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FINAL PROJECT REPORT

RESIDENTIAL ENERGY SAVINGS FROM AIR TIGHTNESS AND VENTILATION EXCELLENCE (RESAVE)

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PREFACE

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Residential Energy Savings from Air-Tightness and Ventilation Excellence (RESAVE) is the final report for the RESAVE project (contract number 500-08-061) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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ABSTRACT

The research objective of the Residential Energy Savings from Air-Tightness and Ventilation Excellence program was to advance the state of the art in California to a “Build Tight, Ventilate Right” paradigm. The program evaluated the air-tightness, contaminant exposure and ventilation systems of residences using field research, simulation and data analysis.

The research results included three key findings:

The annual health impact of chronic exposure to indoor air for California was \$15–\$40 billion annually. Good ventilation was a major way to reduce that cost, but air cleaning and source control options may be more cost-effective and/or energy efficient. Particle filtration was the most promising area and needs to be further examined.

Complying with Title 24 ventilation requirements for the California housing stock and tightening residential envelopes could decrease residential energy demand by up to 25,000 gigawatt-hours annually. The vast majority (72 percent) of that reduction could be achieved by tightening to the International Energy Conservation Code residential air-tightness standard. Tightness beyond that would be subject to decreasing returns, but more research is necessary to determine the appropriate amount of energy to allocate to air-tightness and to recommend optimal systems.

Combining energy costs and monetized indoor air quality allowed for overall optimization to determine the total operating costs (including both energy and health) to consumers. Current ventilation rates were optimal for low-emitting houses as defined by the California New Homes Study emission levels, but consumers would benefit from increased ventilation rates in higher-emitting households. This work demonstrated the technique for measuring these factors, but it was not yet fully developed because it did not account for several other contaminants known to be important such as fine particulates and because the results have not been replicated across the population of California homes.

Keywords: residential, energy savings, air tightness, ventilation, infiltration, envelope leakage, sustainability, indoor air quality, health impacts

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EXECUTIVE SUMMARY

Introduction

The buildings sector has an important role to play as California looks to reduce its carbon footprint. Increasing energy efficiency for both new and existing homes is a key part of any strategy for reducing fossil fuel consumption. California regulations and incentive programs continue to make strides at changing the industry.

Air sealing and air-tight construction have been proven to be able to provide substantial energy reductions. A key barrier to implementation of these approaches is the impact that they would have on indoor air quality (IAQ). Mechanical ventilation is currently required in Title 24 and can provide acceptable IAQ, but at an energy cost. Research is needed to optimize the solution to these twin problems. This issue is recognized broadly at the national and international level.

Project Purpose

The California Energy Commission funded the multi-project Residential Energy Savings from Air-Tightness and Ventilation Excellence (RESAVE) program to focus on residential energy savings, air-tightness and ventilation excellence for California homes. RESAVE's overall goal was to facilitate the substantial reduction of energy and peak power spent in homes to condition air that enters from outdoors.

The program was intended to facilitate the "Built Tight, Ventilate Right" strategy, which implies a process of first constructing a high-quality building with low leakage and low source emissions indoors and then installing the most efficient ventilation system to provide acceptable indoor air quality that ensures health and comfort.

Infiltration and ventilation are responsible for one-third to one-half of the space- conditioning load, but are often underappreciated by occupants because it is difficult to notice air losses. They cannot be arbitrarily reduced below a level that supplies acceptable indoor air quality, however, without providing mechanical ventilation or some other mechanism for doing so.

RESAVE was designed to address two issues: (1) to reduce direct losses from infiltration while controlling key emission sources; and (2) to find the most energy-efficient methods available to supply the needed whole-house ventilation. The "Built Tight, Ventilate Right" strategy generally is accepted as the best approach for building high-quality homes, but it is not easy to implement without strong technical backup and appropriate standards to follow.

Project Results

The RESAVE program in cooperation with the United States Department of Energy, the United States Environmental Protection Agency, and the United States Department of Housing and Urban Development devised a mechanism to monetize indoor air quality. This mechanism has been published in peer-reviewed journals and was based on existing scientific principles and published data.

Researchers estimated that the annual health impact of pollutants in residential indoor air was $400 to $1,100 per person. Annual health impacts of chronic exposure to the pollutants in residential indoor air was $15 to $40 billion annually for California. Good ventilation was a primary strategy to reduce that cost, but air cleaning and source control options may be more cost-effective or provide lower energy solutions. Particle filtration appeared to be especially promising and deserving of further examination.

Complying with Title 24 ventilation requirements such as the ASHRAE 62.2 standard for the entire California housing stock was projected to increase residential site energy by 2,600 gigawatt-hours (GWh) annually at current building envelope air leakage levels, compared with not ventilating at all. Tightening residential envelopes had the potential to decrease residential energy demand by as much as 25,000 GWh annually and the vast majority of that reduction (72 percent) could be achieved by tightening to the International Energy Conservation Code residential air-tightness standard. Tightness beyond that standard would be subject to decreasing returns, but more research was necessary to determine the best range for air-tightness and to recommend optimal systems. Currently Title 24 does not have a specific requirement for home leakage although it does require measures to reduce leakage such as caulking around fenestrations (openings in outside walls such as windows). Title 24 does have default leakage value from which savings can be claimed, but that default is substantially leakier than the International Energy Conservation Code levels. There were opportunities to reduce peak power in addition to overall energy savings. Up to 30 percent of the peak space-conditioning load could be reduced using smart ventilation controls.

This research allowed indoor air quality to be monetized by determining a monetary value of exposures to contaminates in terms of occupant health. Monetizing indoor air quality allowed these costs to be combined with energy costs so that the total consumer operating costs of optimizing both energy use and indoor air quality could be identified.

The RESAVE program developed the procedure to do so using a vetted methodology to monetize health impacts. It conducted a preliminary demonstration based on prototype California homes and typical volatile organic compound emissions to show that current mechanical ventilation rates were optimal for low-emitting houses (from the California New Homes Study emission levels) but that consumers would benefit from increased ventilation rates in higher-emitting households. This demonstration illustrated the technique but it was not yet fully developed because it did not account for several other contaminants known to be important (such as particles at or below 2.5 microns) and the result had not been demonstrated across the varied population of California homes.

The RESAVE program also worked on several research areas that produced stand-alone results: air leakage, the Residential Integrated Ventilation Energy Controller and a ventilation guide.

Researchers believed there was a potential for large energy savings by minimizing air leakage through the building envelope in California residences. Infiltration was attributed to air leakage and typically accounted for one-third to one-half of the energy used for residential space conditioning in the existing home stock. The air-tightness of new homes being built in California has improved over the years, but the lack of representative air leakage data on California and United States homes made is difficult to evaluate trends and retrofit improvements. The air leakage test for a single-zone space such as a detached house was well established, but there was no consensus on the preferred approach for measuring air leakage in multizone spaces such as a house with an attached garage. An evaluation of air leakage test methods for multizone spaces will also benefit retrofit programs in multifamily homes to more reliably measure the improvements in air-tightness.

The RESAVE program gathered a great deal of measured air leakage data from a wide variety of contributors in California and the United States (U.S.) and compiled them into a database. These data were used to characterize the air-tightness of the housing stock in California and the United States and to determine attributes (such as climate zones, dwelling size, and year built) that were useful for explaining the variability in the air-tightness of homes. The resulting statistical model estimated the building envelope air leakage based on user inputs of house attributes and was available online. It has proven useful to practitioners and researchers and a similar capability was being incorporated into Home Energy Saver (http://hes.lbl.gov). RESAVE also estimated the potential energy savings if the air-tightness of homes in California and the United States were to improve to different levels by measures such as air-sealing. The estimated energy saving would be 0.7 quad annually if all U.S. homes were retrofitted for improved tightness, which was nearly one percent of the total U.S. energy demand.

The RESAVE program also identified a preferred method for measuring air leakage in multizone spaces that measured inter-zonal and to-outside air leakages more accurately than other methods. This method will be able to quantify the energy savings and indoor air quality benefits in multifamily retrofits as a result of reducing air infiltration and air exchange between dwelling units once it is further developed.

RESAVE also collected some ad-hoc data on duct system air leakage. Retrofit programs will typically address both sources of air leakages, but different programs might put more focus on one over the other due to practical reasons of costs, time or other factors. More data on duct system air leakage need to be collected to evaluate the combined energy savings. A more comprehensive dataset will support the analysis of energy saving potentials as well as the indoor air quality impacts of retrofitting California homes. The program's analysis of air leakage data suggested that the air-tightness of homes was not constant but rather tended to decline as the homes age. Energy could be saved by targeting homes of a certain age for air-sealing to reduce energy loss through air leakage if the results of this analysis are proved.

Multifamily homes accounted for 30 percent of the residential energy demand in California. Energy loss through a leaky building envelope or an ineffective air distribution system in these buildings can be important. RESAVE identified several viable approaches of measuring air leakage in multizone spaces, but mostly the analysis focused on single-family houses with an attached garage. More air leakage data need to be collected from multifamily homes. Currently, there is no performance credit in Title 24 for air leakage testing in multifamily homes. The ultimate goal of this work was to either establish a testing method capable of generating the data needed for obtaining credits or suggest alternative incentives to promote air-tightness in multifamily homes. The work done by RESAVE took important steps toward achieving those goals.

Typical residential ventilation systems provide the same ventilation each hour of the day. The system's energy use changes over the course of the day in response to larger indoor-outdoor temperature differences. The system may also do less to improve indoor air quality, depending on the pollutants (such as ozone) present in outdoor air. Currently, there is no automated mechanism to vary ventilation rates to account for this variability in the cost and efficacy of mechanical ventilation. Lawrence Berkeley National Laboratory (LBNL) previously developed and patented the Residential Integrated Ventilation Energy Controller (RIVEC) to provide acceptable indoor air quality and lower the cost of ventilation in order to address this issue. RIVEC is a smart ventilation controller that can manage a mechanical ventilation system to optimize peak load, energy, and indoor air quality, thus saving the user money and improving indoor air quality consistent with the intent of Title 24 2008 ventilation requirements. It uses the principle of equivalent ventilation to ensure that a variable ventilation rate results in the same or better (i.e., less) exposure to pollutants as a continuous ventilation system that complies with Title 24 2008.

The performance potential of RIVEC was demonstrated by simulations. The results showed that it can: (1) save 20 to 70 percent of the annual energy used to provide and condition ventilation air (or about 10 to 25 percent of the total space conditioning load); (2) reduce 100 percent of the four-hour peak electrical load associated with providing and conditioning ventilation air; and (3) time-shift ventilation away from periods of poor outdoor air quality such as those experienced in ozone nonattainment areas. The next steps for RIVEC were to find a commercialization partner and to further develop its algorithm to include occupant and contaminant sensing to further optimize energy use and indoor air quality. Incorporating this type of technology into Title 24 would result in energy savings but requires some changes to the code or action by the Commission to implement.

Houses have become more energy efficient over the past twenty years but they have also become much tighter and the indoor air quality has suffered. Much research and industry input has led to the development of consensus-based ventilation standards such as Title 24 and ASHRAE Standard 62.2. Mechanical ventilation requirements are complicated and relatively new in California. Designers, contractors, and installers do not have ready sources of information on how to meet ventilation requirements or how to optimize the choices. LBNL through the RESAVE program began to create an authoritative tool to provide optimal ventilation solutions for California homes to address this issue. These ventilation solutions included low-income weatherization, energy upgrades or new construction. State-of-the-art knowledge was assembled into an online guide to ventilation for existing California homes.

The information was vetted by Californian and national experts, including academics, practitioners and industry members. It reflected the state of the art in compliance with California Title 24 and the only national residential standard (ASHRAE 62.2). The information reflected the requirements of ASHRAE 62.2-2007 as adopted by the California Energy Commission in the 2008 Title 24 Energy Code. It also reflected the hybrid version of ASHRAE 62.2-2010 with the 2011 Supplement changes and two 2012 addenda (Addendum j and Addendum n) as adopted by the Energy Commission for the 2013 Title 24 Energy Code. This information was published as a website (http://resaveguide.lbl.gov/) so that it could be easily accessed and updated. The next steps will be to promulgate the availability of the website to appropriate user groups in California and to revise it regularly to keep the information current. It will be important to revise the information to be consistent with Title 24-2013 as final documentation is developed and disseminated.

Project Benefits

This program evaluated the air-tightness, contaminant exposure and ventilation systems of residences using field research, simulation and data analysis to demonstrate several approaches to improving energy efficiency and indoor air quality. Improved energy efficiency will help reduce greenhouse gas emissions that contribute to climate change. Improved indoor air quality could help reduce respiratory and other health problems for building occupants.

CHAPTER 1: Introduction

The California Energy Commission funded the multi-project RESAVE research and development (R&D) program to focus on residential energy savings, air-tightness, and ventilation excellence for California homes. This report focuses on the program's results and its associated conclusions and recommendations.

The program's overall goal was to facilitate the substantial reduction of energy and peak power that is used in California homes to condition air that enters from outdoors. Ventilation, either by infiltration (the uncontrolled exchange of air through building envelope leaks and penetrations) or deliberately through mechanical or passive systems, typically accounts for over one-third of the energy used for total space conditioning.

While in older, leakier homes infiltration may have provided sufficient air exchange to control indoor-generated contaminants, designed ventilation is required in all new homes in California to provide acceptable indoor air quality (IAQ) because newer homes have much tighter envelopes. As both new and existing homes are made more airtight to reduce infiltration energy losses, the needs for having efficient ventilation are increased.

Currently new homes in California are required to meet the California Title 24 2008 Building Energy Efficiency Standards. This standard specifies minimum continuous mechanical ventilation rates. While it does not specifically address the issues of source control or ventilation load shifting, it does allow alternative approaches to be used if they can be shown to provide equivalent performance. A key objective of the RESAVE program was to develop alternatives that would allow equal or better indoor air quality performance at a substantially reduced energy cost and substantially lower peak power consumption.

The existing building stock is considerably leakier than typical new construction. Given the small percentage of homes built each year, substantially more energy can be saved through retrofitting the existing stock. Therefore, another RESAVE objective was to demonstrate the energy saving-potential of improving the envelope air-tightness of the existing stock.

A key barrier to improved envelope air-tightness is the real concern that indoor air quality will be compromised. Unlike new construction, existing homes have no mandate to meet any ventilation or indoor air quality standard. Therefore, a further RESAVE objective was to generate appropriate guidance for making existing homes more airtight while maintaining acceptable indoor air quality.

1.1 RESAVE Program

The RESAVE program was intended to facilitate the "Built Tight, Ventilate Right" strategy, which implies that first one builds a high-quality building, (e.g., low air leakage, low source emission) and then finds the most efficient ventilation system to provide acceptable indoor air quality (which includes health and comfort related to odor and irritation).

Infiltration and ventilation are responsible for one-third to one-half of the space conditioning load, but are often unappreciated by the occupants because of the difficulty of sensing air losses. These factors cannot, however, be arbitrarily reduced below a level that supplies acceptable indoor air quality without providing mechanical ventilation or some other mechanism for doing so.

Therefore, RESAVE was designed to address two issues: first, to both reduce the direct losses from infiltration and to control key sources, and second, to find the most energy-efficient methods available to supply the necessary whole-house ventilation. This "Built Tight, Ventilate Right" approach is generally accepted as the best for building high-quality homes, but it is not easy to implement without strong technical backup and appropriate standards to follow.

The ventilation technologies found in California homes typically consist of operable windows or envelope leakage with a small mixture of ventilation fans, usually without heat recovery. The technology developed by the RESAVE program can provide equivalent ventilation at much lower energy costs by using efficient fans and control devices, as well as through heat recovery. The cost savings can be achieved through identification of the appropriate systems to use in specific circumstances and identification of where public-sector resources can be used to leverage private-sector activities.

