwelling using assumed occupancy patterns. This approach can decrease annual ventilation flow.
- Zone Occupancy Controls. Unlike the previous tracker controls, these controls apportion the whole-dwelling flow to each zone and then vent only occupied zones, and only apply to multipoint zoned systems. This reduced annual ventilation airflow for the dwelling. Controls used 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.
 - o cocupantVenter 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. This controller used actual contaminant concentrations in each zone and ventilated when they exceed health-relevant thresholds. These controls apply to all multi-point zoned systems.
 - 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 Ventilation rate and air inlets are used to increase ventilation when indoor humidity is high.

Results for Multizone and Contaminant-Controlled Ventilation

Direct Contaminant Control

Using measured contaminant concentrations led to consistently increased ventilation rates in the dwellings to meet the California OEHHA formaldehyde 24-hour target of 9 micrograms per cubic meter (μ g/m³). None succeeded in meeting the limit, though the increased ventilation reduced personal exposures to the generic contaminant, formaldehyde, and CO₂. 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.

HVAC System Type

Two HVAC system types were simulated in this work: ductless mini-split heat pumps that control temperatures by zone, and central forced-air heat pumps that mix air in the dwelling and do not allow for thermal zoning. The results showed that the type of HVAC system had very little impact on personal pollutant exposures, largely due to the small amount of air moved to condition these efficient homes. The central forced-air systems had higher median annual energy use of 1660 kWh compared to 1450 kWh for the mini-split systems. This is due to approximately equal parts of improved Variable Refrigerant Flow (VRF) system efficiency and to air handler energy use.

Ventilation System Type

The selection of ventilation system changes the ability to zonally ventilate, as well as the energy and IAQ performance of baseline and smart control cases. A key issue is that outdoor particles were included in this analysis, which led to increased personal exposure for zoned systems because they more effectively deliver outdoor air to the occupants, including outdoor pollution. This needs to be balanced against reductions in internally generated contaminants in future analyses.

- Exhaust fans behave the least zonally and have little impact on personal exposure through being zoned, with the exception of CO₂. Exhaust fans have the lowest energy use, but the percent ventilation energy savings were often the greatest for controls that shifted ventilation to milder weather periods. The whole dwelling ventilation rates and personal exposures provided by exhaust fans lies between supply and balanced fan types.
- Supply fans are highly capable of providing zonally directed outside airflow, and reduce personal pollutant exposures for the generic contaminant, formaldehyde and CO₂. 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 outdoor temperature-based control types that increased annual outside airflow.

Balanced fans were similarly capable of zonally directed outside airflow, and they
provided the highest dwelling ventilation rates, lowest exposures, and highest annual
HVAC energy use. 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 increased annual flows.

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

The results showed significant differences in energy impacts between a one-story single-family home and an apartment. Smart controls were not able to effectively reduce HVAC energy use in the apartment dwellings, whereas the one-story cases showed a consistent ability to save energy. This is because the apartments had small heating loads and their annual HVAC energy use was dominated by cooling. The mechanical ventilation of the apartments provided ventilation cooling for most of the year, in most climates, to the extent that reducing ventilation rates did not save energy; instead, energy use was increased to offset the loss of "free" ventilation cooling.

Apartment units had overall higher ventilation rates than the one-story dwellings (0.41 vs. 0.31 hr^{-1}), due to their smaller volumes, higher occupancy density, and the sizing calculations used for multifamily fans in 62.2-2016, which do not allow reductions for infiltration. The higher ventilation rates led to reduced personal exposures in apartments for the generic contaminant and formaldehyde (which were emitted proportional to floor area). However, apartments had increased exposure to particles and CO₂ compared to one-story dwellings due to higher occupant density. While smart controls did not effectively save energy in apartments, they were able to improve IAQ by targeting outside airflows to occupied zones. These IAQ improvements were generally greater in apartments than in one-story dwellings for the same control type. The results showed that these effects varied substantially by fan type and contaminant of interest and that it may be possible to allow for energy savings in building energy codes in some restricted cases for apartments.