The key RESAVE products are: (1) technical articles that substantiate the characteristics and performance of the approaches developed, (2) the demonstration of new products or techniques for saving energy and improving IAQ, (3) updates to professional and consensus documents (such as ASHRAE Standards and Handbook), (4) information that can be used in future Title 24 for new and existing homes, and (5) retrofit guidance documents.

1.2 Research Background

As California looks to reduce its carbon footprint, the buildings sector has an important role to play. Increasing energy efficiency for both new and existing homes is a key part of any strategy for reducing fossil fuel consumption. California regulations and incentive programs continue to make strides at changing the industry.

Air sealing and air-tight construction have been proven to be able to provide substantial energy reductions. A key barrier to implementation of these approaches is the impact that they would have on indoor air quality. Mechanical ventilation, as is currently required in Title 24, can provide acceptable IAQ but at an energy cost. Research is needed to optimize the solution to these twin problems. This issue is recognized broadly at the national and international level. RESAVE leverages much of that work and helps focus it on the needs of California.

Pieces of this RD&D are going on around the world, but the specifics in this program are not. The current standards, codes, and guidelines being used in California are themselves relatively new for the State, but they also only represent a first (albeit major) step toward very low-energy, high-quality indoor climates for California residences.

There are existing technologies can meet the current minimum requirements. Advance controls, air-tightness and system integration of the type developed in this program can allow those requirements to be met more efficiently. Understanding the impact of the current requirements can allow performance-based alternatives that can further reduce energy requirements.

Air-tightness and ventilation need ultimately to be included in a whole-building approach to reducing energy requirements. The results of this work should be used for taking that next step to full building specific ventilation system integration

1.3 Link to the PIER Program

RESAVE was funded by a Public Interest Energy Research (PIER) solicitation (resulting in contract #CEC-500-08-061) and was designed to address focus areas of the PIER energy efficiency program. Because this program focused on the cross-cutting issue of reducing the energy impact of air leakage and providing acceptable IAQ, the program addresses several target areas of research of interest to the PIER efficiency program.

RESAVE supports the *Building Envelope* target area because it looks at the quality of construction of the building envelope with respect to both air tightness and contaminant emissions from the building. Insufficient air tightness wastes energy by allowing excess infiltration, and high contaminant emissions from materials may require excessive ventilation. These issues, along with occupant use of building systems, are addressed in Chapters 2 and 3.

The RESAVE program supports the *HVAC Controls and Diagnostics* target area because it looks at ventilation equipment, systems, and controls for providing acceptable indoor air quality. Smart ventilation systems that can make use of knowledge about the way the building and its systems are operating, and they can substantially reduce the energy use associated with the designed ventilation. This topic is primarily addressed in Chapter 4.

The program also supports the *Codes and Standards Support, Information Resources and Market Connections* target area because at every step of the program the RD&D is connected to market players. Chapter 5 focuses on making changes to existing codes and standards (including both Title 24 and ASHRAE Standard 62.2), as well as providing explicit guidance to market implementers. In addition, RESAVE has market players, including cost-sharing manufacturers, as integral participants. The integrated nature of the manufacturers' participation assures that the information generated in the program will be presented in a way that is more likely to be adopted by industry and to address industry concerns.

Although there is cost-sharing from private-sector parties, all benefits generated by RESAVE are public benefits. These benefits will appear through improved codes and standards, public domain implementation guidelines, and technical publications in the open literature, as well as through new technologies (e.g., RIVEC). This output of RESAVE will facilitate the generation of subsequent public and private research that will provide specific technologies to reduce the energy and peak power consumptions associated with infiltration and mechanical ventilation.

1.3.1 Relationship to PIER Goals

The RESAVE program meets the PIER goal of advancing market adoption of research products by encouraging projects which are technically feasible, potentially cost effective, and which have paths to the market through relationships with manufacturers, customers, builders, regulators, and other market participants. This research will advance California Title 24 and facilitate the objective of zero-energy buildings. RESAVE output supports AB 32,[1] and this agreement is consistent with the California Public Utilities Commission's "Big Bold" strategies.

1.3.1.1 Goals of the Research

The RESAVE program's goal was to facilitate the substantial reduction of energy spent in homes to condition air that enters from outdoors. The RD&D attempted to achieve this goal by (1) finding methods and approaches that improve air tightness, (2) determining methods of incorporating source control features in such a way that whole-house ventilation can be reduced, and (3) developing and evaluating procedures and technologies for providing the required whole-house ventilation more energy efficiently, while lowering peak demand.

To facilitate implementation of that RD&D, RESAVE worked to advance relevant codes and standards (including Title24 and ASHRAE Standard 62.2), worked directly with industry to develop practical solutions, and to help industry players readily adopt them, and created information products and direct assistance that allows implementation through voluntary programs.

1.3.1.2 Objectives of the Research

The programmatic objectives of RESAVE were to facilitate the following:

- Eliminate energy demand due to ventilation during four peak hours of each day
- Reduce energy attributable to infiltration by 25 percent in existing homes and 50 percent in new homes
- Reduce the need for whole-house ventilation by 20 percent using contaminant control measures
- Increase the number of quality ventilation and ventilation control technologies by 50 percent
- Improve the energy and/or IAQ performance of existing ventilation strategies by 20 percent using control and commissioning strategies

RESAVE focused on providing information that is helpful in setting standards and providing enabling technologies, approaches and methods. The outputs are primarily information products, including technical reports, potential upgrades to Title 24, and retrofit/commissioning guides.

1.4 Structure of This Report

This report summarizes and documents the findings of the RESAVE program. Chapter 1 provides the background for why the program was important to California and why PIER funded it.

Chapters 2 through 5 summarize the program's technical results. The details of the activities are contained in the various RESAVE technical products, which are referenced in those chapters. The product list is at the end of this report. The chapters are as follows:

[1] The Global Warming Solutions Act of 2006. Assembly Bill 32 (Nuñez), Chapter 488, Statutes of 2006.

- Chapter 2 focuses on the air tightness research. The biggest effort in that area was the creation of an air leakage database. The data were used to determine the stock characteristics of home air-tightness and associated impacts. The researchers also analyzed potential air-tightness measurement techniques for use in multizone (e.g., multifamily) buildings.
- Chapter 3 focuses on key contaminants inside homes. This effort sought to find a short list of key contaminants and to discuss source control methods. Cooking is a major source of indoor contaminants and is discussed.
- Chapter 4 focuses on ventilation systems. Detailed simulations of extant and proposed ventilation systems were conducted to determine optimal paths. The research also investigated a smart ventilation controller and passive ventilation systems. The role of commissioning ventilation systems is discussed.
- Chapter 5 focuses on getting the research results generated in the previous chapters into the hands of institutions that can make use of them. It describes the activities of the program's industry partners and the work with industry and professional groups to implement RESAVE results.

Chapter 6 summarizes the conclusions and recommendations.

CHAPTER 2: Air-Tightness

2.1 Residential Diagnostics Database

Air leakage is a key factor in determining air infiltration, which provides most of the ventilation in existing dwellings. Leaky homes use more energy to heat and cool them. Occupant comfort can also be a problem in drafty homes. On the other hand, homes that are built with a very tight envelope may need mechanical ventilation to maintain good indoor air quality. Therefore, to improve residential energy efficiency and indoor environmental quality, it is important to understand the current air leakage characteristics of U.S. and California homes and the factors that are associated with excess air leakage.

To characterize the U.S. housing stock, researchers analyzed air leakage data of 134,000 single-family detached homes, including 4,500 homes in California. This data was used to develop the Residential Diagnostics Database (ResDB) which contains blower door measurements and other diagnostic test results, such as duct leakage measurements, of U.S. homes. Approximately two-fifths of the data were contributed by various sources in response to a call-for-data issued in 2011. The remaining three-fifths of the data had been analyzed previously by LBNL. A comparison of the house characteristics between the recently gathered data and the previously analyzed data are described in Chan and Sherman (2011). Overall, about half of the data were contributed by low-income qualified Weatherization Assistance Programs (WAPs). Two other major sources of data included residential energy-efficiency programs that are often sponsored by utilities and new homes tested for air leakage to obtain an energy-efficiency rating or to meet air-tightness guidelines. Forty-three states are represented in ResDB. Even though ResDB is not a representative sample of U.S. homes, the median floor area of 140 square meters (m^2) and year built (1970) are similar to the characteristics of the U.S. housing stock (160 m^2 and built in 1974), based on data from the American Housing Survey. The California homes in ResDB have a similar median floor area of 170 m^2, and they tend to be newer. Approximately 20 percent of the California data are from new houses built in 2000s. The remaining houses have a median year built of 1973.

In California, there are ongoing efforts by WAPs and residential energy efficiency programs to improve the air-tightness of homes. The analysis of both types of data quantifies the reduction in air leakage by comparing the pre- and post-retrofit measurements, which has a direct impact on the energy savings achieved by these programs. Another important question for California homes is how the air-tightness of new homes compares with the standard design value used in Title 24. For dwellings with ducted heating, ventilating and air -conditioning (HVAC) systems, the specific leakage area (SLA) design value is 3.8, which corresponds roughly to 6 ACH_{50}.[2]

[2] Air changes per hour induced by a 50 pascal pressure from a blower door.

Air Leakage Analysis of U.S. Homes

Normalized leakage (NL) is the air leakage metric used in the regression analysis. Blower door data measured at a 50 pascal (Pa) pressure difference were converted to NL such that the relative air leakage of residences of different sizes can be compared. The normalization is based on house height and floor area. Chan, Joh et al. (2012a) describes the method used to compute NL and the assumptions that are made to approximate house height and floor area if data are missing. The distribution of NL is roughly lognormal, with a geometric mean of 0.61 and a geometric standard deviation of 2.5. Most of the blower door data only provided a single value of air leakage flow (e.g., CFM_{50}[3]). In those cases, the pressure exponent[4] is assumed to equal the common value of 0.65 when computing NL. In cases where the pressure exponent is given, the reported value is used. There are 7,000 such measurements in ResDB, the distribution of pressure exponent is normal, around 0.65, with a standard deviation of 0.057.

Multiple linear regression is used to identify the housing characteristics that explain the observed variability in NL. Details of the models used, transformation of the explanatory variables, and the regression results are described in Chan, Joh et al. (2012a). The housing characteristics considered include year built, International Energy Conservation Code (IECC) climate zone, floor area, house height, foundation type, duct location, and whether the home participated in WAPs or were energy-efficiency rated homes. Only floor area and house height are continuous variables; all others are indicator variables. Six categories of year built are used to represent homes built from prior-1960 to after-2000. Homes are divided into twelve climate zones following IECC classifications:[5] five in humid (A) climate, three in dry (B) climate, and two each in marine (C) and Alaska (AK) climate (Chan, Joh et al. 2012a). These classifications are used to represent potential differences in the air leakage of homes situated in various climate zones in the US. The foundation types considered were slab, basement (conditioned or unconditioned), and crawlspace (vented or unvented). Ducts were classified as located inside the conditioned space, in the attic or basement, or in the crawlspace.

Different methods were used to account for missing data. For example, only three-quarters of the data provided year built. Using this subset of "year built" data, the analysis showed an inverse relationship between year built and logarithm of Normalized Leakage decreasing by 0.14 per decade. Missing data for year built were calculated using this relationship. A different approach was used to handle missing data for foundation type and duct location. Since only very few data provided this information (12,500 houses with known foundation type, and 526 with known duct locations), the regression analyses were performed step-wise: first leaving out these two parameters using the entire dataset, and then using a subset of the data where the

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[3] CFM_{50} is the airflow (measured in cubic feet per minute) that is needed to create a 50-pascal change in building pressure.

[4] The relationship between airflow and pressure difference across the building envelope is commonly expressed as a power law function, where the pressure exponent is the power of the function.

[5] See http://energycode.pnl.gov/EnergyCodeReqs/ for IECC climate zone classification.

parameter is known. The final regression model simply assumed that the coefficient estimated from each step of the analysis applied to all homes.

Year Built and Climate Zone

The regression model explains 68 percent of the observed variability in NL. Much of the variability observed in NL is associated with climate zone and year built. For example, the study found that the difference in NL between the warmest, humid climate in the United States (Southern Florida), Texas, and other southern states and the coldest (Alaska) was a factor of 2.7 (Chan, Joh et al. 2012b). The difference in NL between prior-1960 and after-2000 homes is a factor of 2.2. The least-squares fitted coefficient is statistically significant at the 95 percent confidence interval. The only exception is IECC climate zone B-4, 5, meaning that the model found homes in climate zone B-4, 5 to be somewhat more airtight than homes in the reference zone A-6, 7, but the difference is small and may have occurred by chance in the data sample. The final model includes all twelve climate zones for completeness, and also because combining homes in B-4, 5 and A-6, 7 has little effect on the resulting coefficient estimates.

Energy-Efficiency-Rated Homes

Energy-efficiency-rated homes tend to have NL 30 percent less than comparable homes. New homes that are ENERGY STAR certified are examples of homes in this category, but there are differences in how the efficiency ratings are defined in ResDB. Such definitions have also changed over time. For example, between 1995 and 2006, ENERGY STAR Version 1 was used. Version 2 became effective in 2007. The current Version 3 specifies ACH_{50} to be less than 6 (or 3 in certain climate zones). Even so, the regression model consistently found energy-efficiency-rated homes to have about 30 percent lower NL throughout these time periods. Therefore, it appears that homes that are rated for energy efficiency continue to be built with a more airtight building envelope than the average U.S. housing stock.

Weatherization Assistance Programs

The regression model suggests homes that participated in WAPs are leakier than conventional homes; they tend to have (pre-weatherization) NLs that were 50 percent higher than comparable homes. Eligibility for WAPs is based on household income, so it is reasonable to assume that the result applies more broadly to homes that are occupied by low-income households in general. In 2009, WAPs used an income upper-limit of 200 percent of the federal poverty level lines as the eligibility criteria, but over the years this had varied between 125 percent and 150 percent. There are 13,100 WAPs homes in ResDB with pre- and post-weatherization blower door measurements. Paired comparison shows a median reduction in air leakage of 30 percent. In comparison, data from 10,000 homes in ResDB that were retrofitted by other non-WAP residential programs show a median reduction of 20 percent (WAPs homes possibly showed greater improvements in air-tightness because they were leakier before they were weatherized and therefore, had more opportunities for air sealing. This is supported by an analysis that showed that the magnitude of air leakage reduction is correlated with NL pre-improvement.

Foundation Type, Duct Location, and Other Factors

The remaining factors considered in the regression model, namely floor area, house height, foundation type, and duct location, each explain some differences in NL in the 10 to 20 percent range. In comparison, their importance is secondary for predicting NL. Houses built on concrete slab are common in some parts of California. The regression results suggest that homes with either a conditioned basement or an unvented crawlspace tend to have NL 16 percent higher than homes on slab. Homes with either an unconditioned basement or a vented crawlspace tend to have NL 24 percent higher than homes on slab. Estimates of the coefficients indicating duct location are more uncertain because the analysis is based on very few homes. In California, homes typically have ducts in the attic or the basement. The regression results suggest homes with ducts inside the conditioned space tend to have NL 18 percent lower in comparison, and homes with ducts in the crawlspace tend to have NL 12 percent higher.

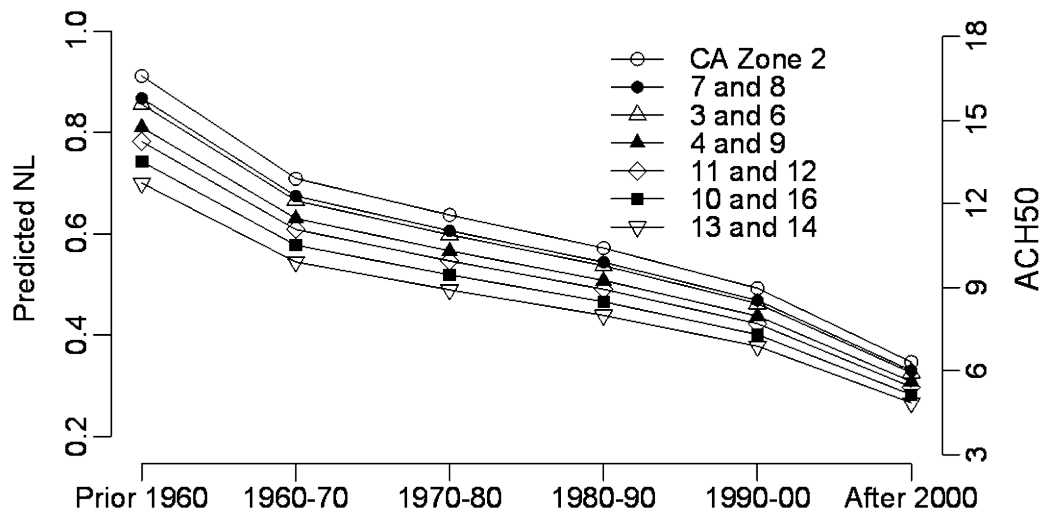
Air-Tightness of California Homes

A separate regression analysis was performed on 4,500 California single-family detached homes. These homes represent 13 of the 16 Energy Commission climate zones; there are no data from zones 1 and 5, and too few data from Zone 15 for our analysis. Some of the climate zones are further grouped together such that they are more equally represented in the model. For example, the initial regression model using all 13 climate zones suggests that houses located in the Central Valley and inland (zones 10 to 16) tend to have lower NL, all else being equal. Houses in the coastal areas have higher NL in comparison, especially in zone 2. This resulted in seven groups of climate zones being modeled (ordered from the leakiest to the most airtight and the representative city):

- Zone 2 (Santa Rosa)
- Zones 7 and 8 (San Diego and El Toro)
- Zones 3 and 6 (Oakland and Los Angeles)
- Zones 4 and 9 (Sunnyvale and Pasadena)
- Zones 11 and12 (Red Bluff and Sacramento)
- Zones 10 and 16 (Riverside and Mt Shasta)
- Zones 13 and 14 (China Lake and Fresno)

Figure 2.1.1 shows the NL of California homes in the different climate zones and year built predicted by the regression model. The model predictions are for a single-story (height at 3.5 meters, m) home with a floor area of 150 m^2. The corresponding air changes at 50 Pa (ACH_{50}) predicted is shown on the right x-axis.

Figure 2.1.1: Normalized Leakage (NL) of California Homes in Different Climate Zones, and as a Function of Year Built, Predicted Using the Regression Model.



The regression model explains 76 percent of the observed variability in NL among the California homes. Houses in zones 13 and 14 are predicted to be 23 percent more airtight than houses in zone 2. The NL of houses in other climate zones are somewhere in between these two extremes. The California model shows a slightly stronger dependency on NL with respect to year built than the U.S. model. Houses built in 1980s tend to have NL 60 percent higher than houses built in 2000s. In comparison, the U.S. model predicts the difference to be 50 percent The California model also predicts a stronger relationship between NL and house height. It predicts that two-story houses tend to have NL 32 percent higher) on average, compared to single-story houses. On the other hand, houses that participated in WAPs in California are less different from non-WAP houses, with a difference of 30 percent compared to 50 percent nationally. The improvement from retrofit for California homes is 20 percent, including WAPs and other energy-efficiency programs. The relationship between NL and floor area for California houses is similar to the U.S. model.

California homes that are rated for energy efficiency tend to have NL 30 percent lower than typical homes. However, it is important to note that data from most of the 170 energy-efficient houses in California used in the study were collected prior to 2001, so this result may be outdated. With the current Title 24 having a standard design value that is equivalent to the envelope air-tightness guideline in ENERGY STAR; it is possible that this difference of 30 percent no longer applies for California homes built to meet Title 24 in 2008. To further explore the changes in air-tightness of California houses that can be attributable to construction improvements, only measurements that were collected within five years of construction were considered. This subset of California data included only houses built since 1985, because prior to this time blower door testing was not a common diagnostic test. After adjusting for other parameters, such as climate zone and floor area, the NL of this subset of California houses continue to decrease with construction year. In the past ten years between 2001 and 2011, this analysis suggests a 23 percent reduction in NL.

Research Implications and Relationship to Home Energy Saver

The regression models for California and the United States can be used to estimate a distribution of normalized leakage based on housing characteristics. This basic information is required to estimate air infiltration rates, and subsequently for evaluating the energy use and ventilation needs of single-family homes. To make these research results more accessible to the building community, the regression model is available online (http://resdb.lbl.gov/). The online calculator accepts user inputs of housing characteristics and gives estimates of NL and ACH_{50} accordingly.

This model enables software tools such as Home Energy Saver to more reliably predict the energy benefits from air sealing based on housing characteristics. This analysis shows that homes with certain attributes tend to have higher air leakage than others. This information can be used to target homes that would benefit the most from air sealing as a measure to reduce their energy consumption on heating and cooling. The pre-and-post retrofit comparisons from WAPs and other residential energy-efficiency programs provide data on air-tightness improvements currently being achieved. This important information is needed by Home Energy Saver to calculate the energy impact of air infiltration, and to recommend energy saving measures that are suitable for homes given their characteristics.

2.2 Multizone Leakage Methods Analysis

Inter-zone leakage can have a negative impact on indoor air quality, through chemical transport from an attached garage to a house or between units in multifamily housing. Inter-zone leakage testing methods are also used for energy-efficiency objectives to identify leakage pathways in multifamily homes or single-family homes with adjacent attic or basement zones, so that these leakages can be reduced to improve energy efficiency of the homes. While a number of strategies have been used to determine inter-zone leakage, currently no standard exists for this measurement. The objective of this subtask was to identify the most accurate methods to quantify the inter-zone leakage using fan-pressurization testing. Various data collection and analysis methods were compared using both synthesized datasets and field data. Results of the field data and simulations are used to identify the most robust methods and to quantify the uncertainty of the different methods. Additional details of this analysis can be found in Hult et al. (2012).

2.2.1 Measurements of House Garage Leakage

A set of field data was collected and analyzed to determine the leakage between a single-family house and an attached garage. The same methods could be used for any adjacent zones, such as townhouses. Data for six homes were collected in a variety of test configurations using one or two blower doors and a variety of test procedures and corresponding analysis techniques. For the homes tested, leakage area between the garage and house averaged 5 percent of the leakage area between the house and outdoors. This varied considerably from home to home; the fraction was as high as 45 percent in one home. These results are consistent with previous studies, which found that the garage-to-house leakage area is typically only 5 to 15 percent, but can be large—as high as 50 percent—in a minority of homes. Estimates for the calculated inter-zone leakage varied over an order of magnitude, depending on the testing and calculation method used, with certain methods providing much more consistent results than others do.

2.2.2 Measurement Technique Analysis

To assess the accuracy of different testing methods under a wide range of conditions, synthesized data analysis using Monte Carlo simulations was used. These simulations varied the magnitude of the leakage area and the magnitude of fluctuations in the systematically generated synthetic data for measured pressure and flow rate. The placement and number of blower doors was also varied. We also explored different assumptions in the calculation process, including measuring the flow through the blower door at a single pressure rather than at a range of pressure stations.

The synthesized data analysis to test the methods and conditions described above first involved generating the exact leakage parameters for a two-zone leakage case. Then measurement noise and bias was added to the exact solution to get a synthesized dataset. Various analysis methods were then applied to the synthesized dataset to determine how accurately the exact parameters could be determined. Because certain quantities in the generation of the synthesized dataset are randomly selected, this process was repeated for a large number of iterations to determine not only the median result, but also the result one standard deviation above and below the median result, to describe the distribution of the uncertainty resulting from different methods. This approach allowed direct comparison between a range of testing and calculation methods by applying the different methods under the same conditions.

2.2.3 Key Results

- The best of the measurement and analysis methods was the method developed by Herrlin and Modera (1988), which uses two blower doors simultaneously to determine the inter-zone leakage to within 16 percent, over the range of expected conditions.
- When two blower doors are used simultaneously, there is a large range of combinations of pressure stations at which testing can be performed. While some two blower door methods consistently obtained accurate results, many did not give accurate results. If using two blower doors, care should be taken to follow a recommended testing procedure such as the Herrlin and Modera method.
- The best single blower door methods (the 991/190 method in Hult et al. (2012)) were able to determine the inter-zone leakage to within 20 percent of its value.
- Poor testing and calculation methods can lead to errors of up to 100 percent in the inter-zone leakage area.
- The choice of analysis method can reduce uncertainty in the calculation of house-garage leakage significantly. Making the assumption that the pressure exponent for the inter-zone wall is 0.65 was better than fitting for that pressure exponent, regardless of how many pressure stations were used. Additionally, the uncertainty was reduced by fitting a single set of parameters to both pressurization and depressurization data, rather than having separate parameters for pressurization and depressurization.

- The single pressure station approach could not reliably be used to determine inter-zone leakage due to uncertainty in measured quantities and the pressure exponents in the different interfaces. If the objective is simply to identify which inter-zone partitions may have high leakage flows for air-sealing purposes, using a single point testing may be sufficient.
- If it is determined that the zone to outdoor leakage of the two zones is comparable, however, then it is possible to use the single pressure station approach to determine the inter-zone leakage to within 20 percent.
- Analysis of field datasets confirmed a level of variation between test methods that was consistent with the analysis of synthesized datasets.
- The Monte Carlo approach was also applied to the air leakage of a single zone, to illustrate the contribution of different assumptions to the overall uncertainty in the leakage area.

2.2.4 Implications

As California homes become more energy efficient, exterior building envelopes will get tighter. For multizone spaces the issue of interzonal leakage will rise in importance, particularly for understanding the transfer of contaminants. This study has shown that it is possible to develop an optimized test method that allows one to measure inter-zonal leakage for two adjacent zones. Furthermore, the optimized test methods are dramatically better than other possible methods to test inter-zonal leakage. In addition, a substantial fraction of homes in California are multifamily structures, and the ability to measure interzonal leakage is crucial for examining IAQ and energy issues in these buildings.

For homes with attached garages, there is ambiguity on where the air barrier and pressure boundary should be. If there is high leakage between the house and the garage, garage contaminants might be drawn into the occupied space when simple exhaust ventilation systems are used. In addition to the leakage area, the operational pressure difference between two adjacent zones will have a strong influence on the transport across inter-zone boundaries, and this pressure difference is not well characterized for homes with attached garages. Further research is necessary to model the impact of this and to set measurable and achievable limits on the house garage leakage. Such research is part of the necessary efforts to ensure that future versions of Title 24 do not create health or safety risks by enhancing contaminant transport.

Interest in energy efficiency in multifamily buildings requires a better understand of the leakage between apartments. Leakage between apartments is an indirect energy issue and a direct indoor air quality issue. This effort has helped to define optimal measurement techniques and reasonable expectations for what could be measured, but they are not yet developed to the point where they can be used programmatically. For example, if more than two adjacent zones are present, as is the case in many multifamily housing buildings, the methods developed here can be extended to determine the leakage between any two adjacent zones. Future work could refine and demonstrate the protocols that have been developed in this section so that they can be more widely implemented in practice.

2.3 Energy Benefits of Air Sealing

Effective residential envelope air sealing reduces infiltration and associated energy costs for thermal conditioning, yet often creates a need for mechanical ventilation to supply acceptable indoor air quality. Current best practice seeks to make homes as airtight as possible and provide controlled ventilation with mechanical systems. Ventilation is required to remove indoor-generated pollutants and excess moisture, and to provide a sufficient supply of outdoor air to ensure acceptable IAQ.

To develop effective programs and protocols for practitioners, it is necessary to develop the analytical capability to predict the benefits of increasing residential envelope air tightness and the costs and IAQ benefits of various ventilation system approaches and technologies.

The potential benefits of air sealing and the costs of mechanical ventilation vary widely across individual homes and for sub-populations by climate; baseline air-tightness and other building structural characteristics; the performance characteristics of existing or replacement HVAC equipment; and occupant-influenced equipment operational schedules and settings.

RESAVE developed an Incremental Ventilation Energy (IVE) model to enable analysis of air sealing and ventilation impacts across sub-populations of homes by type, location, and other factors. A very useful feature of the model is that it provides results in the form of distributions across the housing sub-populations examined. It provides robust estimates of variations of costs and benefits across homes, as well as the uncertainties associated with unknown or poorly understood parameters.

The IVE model applies empirically verified approximation approaches to calculating airflow impacts of air sealing or adding mechanical ventilation to a large sample of homes that have been characterized in existing databases. In the Logue, Turner et al. (2012) report (www.homes.lbl.gov), the IVE model is described and applied to predict results for a range of home types, climates, and ventilation systems that span those features of the U.S. residential housing sector . The energy changes predicted by the IVE model are compared against those predicted by the REGCAP model, which is an extensively validated, physics-based simulation model of air, energy, and moisture flows for residential buildings.

The IVE model was also used to estimate the potential energy savings of implementing air sealing or absolute standards for air-tightness along with mechanical ventilation throughout California and the entire U.S. housing stock (Logue, Sherman et al. 2012). We calculated the change in energy demand for each home in a nationally representative sample of 50,000 virtual homes developed from the 2009 Residential Energy Consumption Survey. Ventilation was provided as required by ASHRAE 62.2-2010 and the proposed 2013 versions of the standard. The estimated impacts of achieving envelope tightening and mechanical ventilation for the entire U.S. housing stock are summarized in Table 2.3.1. Ensuring that all current homes comply with 62.2-2010 would increase U.S. residential site energy demand by 0.07 quads annually. Improving air-tightness of all homes at current average retrofit performance levels would decrease demand by 0.7 quads annually. Upgrading each home to be as airtight as the top 10 percent of similar homes would double the savings (1.4 quads), leading to roughly

$22 billion in annual savings in energy bills. The impacts of achieving envelope tightness for California are summarized in Table 2.3.2.

We also analyzed the potential benefits of bringing the entire stock to air-tightness specifications of IECC 2012, Canada's R2000, and Passive House standards. The results indicated that significant benefits would result from increasing the tightness of weatherization and energy-efficiency programs, though most of the potential benefit of bringing all homes to an absolute air-tightness standard would be achieved at the level of the IECC standard. Additional research should be done to compare the incremental cost of progressively tighter home envelopes with the energy savings derived from the measures. Currently, Title 24 does not have an envelope tightness requirement although it does allow builders to take a credit for energy efficiency based on measured envelope tightness.

Table 2.3.1: Change in Annual Energy Demand Resulting from Air Sealing Improvements or Achieving Air Tightness Standards While Also Ensuring Adequate Ventilation According to ASHRAE 62.2 for the Entire U.S. Housing Stock.