These results imply that consideration of energy savings for smart ventilation should definitely distinguish between single-family and multifamily dwellings.

Envelope Leakage

This study focused on dwellings substantially more airtight than typical new California construction. Combined with the adjustments for natural infiltration in ASHRAE 62.2, this resulted in very little variability in overall air exchange rate. Across all one-story cases, the mean infiltration rates were 0.316, 0.318, and 0.324 hr⁻¹ for the 0.6, 2, and 3 ACH₅₀ cases, respectively. This resulted in envelope leakage rates having very little impact on pollutant exposures, energy use, and energy savings from controllers. The sole exception was for particles, where the leakier dwellings with higher ventilation rates had increased personal exposures from outdoor particles brought indoors. This result implies that, as long as dwellings meet a reasonable three ACH₅₀ maximum leakage limit, credits for smart ventilation do not need to be scaled with measured envelope leakage.

Climate Zone

The outdoor pollution varied for each climate zone only for particles. The outdoor formaldehyde and CO₂ were the same for all climates. The climate had substantial impacts on personal pollutant exposures, with CZ16 showing the highest average personal exposures for the generic contaminant, CO₂, and particles, while having by far the lowest formaldehyde exposures. This is because formaldehyde emission rates depend strongly on indoor relative humidity, and the dry CZ16 had lower emission rates. 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. For example, the best energy savings strategy (varQmz) saved 60 percent in CZ16 but only 27 percent 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 results showed that for most contaminants, treating each zone independently worsened personal exposure in one-story dwellings, and this approach increased ventilation energy savings in these dwellings. The worsened personal exposure and small increase in energy savings are not justifiable, so the project team would recommend that zonal smart ventilation systems use fewer, rather than more zones, which should reduce system costs and complexity.

Multizone and Contaminant Control Summary

Figure 5 shows the results for energy savings and changes in personal exposure to the generic contaminant for all the multizone controllers. This shows how almost all the controllers were not useful in saving energy or reducing exposure, with the exception of controllers that change ventilation seasonally. Most controllers either use more energy or have higher relative exposure. Figure 6 summarizes the small changes in exposure to individual contaminant changes with the ventilation system type and whether the system is zoned (multipoint) or not (single point), and how these tight dwellings with mechanical ventilation have only a narrow range of ventilation rates.

The Aereco RH controller did not significantly change the contaminant exposures or energy use. As with other controllers in the apartment simulations, in spite of the reduction in ventilation compared to the base case in CZ16 (0.41 to 0.24) ACH and a corresponding 120-kWh savings for heating, the very low envelope heating loads were offset by an increase in cooling energy due to reduced ventilation cooling. In the future the project team will evaluate this controller for the one-story prototype where the energy use is less like a passively heated dwelling.

The multizone results have generally shown that zoning itself is not likely to yield significant improvements over single-zone approaches. The ability to target individual zones for ventilation is offset by the introduction of outdoor particles and the need to account for contaminants generated independently of occupancy (for example, formaldehyde). Contaminant control approaches are completely dominated by the difficulty in achieving the OEHHA limit for formaldehyde. This study's systems ventilated at their maximum flow rates and still did not achieve the 9 μ g/m³ OEHHA limit and also doubled ventilation energy use.





Source: Lawrence Berkeley National Laboratory



Figure 6: Ventilation Rate and Personal Contaminant Exposures for Each Fan Type and Zoning Type

Source: Lawrence Berkeley National Laboratory

CHAPTER 6: Technology/Knowledge/Market Transfer Activities

The project team engaged in a combination of activities to inform stakeholders and the public about the project.

Smart Ventilation for Advanced California Homes Website

The project team created website (<u>http://SVACH.lbl.gov</u>) 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 temperaturebased smart ventilation control strategies in advanced California homes. *Energy and Buildings*. <u>https://doi.org/10.1016/j.enbuild.2019.04.028</u>
- 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. <u>https://doi.org/10.1016/j.enbuild.2017.12.051</u>
- Guyot, G., Sherman, M.H. and Walker, I.S. (2018). Performance based approaches for smart ventilation in residential buildings. *International Journal of Ventilation*. <u>https://doi.org/10.1080/14733315.2018.1435025</u>
- 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.