	Site Energy Demand (Quads)		Energy Cost (billion$ 2010)	
	ASHRAE 2010	ASHRAE 2013	ASHRAE 2010	ASHRAE 2013
Baseline: Making stock comply with the ASHRAE 62.2 Standard				
Exhaust	0.07	0.06	$1.6	$1.3
HRV	0.10	0.08	$2.6	$2.2
Savings compared to baseline: Average Tightening				
Exhaust	-0.72	-0.72	-$11.8	-$11.7
HRV	-0.72	-0.72	-$11.5	-$11.5
Savings compared to baseline: Advanced Tightening				
Exhaust	-1.42	-1.39	-$22.9	-$21.2
HRV	-1.41	-1.41	-$23.2	-$21.9
Savings compared to baseline: IECC Standard				
Exhaust	-2.10	-1.89	-$33.8	-$29.8
HRV	-2.23	-2.12	-$35.0	-$32.2
Savings compared to baseline: R2000 Standard				
HRV	-2.63	-2.44	-$41.8	-$36.7
Savings compared to baseline: Passive House Standard				
HRV	-2.86	-2.62	-$45.5	-$39.3

HRV = heat recovery ventilator

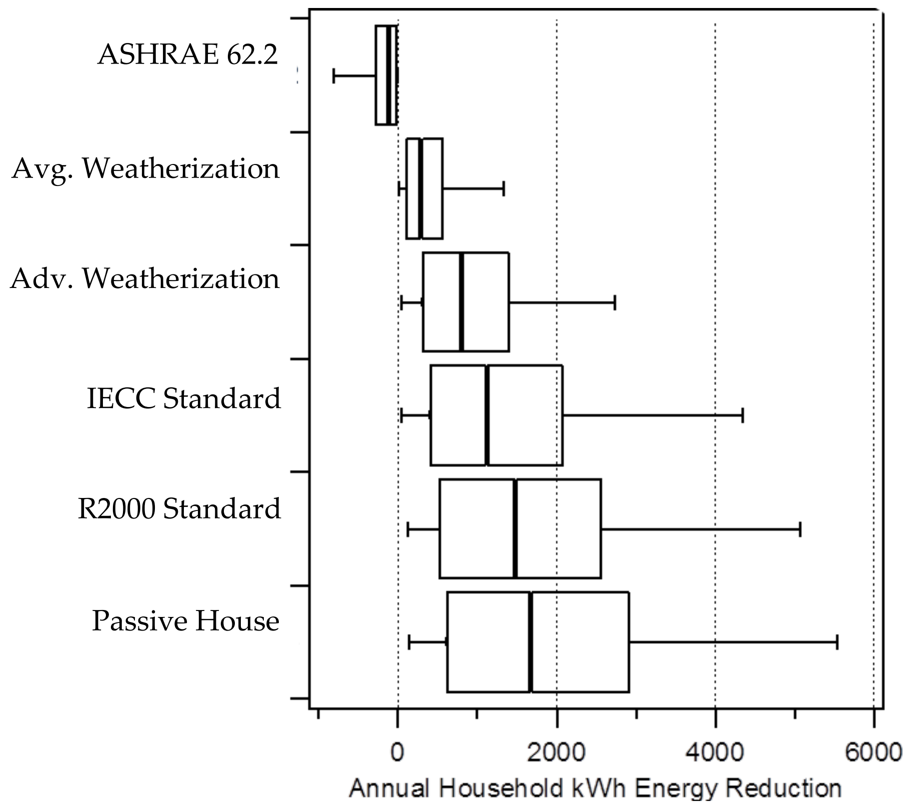
Table 2.3.2: Change in Annual Energy Demand Resulting from Air Sealing Improvements or Achieving Air Tightness Standards While Also Ensuring Adequate Ventilation According to Title 24 for California.

	Site Energy Demand (Quads)		Energy Cost (billion$ 2010)	
	ASHRAE 2010	ASHRAE 2013	ASHRAE 2010	ASHRAE 2013
Baseline: Making stock comply with Title 24				
Exhaust	0.010	0.009	$0.24	$0.20
HRV	0.014	0.012	$0.44	$0.36
Savings compared to baseline: Average Tightening				
Exhaust	-0.022	-0.021	-$0.33	-$0.31
HRV	-0.020	-0.019	-$0.19	-$0.10
Savings compared to baseline: Advanced Tightening				
Exhaust	-0.044	-0.037	-$0.65	-$0.51
HRV	-0.049	-0.043	-$0.62	-$0.46
Savings compared to baseline: IECC Standard				
Exhaust	-0.063	-0.045	-$0.94	-$0.58
HRV	-0.074	-0.062	-$1.00	-$0.63
Savings compared to baseline: R2000 Standard				
HRV	-0.091	-0.074	-$1.27	-$0.74
Savings compared to baseline: Passive House Standard				
HRV	-0.101	-0.081	-$1.43	-$0.81

HRV = heat recovery ventilator

State-specific distributions of benefits are calculated in the analysis reported by Logue, Sherman, Walker, and Singer (2012). Figure 2.3.1 shows California-specific distributions. This figure shows both the variation in benefits across homes and the differences between idealized policy options. It is particularly noteworthy that the benefits of advanced air sealing are substantially greater than the benefits of air sealing at current performance levels, and that such effective air sealing would overlap with the distribution of benefits from achieving the IECC 2012 standard. Advanced air sealing should be seen as a difficult, but not impossible, technical challenge, since it just requires that all homes be brought up to the level currently achieved by the top 10 percent of similar homes.

Figure 2.3.1: Impact of Envelope Tightening on the California Housing Stock. The Graph Shows the Distribution of Home Energy Savings from Retrofitting the Entire Housing Stock to Comply with Title 24 and Tightening the Housing Stock by Various Levels. Scenarios are Described in the Text. Change in Household Kilowatt-Hours Is for Site Energy.



CHAPTER 3: Energy-Efficient Ventilation and Source Control for Health Protection

3.1 Prioritizing Contaminants for Health-Based Ventilation Standards

People spend the majority of their time in residences, and the health burden of indoor air is significant. It is widely accepted that ventilation is critical for providing acceptable indoor air quality (IAQ) in homes. However, the definitions of "acceptable" and "good" IAQ, and the most effective, energy-efficient methods for achieving various levels of IAQ are still matters of research and debate. Considering the adequacy of ventilation standards to protect health requires identification of the pollutants that drive hazard and risk in the residential environment.

This subsection presents results of research conducted to identify and prioritize the pollutants that present a health risk in the indoor residential environment. This research includes a hazard assessment of pollutants in the indoor residential area (Logue, McKone et al. 2011) and development and application of a health-impact assessment framework to quantify the costs of chronic air pollutant exposures in homes (Logue, Price et al. 2011). Results of these related studies are already informing the consideration of changes to ventilation standards to improve health protection through communications with the ASHRAE 62.2 committee.

Prior to the start of this research, the focus of debate about and application of ASHRAE ventilation standards was primarily on the right amount of overall ventilation for a home. This focus was based on the idea that a key health-related objective of ventilation was to provide an adequate supply of outdoor air to dilute and remove pollutants emitted from indoor sources to maintain indoor concentrations at levels that are not hazardous. The lower bound for the overall ventilation rate that has been used was the airflow needed to control body odour, based on studies that have determined how much ventilation is needed to control body odour for hygiene typical of the western world. The general assumption has been that additional airflow is needed to control concentrations of pollutants that have diffuse emission sources in residences or that are caused by occupant activities.

One way of reducing the needed overall ventilation for a home, and the associated energy and cost penalty, is pollutant source control. Currently in the U.S. there is not sufficient information to estimate the benefits of source reduction by simulating the replacement of specific materials or applying specific existing standards or guidelines for material emissions (Willem and Singer 2010). Developing these databases could aid in the reduction of material loading or generation of contaminants of concern such as formaldehyde and acrolein. Implementing standards that reduced material loading in homes would reduce the required ventilation rate and save energy.

3.1.1 Hazard Assessment and Identification

The initial step in this analysis effort was to conduct a residential hazard assessment for non-biological air pollutants, including chemical gases and particles but not dampness and mold (Logue, McKone et al. 2011). The analysis compiled data from 86 published studies reporting air pollutant measurements in residences. Contaminants considered in this study included some emitted purely from indoor sources, some that enter predominantly from outdoors, and some having both indoor and outdoor sources.

Summary results were compiled and used to calculate representative mid-range and upper-bound concentrations relevant to chronic exposures for over 300 pollutants and peak concentrations relevant to acute exposures for a few pollutants. For over 100 pollutants, measured concentrations were compared to available chronic and acute health-hazard standards and guidelines from the U.S. Environmental Protection Agency (U.S. EPA), California Office of Environmental Health Hazard Assessment (OEHHA), the U.S. Occupational Safety and Health Administration (OSHA), the Agency for Toxic Substances and Disease Registry (ATSDR), and the World Health Organization. Fifteen priority pollutants were identified as potential chronic or acute health hazards based on their prevalence in homes and the quality of available measurements in homes. Table 3.1.1 lists the identified priority hazards.

Table 3.1.1: Pollutants That Potentially Pose an Adverse Indoor Health Risk.

Priority Pollutants for Chronic Exposure	**Potential Acute Exposure Concerns**
Acetaldehyde	Acrolein
Acrolein	Chloroform
Benzene	Carbon Monoxide
Butadiene, 1,3-	Formaldehyde
Dichlorobenzene, 1,4-	Nitrogen Dioxide (NO_2)
Formaldehyde	Fine Particulate ($PM_{2.5}$)
Naphthalene	
Nitrogen Dioxide (NO_2)	
Fine Particulate ($PM_{2.5}$)	

The hazard assessment narrowed the list of hundreds of chemicals to a much smaller group of pollutants of concern. But this approach considered only disease incidence for cancer standards and disease potential for non-cancer standards; it did not consider disease severity. Prioritizing mitigation efforts among residential indoor air pollutants and comparing their cumulative health damage to other environmental hazards requires a consistent and comparative metric that accounts for both disease incidence and the severity or costs of the health endpoints. This need motivated development of an impact assessment methodology for indoor air pollutant inhalation.

3.1.2 Prioritizing Chronic Health Hazards

Disease incidence and health damage models were synthesized to develop a methodology for quantifying indoor air quality, and then the methodology was applied to calculate the population average health damage due to chronic inhalation of non-biological air pollutants in U.S. residences (Logue, Price et al. 2011). We first analyzed published data to calculate mean exposure concentrations, and then estimated age-dependent inhalation air intake over the course of a year. Disease incidence and health damage models were used to predict the pollutant-specific and total health damage in Disability Adjusted Life Years[6] (DALYs) and to identify the pollutants that dominate impacts on human health.

This analysis used the compilation of measured concentration data developed for the hazard assessment to calculate total DALYs lost due to inhalation of air pollutants in residences. Figure 3.1.1 shows the damage in DALYs per year per 100,000 people from exposure to the 15 pollutants with the highest central estimate of damage. The whiskers indicate the aggregate uncertainty (95th percentile confidence interval) in the disease incidence and disease damage factors.

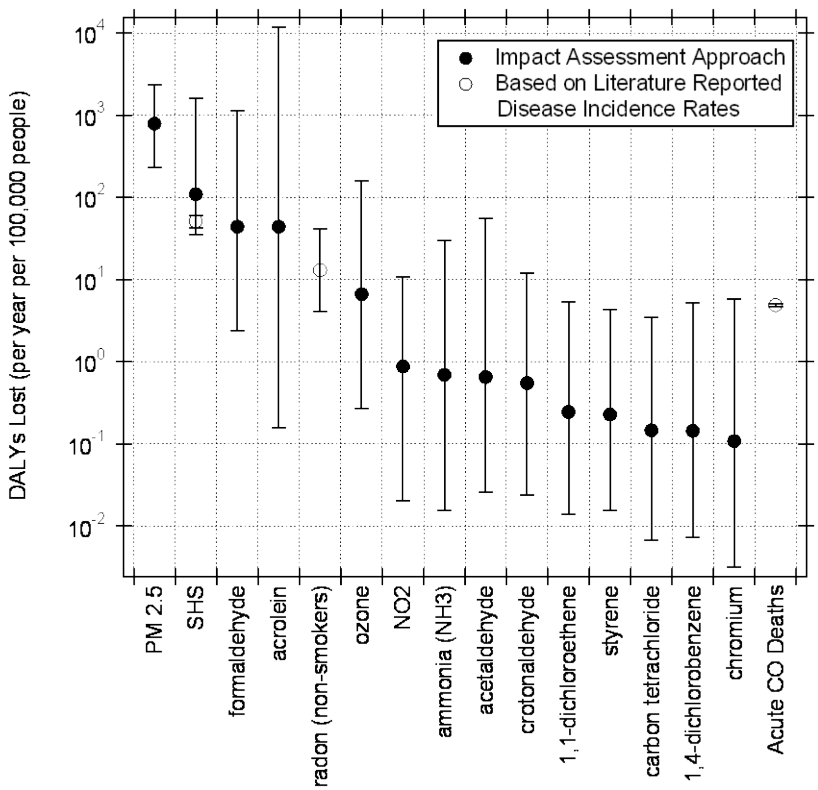
Figure 3.1.1 shows a clear result of this analysis: on a population average, the most harmful chronic pollutants in residential indoor air are $PM_{2.5}$, secondhand tobacco smoke (SHS), formaldehyde, acrolein, radon, and ozone. The hazards of SHS and radon are widely recognized, focused in a smaller fraction of homes, and already addressed through a wide range of controls. By contrast, $PM_{2.5}$, acrolein, and formaldehyde are present at substantial levels in most homes, yet there may be less widespread recognition of these hazards. Formaldehyde is primarily emitted from materials throughout the home. Acrolein is primarily emitted from materials and cooking. $PM_{2.5}$ concentrations indoors, unlike acrolein and formaldehyde, are due to both indoor and outdoor sources, and outdoor concentrations may exceed indoors in many locations.

To explore possible variations in the health impact rankings of pollutants across homes, a Monte Carlo approach was used to calculate the total chronic health damage from exposure to all pollutants included in the analysis, except radon and SHS. For each model run, we sampled with replacement from the distribution of estimated damage for each pollutant and calculated an estimate of total health damage for the occupants of the home. Sampling with replacement is a technique in which each time a parameter value is selected from the distribution of possible values, all possible values are available. In other words, it is theoretically possible for the same value to be selected more than once. An independent variability of all pollutants was assumed. This was repeated for a sufficient number of samples to yield a stable mean and standard deviation for the total health damage. It was assumed that individual pollutant damages vary

[6] Disability Adjusted Life Years refers to the years of full life lost due to ill-health, disability, or premature death.

independently. This approach did not account for any synergistic or antagonistic interactions of pollutant health effects. The resulting distribution of total health damage and the characteristics of each set of individual pollutant contributions to the total health damages were analyzed. For 80 percent of the sample sets (calculated damages for individual homes), $PM_{2.5}$ was the largest contributor. For 16 percent of the sample sets acrolein was the dominant contributor. For 4 percent of the sample sets, it was formaldehyde. The dominant contributor was a compound other than these three in less than 0.25 percent of the sample sets. For 90 percent of the sample sets, acrolein, formaldehyde, and $PM_{2.5}$ contributed more than 80 percent of the total health damage. This reinforces the finding that these three pollutants account for the majority of chronic health damage from intake of air pollutants in non-smoking homes. We estimate that the current indoor air quality-related heath damage to the U.S. population from all sources, excluding SHS and radon, is in the range of 4–11 mili-DALY/p/yr (mili-DALYs per person per year). This indicates that the damage attributable to indoor air is, comparatively, somewhere between the health effects of road traffic accidents (4 mili-DALY/p/yr) and all-cause heart disease (11 mili-DALY/p/yr) in the United States. The compounds that dominate that total are $PM_{2.5}$, acrolein, and formaldehyde.

Figure 3.1.1: Estimated Population Averaged Annual Cost, in Disability Adjusted Life Years (DALYs), of Chronic Air Pollutant Inhalation in U.S. Residences. This Figure Presents Only the Results from the 15 Pollutants with Highest Mean Damage Estimates.



3.2 Ventilation Control of Formaldehyde and Other VOCs

Residential IAQ can be adversely affected by volatile organic compounds (VOCs) that are emitted by various sources in homes. The majority of existing homes do not currently meet health-based guidelines for formaldehyde chronic exposure levels, and guidelines for other VOCs are exceeded in a non-negligible minority of homes (Logue et al. 2011). New homes typically have elevated concentrations of formaldehyde and other VOCs that are emitted from new building materials or new furnishings brought into the home. Homes with lower outdoor air exchange rates, a condition that occurs when building envelopes are tightened to reduce uncontrolled infiltration, also typically have higher concentrations of VOCs from indoor sources.

Dilution and removal via ventilation is a straightforward and common approach to managing concentrations of pollutants from indoor sources. Historically, homes were leaky enough that the rate of infiltration of outdoor air (through cracks and other leakage pathways) was so large that there was no need to install mechanical systems to ensure minimum air exchange rates. Recent years have seen a substantial increase of more airtight, energy-efficient homes. If the air change rate is sufficiently low, then mechanical ventilation must be provided in order to provide adequate ventilation. As envelopes have been tightened and sealed to reduce uncontrolled infiltration, the minimum mechanical ventilation rate has become a design element.

Managing levels of VOCs from indoors sources is an implicit objective of ventilation, and it is commonly assumed that increasing the air exchange rate can be an effective measure to reduce in-home concentrations of VOCs that are emitted from materials built or installed in the home. The effect of ventilation on VOC concentrations in existing homes has been explored primarily through cross-sectional studies. The limitation to this approach is that large sample sizes are needed to identify an effect of ventilation within the context of variation in material and product-related emissions; variations in material emission rates related to temperature, relative humidity, and solar insolation; and other factors. To understand how formaldehyde emissions depend on environmental factors, emissions from single materials have been measured under varied conditions in controlled, laboratory environments. However, constructed homes contain a wide range of materials compared to chamber tests designed to evaluate one material or a small collection of materials. While lab experiments have been instrumental to understanding emission from a single material, it is very difficult to extrapolate from experimental studies what indoor VOC concentrations from building materials and furnishings are likely to be, due to the different varieties and quantities of VOC containing materials present in homes.

As a complement to existing datasets that allow cross-sectional analysis of ventilation impacts on VOC levels, we designed and implemented a field study in which ventilation rates were varied while environmental factors were either held constant or at least consistent between ventilation settings in new U.S. homes. This field study, termed the Ventilation and Indoor Air Quality study (VIAQ), sought to answer the following research questions:

- To what extent does increasing the air exchange rate in new homes reduce pollutant concentrations in the short term, and thus help to mitigate residents' exposure?
- For which chemicals does increasing the air exchange rate result in proportional reductions of indoor chemical concentrations, and for which chemicals is the relationship not proportional?

Answers to these questions are needed to inform the development of optimal strategies for controlling VOC exposures in relatively new or retrofit homes.

Provided below is a brief summary of the methods and results of the VIAQ study. Detailed results are available in Willem et al. (2012).

3.2.1 Methods

The impact of air exchange rate on indoor concentrations of VOCs was investigated in nine residences, listed in Table 3.2.1. Using the installed ventilation systems as well as additional ventilation equipment where necessary, the experimental setup was designed to establish three distinct air exchange rates, with other environmental parameters consistent, then measure the resulting indoor VOC concentrations at each ventilation setting in each one of the study homes. This controlled approach provides information about how VOC concentrations in real residences respond to changes in ventilation.

The study design required that three ventilation settings in each home be achieved and maintained. Air samples were collected for each ventilation setting after a pseudo-steady-state condition had been achieved. The impact of air exchange rate on the indoor concentrations of 39 target VOCs was assessed by measuring air exchange rates and VOC concentrations at three ventilation settings in nine residences. Active sampling methods were used for VOC concentration measurements, and passive perfluorocarbon tracer gas emitters with active sampling were used to determine the overall air exchange rate corresponding to the VOC measurements at each ventilation setting.

3.2.2 Key Results

Summary results are presented in Figure 3.2.1 for formaldehyde and acetaldehyde and in Figure 3.2.2 for six other representative VOCs that have major indoor sources. These figures show several major features of the results obtained.

This study found, as many have in the past, that VOC concentrations varied widely across homes. The concentration levels and emission rates of the target VOCs varied widely among sites. For a given VOC, the measured concentration at the lowest ventilation setting varied by up to two orders of magnitude at the different sites. Aldehydes and terpenes were the classes of VOCs typically found in the highest concentrations, followed by alkanes, aromatics, and siloxanes.

Table 3.2.1: Summary Characteristics of Homes for Which Ventilation Was Varied to Study the Impact of Air Exchange Rate on VOC Concentrations and Emission Rates.

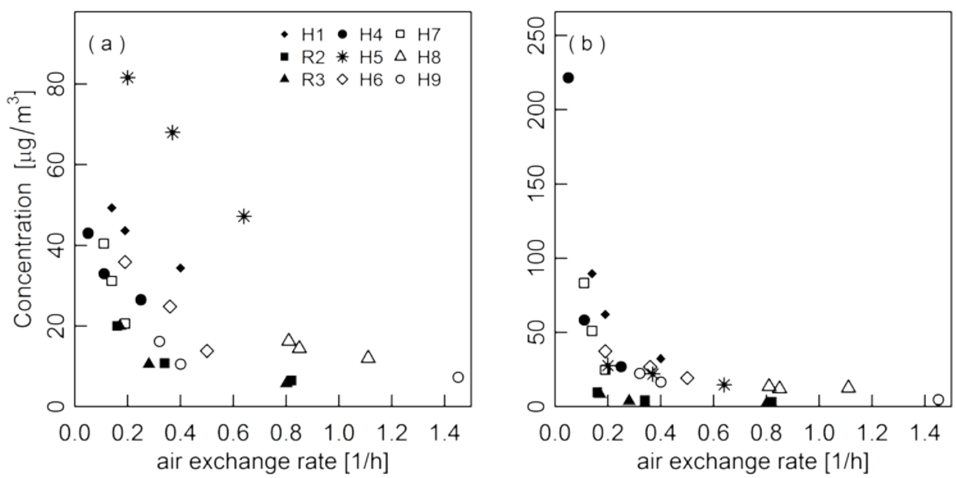
ID	Generally in-use for habitation	Occupied during sampling	Age^ (yrs)	Floor area (m^2)	# of story	# of bedrooms/ # of occupants	Air tight-ness (ACH_{50})	Low-emitting materials#	Ventilation system	Air distribution system	Study dates
H1	No	No	2.0	195	2	4/ 0	1.2	1,2	ERV with enthalpy wheel	Ducted exhaust	07-08/ 2011
R2	Yes	No	1.5	14[4]	1	1/ 0	4.0	1,2,3	Added balanced system	Single supply & exhaust	12/2010
R3	Yes	No	1.5	14[4]	1	1/ 0	4.0	1,2,3	Added balanced system	Single supply & exhaust	12/2010
H4	Yes	No	0.3	230	2	3/ 0	0.6	2,3	HRV	Ducted supply	08/2011
H5	Yes	No	7.5	141	1	3/ 0	4.3	NA	Added balanced system	Ducted supply	07-08/ 2011
H6	Yes	Yes	0.8	146	2	3/ 4	1.0	2,3	ERV	Single supply	05/2011
H7	Yes	Yes	1.0	210	2	3/ 4	0.7	2,3	ERV	Ducted supply	05/2011
H8	Yes	Yes	2.5	150	2	3/ 3	1.0	2	ERV	Ducted supply	07/2011
H9	Yes	Yes	2.5	320	2	4/ 2	4.0	2	Added balanced system	Single supply & exhaust	09/ 2011

^Age of home when study was conducted; #1= Wood products for the building structure, finishing, and cabinetry certified compliant with CA Title 17 or equivalent low- or no- formaldehyde standards, 2= Wet surface finishing product certified as low-emitting in accordance to CA Section 01350 requirements or equivalent low- or no-VOC standards, 3= Carpet materials and backing certified as low-emitting in accordance to CA Section 01350 requirements or Carpet and Rug Institute (CRI)-certified low-emitting carpet and backing system; ERV = Energy Recovery Ventilator; HRV = Heat Recovery Ventilator, 4= R2 and R2 are small rooms in the LBNL guesthouse (i.e. hotel rooms)

Concentrations of VOCs associated with indoor sources generally decreased as the air exchange rate was increased. Generally, concentrations were substantially lower when the air exchange rate was above about 0.4 air changes per hour (ACH). The dependence of indoor concentration on air exchange rate for each home was linear for most of these VOCs, meaning that concentrations decreased proportional to the increase in ventilation. For a subset of compounds, including formaldehyde, the indoor concentration exhibited a non-linear dependence on air exchange rate. This result is indicative of a chemical whose emission rate from materials is suppressed when there are substantial concentrations in the air, relative to those that would exist in an equilibrium condition. In other words, there is enough of the compound already in the air to affect the rate at which it is emitted from materials. At low air exchange rates, emissions are reduced because of this. When ventilation is increased, the concentration of the compound in air is lowered and the emissions then increase. The result is that the concentration in the air is not reduced proportional to the increase in ventilation rate.

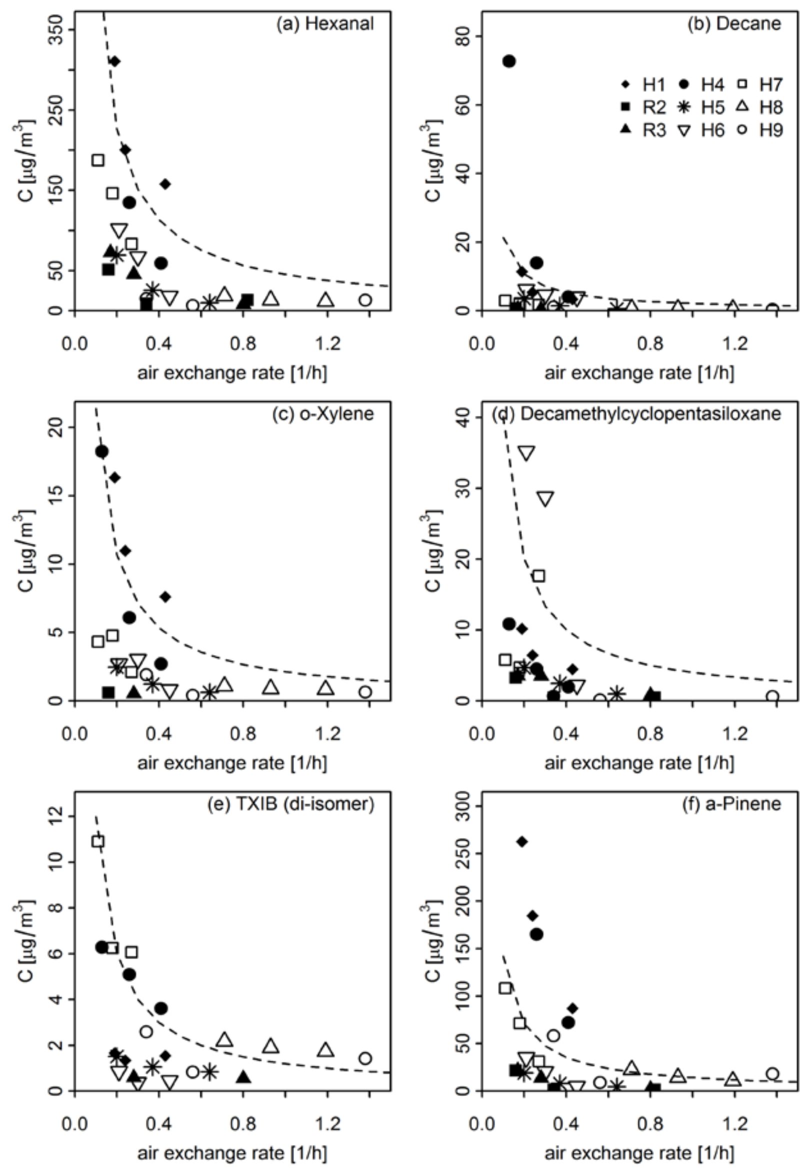
Despite efforts to control environmental factors, it was difficult to maintain constant ventilation conditions in the residences (particularly in occupied homes). For example, intermittent sources of VOCs from cleaning, as well as opening of windows, affected the results. The uncertainty in some of the measured and calculated quantities, principally the air exchange rate, was considerable; this affected the degree to which the impacts of interest (which are the changes in concentration and especially calculated emission rate as a function of air exchange rate) could be resolved. Nevertheless, the experiments still provided a clear indication that increasing ventilation can be used to mitigate high concentrations of VOCs in new homes.

Figure 3.2.1: Concentration of (a) Formaldehyde and (b) Acetaldehyde for Three Air Exchange Rates at Each Study Home.



The results of this study indicate that increasing the ventilation rate tends to lower indoor concentrations of VOCs with indoor sources. For most compounds for which indoor sources are much larger contributors than entry from outdoors, the indoor concentration is proportional to the inverse of the air exchange rate in the space. For a minority of the target compounds studied here, it appears that the concentration does decrease with increasing air exchange rate, but that the reduction is less than proportional (i.e., for chemicals with a large amount of material in storage in building materials and furnishings, doubling the air exchange rate will reduce the indoor concentration, but not to as low as one-half of the original concentration). This improved understanding of the chemical specific dependence of indoor concentration on air exchange rate is helpful. However, increasing the air exchange rate remains an effective mitigation strategy to reduce the indoor concentration of VOCs with indoor sources. Reductions in indoor VOC concentrations are most dramatic when increasing the ventilation rate up to roughly 0.4 ACH or greater. To understand how VOCs may be depleted from building materials and furnishings over time, further research is needed. Of particular value would be data collected from the same buildings over months and years, rather than just days. The ventilation rate can alter not only the immediate indoor concentration but also the rate at which compounds are depleted from building materials and furnishings. When short-term concentrations are reduced in a manner that is not proportional to the inverse of the air exchange rate, it is because the emission rate increases. A higher emission rate means faster depletion of the source. The impact of this increase in depletion rate varies, but in general it leads to lower concentrations over time.

Figure 3.2.2: Concentrations of Selected VOCs for Three Air Exchange Rates at Each Site. The Dashed Line Represents Results for a Reference Case in Which Concentrations are Proportional to the Inverse of the Air Exchange Rate (i.e. Doubling Ventilation Would Half Concentrations).



3.2.3 Model-Based Estimates of Ventilation Benefits and Costs

The hazard assessment identified chronic VOCs that exceed standards in some or many homes. Those with indoor sources potentially could be controlled with ventilation. The DALY-based impact assessment later identified acrolein and formaldehyde as the most important of these

VOCs with indoor sources that need to be controlled in homes. A theoretical analysis was conducted to determine if ventilation using clean outdoor air could be cost-effectively employed to mitigate exposures to VOCs generated in the home. We developed and applied a mass-balance indoor pollutant simulation modeling approach that works with the incremental ventilation energy (IVE) model and REGCAP model results to calculate pollutant concentrations for California homes based on air leakage inputs and mechanical ventilation and indoor emission data (Logue, Price et al. 2011). The analysis assumed a whole-house continuous emission rate of acrolein, though more work is needed to determine the intermittent versus continuous emission rate of acrolein in homes. This analysis found that the cost of increasing ventilation to reduce exposures to VOCs emitted in the home was balanced by the health benefits as assessed with the DALY-based approach. The caveat is that the analysis did not consider the costs of bringing in more outdoor particles, nor the benefits of diluting and removing particles generated indoors. More detail is presented in the Willem 2013 report.

3.3 Source Control for Cooking Burners

3.3.1 Importance of Cooking Burners to Pollutant Exposures

Cooking activities and natural gas burners can emit significant quantities of pollutants into the indoor space. We conducted an analysis to assess the impact of natural gas cooking burners on indoor pollutant concentrations and the potential benefits of widespread range hood use. This work was initiated as part of the Natural Gas Variability in California: Environmental Impacts and Device Performance activities, and advanced as part of the current project.

A mass balance model was applied to calculate time-dependent concentrations of nitrogen dioxide, carbon monoxide, and formaldehyde for one week each in summer and winter for a representative sample of homes in Southern California. The model simulated pollutant emissions from cooking, nitrogen dioxide, and carbon monoxide entry from outdoors, dilution throughout the home, and removal by ventilation and deposition. Residence characteristics were obtained from the Residential Appliance Saturation Survey and other sources. Ventilation rates, occupancy patterns, and burner use were inferred from household characteristics. Pollutant emission factors were measured for the Natural Gas Variability in California project mentioned above. The current project advanced this analysis by improving several of the model parameterizations, by incorporating an analysis of range hood use, and by producing a scientific paper to report this work through the peer-reviewed archival literature.