Team members gave presentations for this project at Air Infiltration and Ventilation Centre workshops and the following conferences: Home Performance Coalition, RESNET, Indoor Air, and ASHRAE. Team members have spoken with many ventilation equipment manufacturers at

the trade shows associated with these conferences, and consequently 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 U.S. DOE co-funding of this project, the team 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 indooroutdoor 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, system pressures or fan energy use in such a way that system failures can be detected and repaired, or when system components need maintenance, such as filter replacement."

Technical Advisory Committee

The technical advisory committee (TAC) was chosen specifically to be a major part of the technology and 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 U.S. 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 Building Energy Efficiency Standards compliance software (CBECC Res); the best way to group rooms into zones for zonal control; ensuring that controls meet acute exposure limits as well as address long-term chronic exposure; discussing how systems might be certified for a product directory; and 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 Building Energy Efficiency Standards 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: Benefits to California Ratepayers

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 we need to minimize the energy impact of this mechanical ventilation. This project addresses these issues by developing smart ventilation approaches that are important to ratepayers because they:

- 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.
- 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 370–465 kWh/year or about 8–11% of whole house HVAC energy. In TDV this is increased to about 1,200–2,600 kWh/year. These savings can be significantly increased by sensing operation of other fans (kitchen/bath/laundry exhaust and economizers).
- Enable peak demand reductions of about 400W for a period of 2 hours that help to ensure grid reliability at peak times. This is a greater contribution than other grid-responsive technologies, such as refrigerator modulation, or control of other appliances such as dishwashers and washing machines. Moreover, it comes at no penalty or 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.
- 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 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.

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.

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.

CHAPTER 7: Conclusions and Recommendations

Title 24 Next Steps

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

One option would be to incorporate the ability to model dynamic ventilation systems and relative exposure into CBECC-Res, or to 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 this project's work. This is also the only way to provide adequate market flexibility for future changes to control schemas by manufacturers, new code requirements, and other factors.

Another option is to use third-party compliance verification where a particular smart ventilation control approach is simulated using agreed-upon assumptions and scenarios. Any control that met a set energy reduction requirement would be allowed to use this reduction in compliance calculations. The CEC would also need to develop requirements or guidelines for manufacturers to use in demonstrating the compliance of their systems with state Building Energy Efficiency Standards requirements. This would include which housing types to model, ventilation system types, climate regions, and other such variables.

Notably, the reference case in this project's 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 using the measured envelope airtightness of the home as an input to the calculations, the envelope airtightness is fixed at two ACH₅₀ for all homes (homes that are tested below two ACH₅₀ must use the lower number and increase the required fan size).Overall, this will increase the baseline fan sizes compared with this project's 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. The project team suggests that this be fixed in ASHRAE 62.2 itself, but absent that, the CEC could consider amending the calculation procedures used in California. Specifically, the project team would recommend the equation used to estimate whole house airflow for exposure calculations in Normative Appendix C of the ASHRAE standard be changed so that it is an identity (that is, the same forwards-backwards) with the fan sizing equation as outlined in Appendix B of this final report.

Indoor Air Quality Metrics

For IAQ to have greater value in the buildings industry, it is necessary to to go beyond simply specifying air flows and develop metrics and scoring systems that builders and the real estate industry can use. 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 (for example, children, individuals with allergies and/or asthma). 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 to flag certain thresholds of acceptability (for example, scores of 80 and higher) for certain sensitive populations.