Our analysis indicates that unvented cooking is a substantial health hazard in California and potentially nationwide. Measured indoor concentrations were compared to outdoor standards (the National Ambient Air Quality Standards) for carbon monoxide and nitrogen dioxide and published guidelines for formaldehyde. Unvented natural gas cooking significantly affects occupant exposures on acute and chronic exposure time frames. For winter conditions the model estimates that 59 percent, 8 percent, and 53 percent of residents in homes that cook with natural gas without regular use of vented range hoods are exposed to nitrogen dioxide, carbon monoxide, and formaldehyde respectively at levels that exceed federal guidelines for acute exposure. Table 3.3.1 presents the statistics on the frequency of homes that exceed relevant air quality metrics. This means that indoor environmental concentrations in many California homes are at levels that, if they existed outdoors, would make those areas "nonattainment" with respect to ambient air quality standards.

The analysis was repeated for the hypothetical situation that all homes in the virtual sample used a venting range hood for the duration of each cooking event. We used a pollutant capture efficiency of 55 percent for the range hood based on measurements from (Delp and Singer 2012). With regular use of even such moderately effective range hoods, the number of homes and individuals experiencing concentrations in excess of standards was reduced dramatically. The percentage of homes exceeding an acute standard decreased by over 70 percent. As shown in Table 3.3.1, when a range hood was used, the percentage of homes with an exceedance for nitrogen dioxide was reduced from 52 percent to 15 percent; for carbon monoxide, from 7 percent to 2 percent; and for formaldehyde, from 51 percent to 27 percent.

Table 3.3.1: Households with Concentrations Exceeding an Acute Health-Based Pollutant Standard from Use of Natural Gas Cooking Burners.

Homes in SoCal (n=6,634)	Winter no hood	Summer no hood	Winter with hood
NITROGEN DIOXIDE			
1-hour Standard Exceedances (NAAQS)			
Percent of homes with exceedance	52%	37%	15%
Percent of homes with exceedance due to indoor emissions only	48%	34%	14%
Mean exceedances per home exceeding standards	3.5	3.2	3.0
CARBON MONOXIDE			
1-hour Standard Exceedances (CAAQS)			
Percent of homes with exceedance	6%	3%	1%
Percent of homes with exceedance due to indoor emissions only	6%	3%	1%
Mean exceedances per home exceeding	2.5	2.4	2.4
8-hour Standard Exceedances (NAAQS)			
Percent of homes with exceedance	7%	2%	2%
Mean exceedances per home exceeding standards	2.4	2.1	1.8
FORMALDEHYDE			
1-hour Standard Exceedances (CAAQS)			
Percent of homes with exceedance	25%	17%	11%
Mean exceedances per home exceeding	3.5	3.3	2.8
8-hour Standard Exceedances (NAAQS)			
Percent of homes with exceedance	51%	26%	27%
Mean exceedances per home exceeding standards	3.3	3.1	3.0

3.3.2 Performance of Currently Available Range Hoods

Controlled laboratory experiments were conducted to characterize the performance of a sample of range hoods that span the range of designs and nominal capabilities of hoods costing up to about $650 in 2011 (Delp and Singer 2012). These experiments were designed to build on performance measurements conducted on installed units in residences for the Natural Gas Variability in California project. The installed, in-use devices were in many cases found to have flow rates below those advertised in product literature and to have capture efficiencies that allowed a large percentage of cooktop or oven exhaust to enter the living space of the home. It could not be determined from the in-home measurements how much the specifics of the installation or equipment aging contributed to the measured performance. The experiments for the current project used new range hoods installed and operated under standard conditions; this enabled a more clear and objective assessment of currently available cooking exhaust devices.

Table 3.3.2 presents summary characteristics of the range hoods evaluated in the laboratory study. All hoods were purchased new from retailers. The experimental protocol included measurement of airflow across a range of duct static pressures and measurement of capture efficiency across a range of airflows. The latter set of measurements enables assessment of the capture efficiency (CE) performance of the basic hood geometry independent of the fan performance. First pass capture efficiency is the fraction of pollutants emitted at the burner that are drawn up into the hood before they can mix throughout the kitchen and potentially other parts of the house, i.e. they are captured on their first pass up from the stove and past the range hood. Also quantified was fan efficacy, an efficiency measure defined as the volumetric airflow per unit of power input. The current ENERGY STAR qualification for range hoods is that they produce at least 2.8 cubic feet per minute of airflow per watt of power input (cfm W^{-1}) at a setting that also produces less than 2 sones of sounds. The rightmost column of Table 3.3.2 shows that only one of the seven hoods achieved the rated or advertised airflow at the high speed setting with duct pressure at the standard rating point of 25 Pa. Three more of the hoods achieved airflows above 90 percent of rated and two more had airflows above 80 percent of rated flow. It is noteworthy that one of the ENERGY STAR-qualified hoods only achieved 52 percent of the rated flow. This result was confirmed by purchasing a second unit of the same model.

Table 3.3.2: Characteristics of the U.S. Cooking Exhaust Devices Evaluated in This Study.

Hood[a]	Description	Price	Fan Type	Rated sound (sone) and flow ($L \cdot s^{-1}$) at 25 Pa				Measured flow at 25 Pa
				Low		High		High
				Sound	Flow	Sound	Flow	(% of Rated Flow)
L1	Basic, Low cost	$40	Axial	n/a [b]	n/a [b]	6	90	86
B1	Basic, Quieter	$150	Axial	n/a [b]	n/a [b]	4.5	104	93
A1	ASHRAE 62.2 [c]	$250	Centrifugal	0.3	52	5.5	132	80
E1	ENERGY STAR	$300	Centrifugal	1.5	71	4	127	52
E2	ENERGY STAR	$350	Centrifugal	1.1	57	6	118	94
M1	Microwave	$350	Centrifugal	n/a [b]	61 [d]	n/a	198 [d]	95
P1[c]	Premium	$650	Centrifugal	- [e]	- [e]	5.4	129	100

[a] All devices were 30” (76 centimeter, cm) nominal width, designed to mount against a wall. Depth is the length from back to front of the device; air inlets spanned only part of this distance for most devices (see Supplemental Information in Delp and Singer 2012 for details).

b Rating information not available.

c Compliant with requirements of the ASRHAE 62.2 residential ventilation standard. Hood A1 was the least expensive hood that was found to be a commonly available hood and compliant with the standard.

d Airflow and sound provided in product literature without a specified backpressure condition.

e Single-speed unit.

Figure 3.3.3 shows the summary results of the CE experiments for these hoods. Complete results, including calculated fan efficacy and the method for measuring CE, are presented in Delp and Singer (2012).

This study demonstrates the importance of considering multiple criteria to evaluate cooking exhaust hood performance. The low- to moderately-priced devices evaluated in this study achieved high CE, high fan efficacy, and quiet operation, but not all at the same time. A microwave hood (M1) and an ultra-quiet hood (A1) demonstrated capacity for quiet operation at low speed and first-pass CE exceeding 70 percent for oven and front burners and exceeding 90 percent for back burners when operated at high speed. These devices use very high flow rates to overcome physical designs that are less conducive to capturing cooktop burner exhaust. The best and most robust device for CE (P1) has a large volume, open hood that extends farther over the cooktop and exhausts air at Home Ventilating Institute (HVI)-recommended flows.

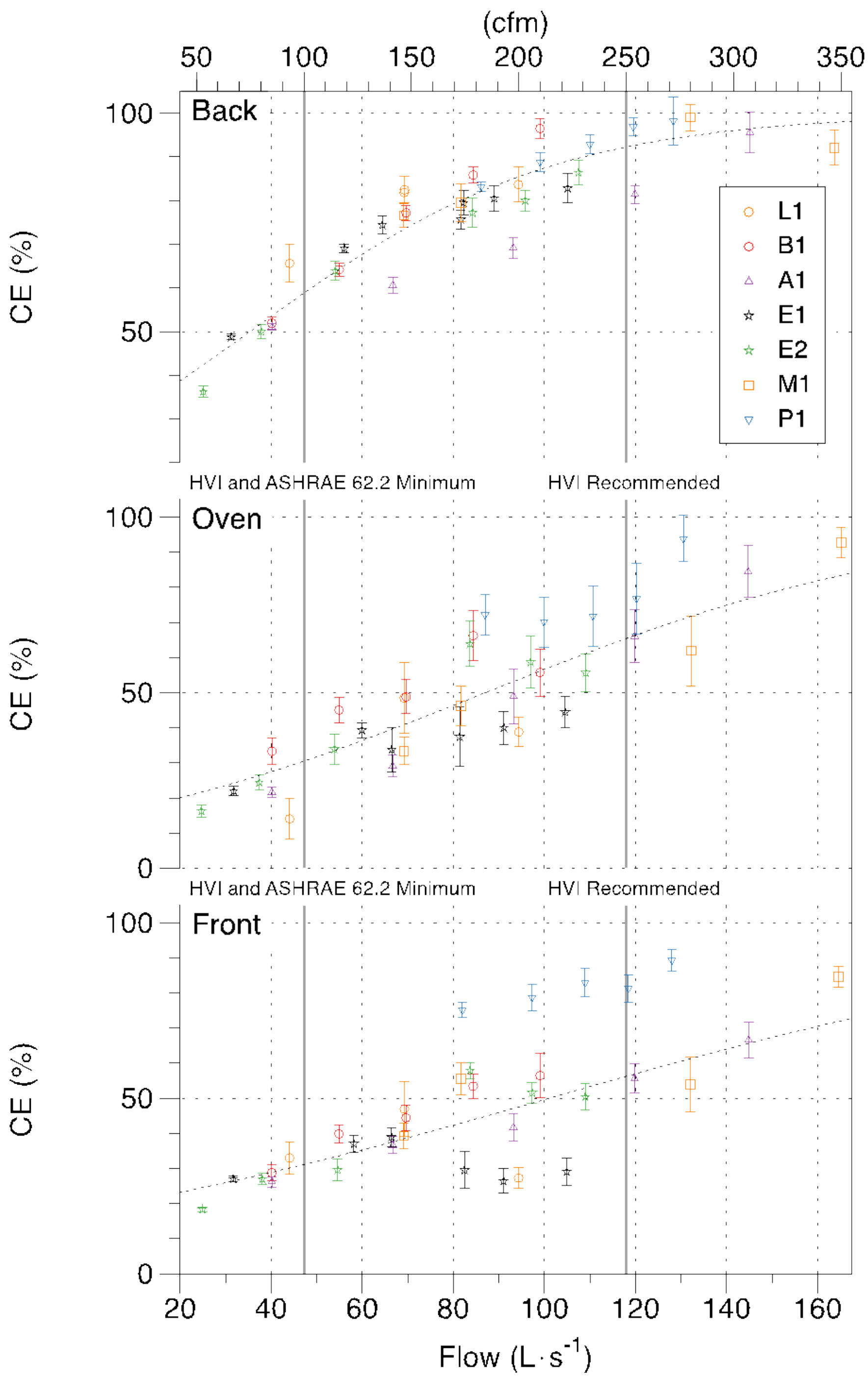
This hood achieved CEs exceeding 90 percent for back burners and more than 80 percent for oven or front burners, even when added airflow resistance reduced air flow rates below HVI recommended levels. Fan efficacy for this device was just below the ENERGY STAR criterion, but sound levels were significantly above the 2-sone ENERGY STAR limit. Current ENERGY STAR standards do not consider the pollutant removal purpose of cooking exhaust fans and therefore do not adequately address performance efficiency.

Currently there is no standard test or rating system for CE of residential cooking exhaust hoods. Development of a test and rating system would allow incorporation of capture efficiency into ENERGY STAR, ASHRAE 62.2, and other standards.

To avoid increasing the backdrafting risk for natural draft appliances and to reduce energy penalties, it is necessary to improve pollutant removal performance without resorting to increased air flows. Our results indicate that products can be improved by (1) improving geometry of hood construction by being deeper front to back, and having recessed grease traps and blower entries up inside the hood; and (2) incorporating better fans and motors.

Routine use of even moderately effective venting range hoods can substantially reduce in-home exposures to cooking and burner-generated air pollutants. Effectiveness can be substantially enhanced by preferential use of back versus front cooktop burners and by using higher fan settings.

Figure 3.3.3: Measured Capture Efficiency of Common U.S. Cooking Exhaust Hoods. Stacked Panels Present Results for Back, Oven, and Front Burners from Top to Bottom. The Heavy Vertical Gray Lines Indicate Minimum Flow Specified by HVI and ASHRAE 62.2, and the HVI-Recommended Flow HVI. Error Bars Reflect Variations in Exhaust CO_2 Measurements (Refer to Text for Details). Dashed Lines Present a Logistic Function Fit to the Data to Aid Identification of Hoods That Perform Better or Worse than the Trend.



3.4 Summary of Findings

Formaldehyde and acrolein and $PM_{2.5}$ were found to be the pollutants of highest concern in homes. Increasing ventilation in the home reduces exposure to formaldehyde and acrolein. However, increasing airflow through the home can increase the rate at which outdoor pollutants are brought indoors, particularly $PM_{2.5}$. This study identified $PM_{2.5}$ as the most important pollutant for chronic health impacts in residential environments. While indoor sources such as combustion and chemistry significantly impact indoor $PM_{2.5}$ concentrations, a significant fraction of homes may have higher concentrations outdoors than indoors, indicating that more ventilation may actually increase health risks. Providing ventilation air via filtered supply or filtered balanced ventilation using heat/enthalpy recovery ventilators is one potential solution. Another option is to filter the indoor air independent of the ventilation system to reduce indoor $PM_{2.5}$ concentrations. Including measures to reduce indoor particle concentrations in ventilation standards could greatly improve IAQ from a health perspective.

Our analysis indicates that removing pollutants near their point of release using effective localized exhaust ventilation is key to maintaining good IAQ. The two main types of localized exhaust in ventilation standards are kitchen and bath ventilation. Effective kitchen ventilation is needed to mitigate acute pollutant events resulting from combustion-based cooking appliances and food preparation activities. Task ventilation (e.g., range hoods) can also significantly mitigate chronic exposures by removing pollutants at their source. ASHRAE 62.2 requires a kitchen exhaust fan that is above the cooktop and provides at least 100 cubic feet per minute (roughly 50 $m^3 h^{-1}$) of airflow while producing 3 sones or less of noise. The standard does not specify a minimum pollutant capture efficiency or sound limits at higher flow rates. Our experiments found that for common hood designs, meeting the current ASHRAE standard of 100 cfm does not ensure high capture efficiencies. When front burners are used, common hood designs can require 200 cfm or greater to achieve capture efficiencies exceeding 80 percent. Requiring a high pollutant capture efficiency and potentially requiring automatic fan use when the range is operated could significantly improve indoor air quality. Four out of five of the identified acute contaminants of concern (except chloroform) are emitted by combustion or cooking. It is critically important to make sure that there is effective ventilation for all indoor combustion. Research is needed to determine if the health benefit of adding a commissioning requirement to ventilation standards is worth the cost.

The identification of formaldehyde, acrolein, and $PM_{2.5}$ as the highest priority pollutants for chronic exposure opens opportunities to improve energy efficiency through consideration of control measures complementary to ventilation.

Chapter 4:
Ventilation Systems

4.1 Optimized Mechanical Ventilation with the Residential Integrated Ventilation Controller

Ventilation systems are becoming commonplace in new construction, remodeling/renovation, and weatherization driven by combinations of specific requirements for indoor air quality and health and compliance with standards, such as ASHRAE 62.2. California has required compliance with ASHRAE 62.2 in its residential energy code (Title 24) since 2010. At the same time, there is an effort to reduce energy use in homes and therefore to minimize the energy used to provide ventilation. One way to reduce the energy used to ventilate homes is to use a ventilation controller that ensures equivalence with ASHRAE 62.2 while operating the whole-house ventilation system in such a way as to minimize energy use. The Residential Integrated Ventilation Controller (RIVEC), suitable for use in homes, was initially developed by the California Energy Commission through its Energy Innovation Small Grant program. The initial development of RIVEC was refined and then evaluated in this study.

The RIVEC energy reductions are achieved by:

- sensing the operation of other exhaust and supply fans in the house and reducing the operation of the whole-house fan to account for the extra ventilation these fans provide.
- turning off whole-house mechanical ventilation during times of peak indoor-outdoor temperature differences while ventilating more during off-peak times.
- lowering ventilation rates when there are high levels of outdoor pollutants, e.g., ozone.
- turning off whole-house mechanical ventilation during unoccupied times.
- accounting for infiltration. (This will be of increasing importance for the 2013 version of ASHRAE 62.2, which requires much higher baseline mechanical air flow rates and greater infiltration credit.)

To accomplish these reductions, RIVEC must be able to regulate the state of the installed mechanical ventilation system and sense when all significant exogenous mechanical ventilation systems are operating. For example, if a vented clothes dryer is running it is likely that the minimum whole-house ventilation rate will be satisfied by this alone, and so the RIVEC-controlled device does not need to operate at the same time once the indoor air quality has reached a desirable level. To prevent rapid cycling or switching of the whole-house ventilation fan, the controller makes decisions at fixed times. A reasonable strategy to balance between rapid cycling and overshooting is to use time steps of 10 minutes between decisions about turning the fan on or off. To ensure that RIVEC maintains equivalent indoor air quality to a continuously operating system, it uses the principles and physical relationships from Sherman, Walker and Logue (2012) and Sherman, Mortensen and Walker (2011). Sherman and Walker

(2011) showed specifically how this equivalence principle can be applied to meeting ASHRAE Standard 62.2, and therefore Title 24.

To provide ventilation equivalent to ASHRAE 62.2, RIVEC must be programmed with specific house and system parameters:

- Floor area of the house
- Volume of the house
- Number of bedrooms (a surrogate for the number of occupants)
- Target ventilation rate
- Peak hours for turning off the whole-house fan
- Airflow capacity of the whole-house mechanical ventilation system
- Airflow capacities of each exogenous mechanical ventilation system (e.g., bathroom fans, kitchen range hoods, and vented clothes dryers)

RIVEC uses these inputs in an algorithm to estimate the dose and exposure for the home relative to that provided by a continuously operating fan that complies with ASHRAE Standard 62.2. The fan controlled by RIVEC must be oversized relative to a continuously operating fan to compensate for the times while the fan is off. A fan sized to 125 percent of the ASHRAE 62.2 minimum ventilation rate is required for a fan that will be switched off for at least four hours every day. The relative dose and relative exposure are the ratio of the dose and exposure using the RIVEC controlled fan to the dose and exposure if a continuously operating fan were used.

4.1.1 Development of New RIVEC Algorithms

The RIVEC control algorithm has recently been modified as part of the RESAVE project to dispose of the pre-peak and post-peak shoulder periods, to remove minimum and maximum ventilation rates, and to include occupancy sensing (Turner and Walker 2012). These measures were implemented to both simplify the control algorithm and make it more robust for a larger range of houses with different ventilation strategies.

The new algorithm recognizes only two time periods: a peak energy demand period and a non-peak energy demand period (i.e., normal operation). During normal operation the whole-house ventilation strategy is controlled by controlling the upper limit of both the relative exposure and the relative dose. The values of these upper limits depend on the occupancy of the house. While the house is occupied, the relative exposure is limited to a maximum of 0.95. The relative dose is limited to a maximum of 1.0 such that occupants experience indoor air quality at least as good as if a fan were continuously operating. If the relative dose and exposure are less than these values, RIVEC switches off the ventilation device. As soon as either of these values has been exceeded, the ventilation device is switched back on. During unoccupied periods the algorithm will activate the ventilation system only if the upper limit to the relative exposure is exceeded. This allows the ventilation device to be off for longer periods while the house is unoccupied, as the inhabitants will not be exposed to the higher levels of indoor contaminants, while limiting the peak levels that a returning occupant is exposed to at the beginning of the occupancy period.

The peak periods are hardcoded into the controller. For this study, 4 a.m. until 8 a.m. was used for heating days, and 2 p.m. until 6 p.m. was used for cooling days. As heating and cooling set points were used to control the furnace and the air-conditioning, very occasionally there would be both heating and cooling on the same day. The RIVEC algorithm allows there to be no more than one peak period with reduced whole-house ventilation on these days, to avoid a situation where the ventilation system could be off for two four-hour periods (eight hours total) in any single calendar day.

The 2010 edition of ASHRAE Standard 62.2 has a default infiltration credit of 10 liters per second (L/s) per 100 m^2 (2 cfm/100 ft^2) of floor space. This infiltration credit is used to reduce the installed mechanical fan airflow requirements for the whole-house ventilation system. It does not apply to local exhaust ventilation.

The RIVEC controller cannot sense the contribution of infiltration toward ventilation, but this contribution still needs to be accounted for in the calculations. This study used the ASHRAE 62.2-2010 approach of including the default infiltration credit of 10 L/s per 100 m^2 in the target whole-house ventilation rate. This was to allow easy comparison with the existing ASHRAE 62.2 standard. Consequently, for the simulations the default infiltration credit was used as a baseline ventilation rate in the RIVEC calculations.

Addendum N to ASHRAE 62.2 has recently been published (and will be part of the 2013 version of the standard). It revises the standard to:

- explicitly include the default in the total airflow requirements,
- include the full infiltration credit (rather than the current half-credit),
- update the weather factors (including adding many hundreds more weather stations), and
- move all the required calculations into Standard 62.2, thus eliminating the references to Standards 119 and 136.

The difference between the old ASHRAE 62.2 method and new Addendum N in terms of total ventilation rate is usually small, but tighter homes will require more mechanical ventilation.

It is envisioned that the RIVEC controller will have a preprogrammed look-up table that will allow the appropriate ventilation credit to be set by selecting a building envelope leakage and weather factor. The infiltration credit will be a fixed value dependent on climate zone and independent of local fluctuations in the weather data.

Currently ASHRAE 62.2 only allows the use of intermittent ventilation operating to a *fixed* schedule. This prohibits the use of RIVEC as it operates to a *non*-fixed, adaptive schedule based on levels of relative dose, exposure, and occupancy, so further amendments to the standard are being proposed as a result of the RIVEC work. Because Title 24 references the 2007 version of ASHRAE 62.2, it does not include changes made to later versions of ASHRAE 62.2 that allow the use of the equivalence principle that RIVEC is based on. The next version of Title 24 will use a more recent version of ASHRAE 62.2 that allows the use of controllers like RIVEC.

4.1.2 Simulations of Ventilation Systems Controlled by RIVEC

Four different residential ventilation strategies were simulated, operating with and without the RIVEC controller incorporated into the system:

1. Whole-house exhaust ventilation fan sized to meet ASHRAE 62.2 that operated either continuously or under RIVEC control.
2. Heat Recovery Ventilator (HRV) sized to twice the ASHRAE 62.2 minimum ventilation rate and synched to the air handler, operating on a timer (30 minutes out of every hour so as to meet ASHRAE 62.2 intermittent ventilation requirements) or under RIVEC control.
3. Central Fan Integrated Supply (CFIS) system sized to meet ASHRAE 62.2 flow rates when the heating or cooling system operates combined with a whole-house exhaust fan (that also meets 62.2). The whole-house exhaust fan operated continuously or under RIVEC control.
4. Economizer system that uses the air handler and an outside air vent to provide night cooling, combined with a whole-house exhaust fan sized to meet ASHRAE 62.2 that operated either continuously or under RIVEC control.

Each ventilation strategy was simulated for three house sizes based on the prototypes in Title 24, for three different house envelope air leakage levels, and for all 16 California climate zones.

The energy consumption and IAQ of the modeled houses was evaluated by minute-by-minute simulations of the heat and mass balances of the home for a year. The airflows, heat transfer, heating and cooling system operation, and energy use were simulated using the REGCAP residential building simulation tool. REGCAP was modified to simulate RIVEC in previous studies (Sherman et al. 2009; Sherman and Walker 2011). The simulation tool has been validated by comparison to measured data in homes in previous studies (Walker et al. 2006). The simulation program treats the attic volume and house volume as two separate well-mixed zones, but connected for airflow and heat transport, and includes heating and cooling system airflows. It combines mass transfer, heat transfer, and moisture models. The program allows the modeling of distributed envelope leakage and mechanical system airflows for ventilation and heating and cooling, as well as individual localized leaks such as passive stacks. Inputs are building air leakage characteristics (total leakage and leakage distribution), minute-by-minute weather data, weather shielding factors, building and HVAC equipment properties, and auxiliary fan schedules.

4.1.3 Energy and IAQ Results of RIVEC Simulations

For all simulations the estimated relative dose and exposure were controlled by RIVEC, so in none of the cases was the annual relative dose greater than one. The results showed that the RIVEC controller provided equivalent (or better) ventilation compared to ASHRAE Standard 62.2.

On average across all climate zones, house sizes, and envelope leakages (Figure 4.1.1), the RIVEC controller reduced the ventilation-related energy by 46 percent for strategy 1 (whole-house exhaust), 31 percent for strategy 2 (HRV), 43 percent for strategy 3 (CFIS plus whole-house exhaust), and 53 percent for strategy 4 (Economizer plus whole-house exhaust). This is an average of 43 percent across all mechanical ventilation strategies. The changes in ventilation-related energy reductions had greater climate variability than the fractional savings but small variability between house sizes and envelope leakage. The following results for climate variability are averaged over all house sizes and envelope leakages. For the whole-house exhaust, CFIS, and economizer systems the ventilation-related energy reductions were similar, ranging from a little over 300 kilowatt-hours (kWh)/year in Los Angeles to about 1,000 kWh/year in Arcata and Mount Shasta. For the HRV, RIVEC reduced the ventilation energy penalty in colder climates. The smallest reductions in ventilation-related energy were about 600 kWh/year in Oakland, and the greatest reductions were 1,600 kWh/year in El Centro.

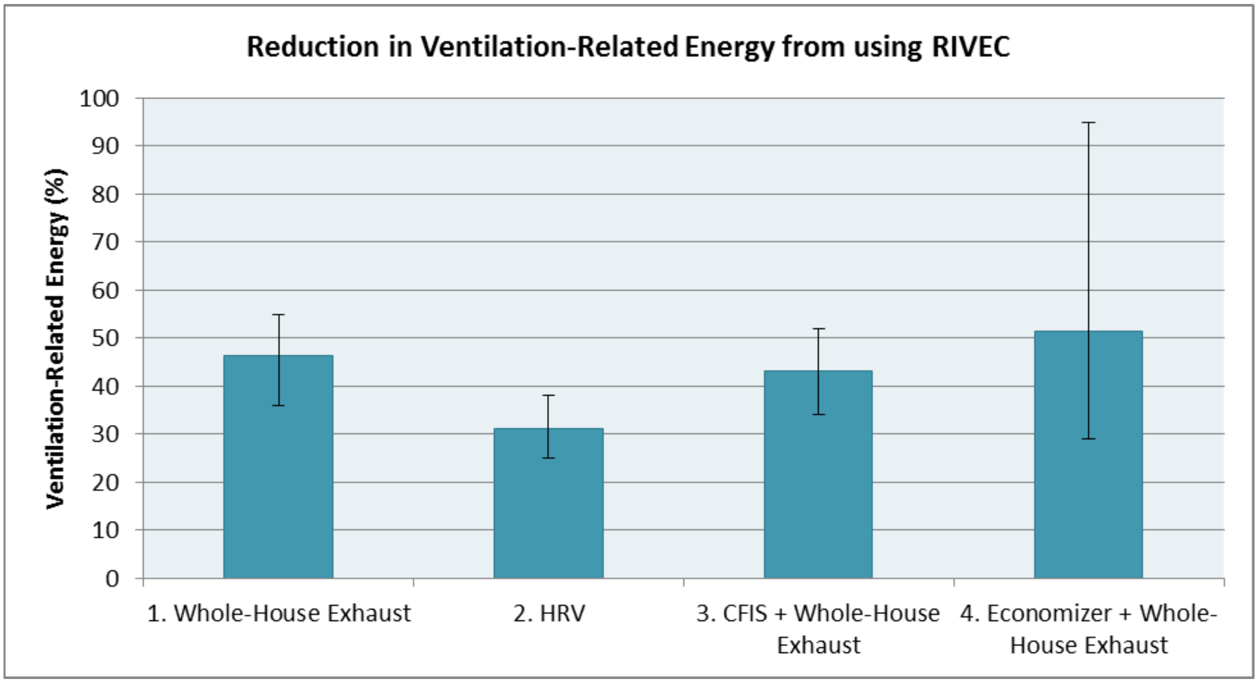
4.1.4 Recommendations for RIVEC Algorithms for Use in California Homes and Requirements for Acceptability in Building Codes

The RIVEC advanced ventilation controller will:

- typically reduce the ventilation-related energy from whole-house ventilation systems by at least 40 percent, while maintaining equivalence to ASHRAE Standard 62.2.
- ensure that exposures to constantly emitted indoor pollutants are within limits for acute exposure.
- provide ventilation energy reductions that are robust across climate, house size, and air leakage.
- provide absolute energy savings per household of 500 to 7,500 kWh/year, depending on climate—with more temperate climates at the lower end of energy savings estimates.
- allow significant peak power reductions of up to 2 kW for a typical home.

A RIVEC type advanced ventilation controller could provide an energy saving compliance option if it were allowed by Title 24. The annual energy savings could be included in Title 24 compliance calculations using the results of this study. Given that the savings are robust across climate zones, house size and air leakage a relatively simple approach is justified. If the Title 24 compliance software calculates the energy due to mechanical ventilation separately from other building loads, then the use of RIVEC should reduce this energy use by 40 percent. If the mechanical ventilation loads are not calculated separately, then the savings could be set at a fixed number of kilowatt-hours that varies by climate zone, as shown in Turner and Walker (2012).

Figure 4.1.1: The Reduction in Ventilation-Related Energy from Using RIVEC Averaged across All House Sizes, Envelope Leakages, and Climate Zones (with Maximums and Minimums Shown).



4.2 Sustainable Ventilation

Another approach to reducing the energy costs of ventilation is to use passive systems that reduce fan power requirements and installation costs. Passive ventilation has been used for centuries and is still popular in many European countries as a way to provide local exhaust and whole-house ventilation. The principle behind passive stack is that no fan is used, instead a vertical vent from inside to outside is used. A combination of stack and wind pressures on the vent cause air to be drawn from the house—specifically from the room in which the base of the vent is located (usually kitchens and bathrooms). Passive stacks have the advantage of not needing any electrical supply or maintenance of a fan. However, the airflow is much less controlled, and so this study also investigated the use of flow-limiting devices and auxiliary fans to create hybrid systems. The flow-limiting devices in this study limited airflow to 125 percent of that required by ASHRAE 62.2 for whole-house mechanical ventilation. In hybrid systems a fan is only used when the airflow in the stack is too low to provide sufficient ventilation. More details can be found in Turner and Walker (2012).

4.2.1 Summary of Passive and Hybrid Ventilation Techniques

Passive Stack Ventilation

Natural ventilation utilizes naturally occurring renewable energy sources such as wind and stack effects to achieve the same goal of bringing fresh air inside. The wind blowing over the top of the stack depressurizes the stack relative to the house. The magnitude of this wind pressure depends on the stack height and rain cap design, as well as the wind speed. The stack effect is due to differences in hydrostatic pressure between the inside and outside of the house due to the air being at different temperatures. The density of air is inversely proportional to its temperature, such that warm air is less dense than cold air, and the hydrostatic pressure in air depends on its density. With two columns of air—one inside and one outside the house—at different temperatures we can determine the resulting pressure difference between the two columns of air.

A *passive stack* is a device that exploits the wind and stack effect to provide ventilation. It is usually a vertical pipe or duct that extends upwards from the ceiling inside the occupied zone, and then protrudes through the roof. It provides an airflow pathway for ventilation air and protrudes above the roof of the house to maximize exposure to wind effects.