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 for an optimization routine. Controls of this nature reduced weighted average site ventilation energy use by 31 - 39 percent (370 - 465 kWh/year; 8 - 11 percent of whole house HVAC energy), while TDV weighted average ventilation energy reductions were higher, at 31 - 64 percent (1,235 - 2,654 kWh/year; 5 - 10 percent of whole house TDV HVAC energy). Auxiliary fan sensing (that is, kitchen, bathroom, and dryer exhausts) increased site energy savings in all cases, from roughly 5 to 15 percent, with smaller increases in the highest performing control cases. This procedure increased the average non-normalized site ventilation savings for the best control types to a range between 40 and 48 percent (TDV ventilation savings between 40 and 65 percent). More than 90 percent 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 2:00 p.m. – 6:00 p.m. period on the hottest days of the year was reduced through use of the smart controls, with peak load reductions of 0 - 400 watts. The project team believes 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 in all previous occupancy-based controls, the project team 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 limits the benefits of air sealing, and the project team would not recommend that the state adopt air tightness requirements.

Current products available for \$150 to \$300 on the consumer market have the core hardware capabilities to act as smart ventilation controls, but none of the currently available products actually ensure compliance with the ASHRAE ventilation standard and Title 24.

Zonal Smart Ventilation and Contaminant Controls

The multizone results have generally shown that zoning itself is not likely to yield significant improvements over single-zone approaches. The ability to target individual zones for ventilation is offset by the introduction of outdoor particles and the need to account for contaminants generated independently of occupancy (for example, formaldehyde). Typically, zonal controls and zonal ventilation systems resulted in mixed effects for different pollutant types, often increasing exposure to some types and reducing exposures to others. Because no current framework or metric exists to integrate these effects, the project team cannot determine the overall IAQ or health effects of the various changes. Without these metrics, controls cannot be designed to satisfy these overarching health or IAQ goals. The smart ventilation control tested in the zonal simulation models that both saved energy and provided consistent equivalent IAQ across all contaminant types was the same as the best-performing single-zone temperature-based smart control that shifts ventilation between seasons. That control provided average site ventilation savings between 45 and 53 percent in most California climate regions (63 to 93 percent average TDV ventilation savings), which makes it nearly as effective as most heat recovery ventilators. The zonal controls offered some additional energy savings potential, but they consistently compromised IAQ for at least one contaminant. Further, the ability of homes to be effectively zoned from an IAQ perspective is limited by the 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. 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 μ g/m³ OEHHA limit and also doubled ventilation energy use.

The simulation of advanced homes led to results that could be somewhat counter-intuitive. The greatest example of this is the apartment building that had very little heating or cooling load from the envelope. The apartments were dominated by internal loads where the ventilation flows provided ventilation cooling for much of the year, even in Climate Zone 16. In this particular case, reducing ventilation air flows (which was the aim of many of the controls) reduced this ventilation cooling to the extent 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. The project team plans to further investigate some of these controls in future work on more typical existing homes, where the team expects them to deliver improved energy savings.

Future Work

More work is required to allow builders and designers to take credit for smart ventilation control strategies in demonstrating compliance with California's Title 24 Building Energy Efficiency Standards. 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.

One focus of this work was 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. This study found that including outdoor particles can have a significant effect on IAQ and ventilation system performance. 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.

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 nitrogen dioxide.

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

LIST OF ACRONYMS

Term	Definition
ACH50	Air Changes per Hour at 50 Pa
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
m ³ /h	cubic meters per hour
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
ppb	parts per billion
ppm	parts per million
RESNET	Residential Energy Services Network
RH	Relative Humidity
TAC	Technical Advisory Committee
TDV	Tine Dependent Valuation
TRV	Toxicity Reference Value
TVOC	Total Volatile Organic Compounds
US DOE	US Department of Energy
VRF	Variable Refrigerant Flow
WHO	World Health Organization
ZNE	Zero Net Energy
µg/m³	micrograms per cubic meter

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APPENDICES

The following appendices are available under separate cover (Publication Number CEC-500-2020-050-APA-C) by contacting Susan Wilhelm at <u>Susan.Wilhelm@energy.ca.gov</u>.

- Appendix A: Valuing IAQ in the Marketplace: Metrics and Appraisals
- Appendix B: Smart Ventilation for Advanced California Homes Single Zone Technology
- Appendix C: Multi-Zone Smart Ventilation Controls