The naturally occurring pressure differences due to wind and the stack effect lead us to a residential ventilation strategy that requires zero energy expenditure on mechanical driving forces such as fans. However, the variable nature of the wind and the outdoor temperature mean that passive stack ventilation is both unpredictable and potentially unreliable. There will be times throughout the year of large, naturally occurring pressure differences resulting in over-ventilation. There will also be times of under-ventilation when these pressure differences are low. It is therefore important to have an appropriately sized passive stack to minimize the times of over- and under-ventilation. The airflow rate through the stack can also be augmented to desirable levels via the deployment of control strategies, such as flow dampers, to limit high ventilation rates, or auxiliary fans to increase it.

A *hybrid* or *mixed-mode* ventilation system utilizes both mechanical and natural ventilation. To overcome the unpredictable nature of natural ventilation, some form of mechanical control is used to regulate the airflow rate. The mechanical and natural components may be used in conjunction with each other or used separately at different times of the day. While acting as a control measure, the mechanical component may be used to regulate the natural ventilation process by restricting the airflow rate during periods of high natural driving forces or to provide additional ventilation at times of low natural driving forces (Buonomano and Sherman 2009).

4.2.1 Simulations of Passive and Hybrid Systems

The same REGCAP simulation tool was used for passive and hybrid systems as for the optimized mechanical ventilation systems. REGCAP includes algorithms for determining airflows through passive stacks, so it was ideally suited to these simulations. The same range of climates, house size, and envelope leakage that was used for the RIVEC simulations was used for the passive and hybrid simulations.

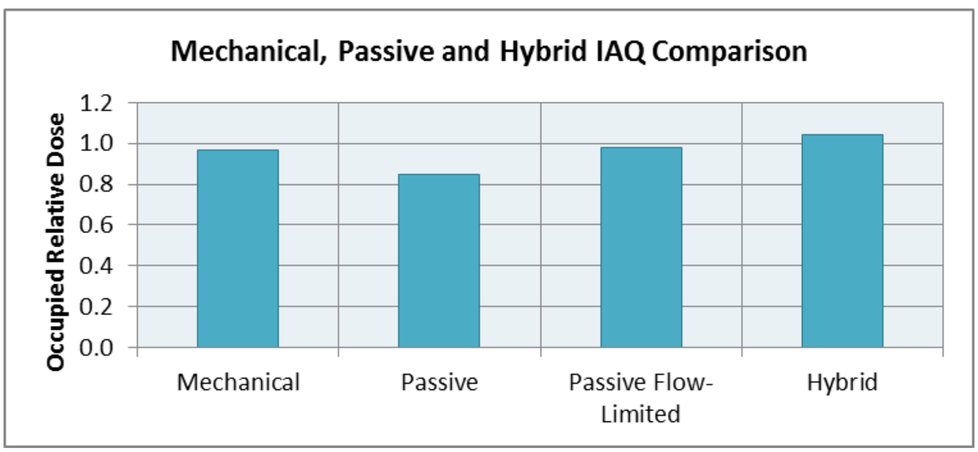
Two cases of passive stacks were simulated. The first was sized so that the daily average airflow would meet ASHRAE 62.2 airflow rates for at least 80 percent of the year (based on Mortensen Walker, and Sherman 2011a). The second used oversized passive stacks that would meet ASHRAE 62.2 for more of the year, but included an automatic damper to limit the maximum airflow to 125 percent of the ASHRAE 62.2 airflow rate to reduce over-ventilation.

The hybrid ventilation system used the same oversized passive stacks as the passive systems, but mechanically limited to 100 percent of the ASHRAE 62.2 minimum airflow rate, and in conjunction with a whole-house exhaust fan operating under RIVEC control, so that airflow rates never dropped below the ASHRAE 62.2 requirements.

4.2.2 Energy and IAQ Results for Passive and Hybrid Systems

In the simulations, the relative dose for several passive and hybrid systems was tracked during occupied times and then averaged over the year (Figure 4.2.2). The results for relative dose show that a passive stack sized to meet ASHRAE 62.2 for 80 percent of the year would be compliant with ASHRAE 62.2 on an annual basis. The occupied dose for the passive stack ventilation with no flow limiting was 12 percent lower than the baseline ASHRAE 62.2 complaint mechanical exhaust. This indicates over-ventilation, which results from there being no control over the ventilation rate. For the oversized and flow-limited and hybrid strategies, the airflow-limiting control measures mean that the relative dose was much closer to unity.

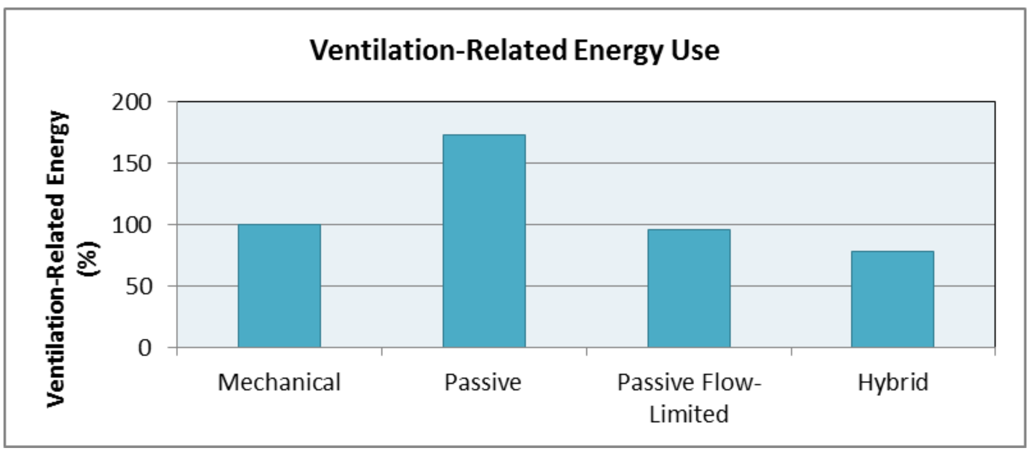
Figure 4.2.2: Mean Annual Occupied Relative Dose Averaged over All House Sizes, Envelope Leakages, and Climate Zones.



It is important to ensure that acute exposure levels are not exceeded too often or for too long. For example, asthmatics or rhinitis sufferers sensitive to contaminants such as formaldehyde could face considerable discomfort when exposed to high pollutant levels over short time scales, even though the annual averages are below the acceptable levels. The maximum occupied relative exposures averaged over 1-hour time periods for the passive stack ventilation systems were far below the maximum allowed value of 4.7, outlined by Sherman, Logue, and Singer (2011). Consequently, the 8-hour and 24-hour maximums were also not exceeded, as the peak hourly occupied relative exposure over the year never exceeded 1.93.

Figure 4.2.3 shows the fractional ventilation energy for the mechanical, passive, and hybrid ventilation strategies averaged over all climate zones. The results have been normalized so that the ventilation-related energy for the mechanical strategy represents 100 percent. The passive stack, on average, used 69 percent more ventilation-related energy than the mechanical exhaust strategy. The lack of flow regulation for the passive stack meant that the space-conditioning load increased considerably. The oversized and flow-limited passive stack strategy used 6 percent less ventilation-related energy than the mechanical exhaust strategy. This is a difference of 75 percent between the non-flow-limited passive system and the flow-limited passive system. The over- and under-ventilation tended to cancel each other out over the year. The remaining difference can be attributed to the fan energy, which was not required by the passive stacks. The hybrid strategy used 24 percent less ventilation-related energy than the whole-house exhaust. There was reduced fan energy compared to the mechanical exhaust strategy, and the airflow was limited to 100 percent of the ASHRAE 62.2 whole-house rate, so there was no over-ventilation with a subsequent increase in space-conditioning load. Combining the flow limiting in the passive stacks with the RIVEC-controlled whole-house exhaust fan successfully limited the extra ventilation-related energy use that results from over- and under-ventilation. The hybrid strategy used less energy than the mechanical strategy because the RIVEC controller prevented the whole-house exhaust fan from operating while the auxiliary exhaust fans operated, thus saving both fan energy and ventilation-related space-conditioning energy.

Figure 4.2.3: Fractional Ventilation Energy for the Four Whole-House Ventilation Strategies, Averaged over All Climate Zones and Normalized to the Mechanical Exhaust Strategy.



For most California climate zones there was very little difference in absolute energy use between the ventilation strategies; most of the difference in the averages is dominated by the climate zones with severe weather, such as Arcata and Mount Shasta. A decision to use passive or hybrid ventilation instead of mechanical ventilation would then come down to user preference, or installation and maintenance costs. More details of these simulation results can be found in Turner and Walker (2012).

4.2.3 Recommendations on Optimizing Passive and Hybrid System Sizing and Controls and Requirements for Acceptability in Building Codes

If passive systems are to be adopted, it is recommended that they include damper controls to limit over-ventilation to 125 percent of the ASHRAE 62.2 airflow rates. Table 4.2.1 can be used to determine the appropriate size of passive stacks for the three Title 24 Prototype Homes (Pro B, C, and D). The table gives the total required stack size that can be made up of one or more individual stacks of 15 cm and 20 cm diameter (these sizes are used as they are commonly available vent sizes that fit in typical construction). A table entry of 20 corresponds to a single 20 cm diameter stack, an entry of 35 is for a 20 cm diameter stack and a 15 cm diameter stack, an entry of 40 is for two 20 cm stacks, an entry of 55 is for two 20 cm stacks and a 15 cm stack, and the 60 entry is for three 20 cm stacks.

Table 4.2.1: Oversized and Flow-Limited Passive Stack Diameters for the Prototype Houses.

	Flow Limited Passive Stack Diameter* [cm]															
CZ	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Pro B (1200 ft^2)	20	35	20	35	20	20	35	40	40	40	40	35	40	40	60	35
Pro C (2100 ft^2.)	20	35	20	35	20	20	35	40	40	35	35	35	40	40	60	35
Pro D (2700 ft^2)	20	35	20	35	35	35	35	55	40	35	40	40	40	40	60	35

4.3 Ventilation System Commissioning

4.3.1 Introduction

Beginning with the 2008 version of Title 24, new homes in California needed to comply with the ASHRAE Standard 62.2 (2007) requirements for residential ventilation. These requirements include minimum airflows for whole-house mechanical ventilation, as well as minimum airflows for local ventilation, maximum total exhaust airflow for combustion safety, garage and duct air-tightness, and maximum specific fan power. Designs that comply with prescriptive requirements or manufacturer's criteria do not require field verification of airflows or power, but central-fan-integrated systems do require these field tests. These requirements do not account for the fact the many homeowners are already running exogenous ventilation systems (including economizers, direct evaporative coolers, dryers, or kitchen hoods). They also do not consider that low-emission materials may be used to reduce ventilation needs or that high-emission materials lead to increased ventilation needs.

Currently, few California houses have mechanical ventilation systems. Where installed, the limited data available indicate that ventilation systems do not always perform at the expected level based on system specifications, or even as many codes and forecasts predict. Deficiencies occur in part because there is no consistent process to identify and correct problems, and also because the value of such activities in terms of reducing energy use and improving IAQ is unknown. Commissioning such systems when they are installed or during subsequent building retrofits is a step toward eliminating deficiencies and optimizing the trade-off between energy use and acceptable IAQ.

Work funded by the Energy Commission about a decade ago at LBNL documented procedures for residential commissioning and demonstrated the value of the overall process, but it did not focus on ventilation systems and did not disaggregate the related potential savings. Since then, standards and approaches for commissioning ventilation systems have been an active area of work in support of European standards, and new analytical methods have been developed to assess the potential value of energy use and IAQ benefits on a common scale. To take advantage of these opportunities, we:

- collected new literature on commissioning procedures and identified information that can be used to support the future development of residential-ventilation-specific procedures.
- determined the combined energy and IAQ potential value of commissioning systems that are intended to comply with the whole-house ventilation component of the California Title 24 residential ventilation requirements.

The following sections provide background about the residential ventilation commissioning process that we envision, describes the literature review findings and potential value assessment (i.e. the monetization of potential energy and health costs and benefits), summarizes this study's findings and the benefits to California, and lists recommendations for future work.

4.3.2 Procedures and Standards for Commissioning

4.3.2.1 The Residential Ventilation System Commissioning Process

Every commissioning process includes three principal elements: metrics, diagnostics, and norms. The following bullets define these elements and offer examples to aid understanding:

- *Metrics*: For whole buildings, there are two broad performance objectives of interest: energy performance and indoor environmental performance (e.g., indoor air quality and comfort). Each objective can be represented by various performance metrics, which are defined as a quantification of the performance of relevant components or systems. Three examples are: (1) unbalanced ventilation airflow, which represents the difference between supply and exhaust ventilation airflows, (2) specific leakage area, which represents the air-tightness of the building envelope, and (3) house depressurization, which is often used to represent the backdrafting potential for combustion appliances. Each of these metrics has implications in terms of energy and indoor environmental performance. However, the importance of a particular metric to each performance objective may be weighted differently, and therefore each must be able to stand on its own.
- *Norms*: A metric itself does not indicate good or bad performance. However, when quantified, each metric forms the basis for developing the norms against which component or system performance is compared. As with the metrics, the norms will vary depending on the objective of the commissioning. They will also depend on the stage of the house in its life cycle. For the metrics related to building performance, consider that various building standards could specify requirements for maximum airflow imbalance, for minimum or maximum specific leakage area, and for maximum house depressurization levels.

- *Diagnostics*: Diagnostics are defined here as relatively quick, short-term field procedures involving measurements (and perhaps analyses) to evaluate performance metrics for a system or component under a functional test or actual building site conditions. While it is also possible and sometimes preferable to evaluate metrics using data taken over an entire season, time limitations make it impractical to collect and analyze such long-term information during ventilation system commissioning. Such limitations will be largely dependent on the value of the commissioning process to the involved parties. In some rare cases, for an existing house, commissioning might be able to use readily available historical data, either as part of diagnostics or to set norms, if appropriate measurement equipment was already installed. From the building performance examples above, consider ventilation airflows. A possible diagnostic is to use airflow measuring equipment, such as a commercially available flow capture hood.

The same metrics and diagnostics can be used in new and existing houses, although some diagnostics may not be appropriate early in the construction process. However, the norms for existing houses will have to be adjusted to account for the economic viability of meeting stricter standards than those in place at the time of construction. For example, a house built in 1930 does not come close to meeting current Title 24 specifications for air-tightness and mechanical ventilation. The retrofitting required to meet Title 24 air-tightness levels in this example would be prohibitively expensive.

Published commissioning processes for commercial buildings are too onerous for houses. The ventilation system commissioning process proposed here is simpler and has three main phases that combine auditing, testing, and implementing improvements to enhance component and system performance:

- *Audit and Diagnostic*: In the first phase of commissioning, metrics for the house are surveyed using instrumented and non-instrumented techniques. The survey results are then compared with the house norms. For new construction, the norms will be those of the Title 24 compliance material or of the equivalent local building codes. For an existing house, the norms may be based on design intent (in the rare cases where any was documented) or on what a particular component should be able to do compared to other similar houses.
- *Tuning and Tweaking*: The performance of many components and systems may not meet the norms, but it will be possible to improve their performance by making minor adjustments, repairs, or retrofits on the spot. An example is adjusting airflows so that they balance. Tuning and tweaking can often provide significant performance improvements for very little marginal cost. The purpose of this step is to improve house performance to at least the design intent. Sometimes that intent will be unknown. In those cases, the optimization will be to other norms, such as the best performance achievable without repair or retrofit.
- *Opportunity Identification*: After tuning and tweaking, there still may be components that are not performing to their potential. This commissioning step provides the client with information about potential repair or retrofit opportunities that could be investigated

further (e.g., sealing the garage-house interface). Even when components are performing to their norms, newer technology may make replacement worth considering.

4.3.2.2 Literature Review

We carried out a topical literature review related to ventilation system commissioning and produced an annotated bibliography to build upon our past literature review and to support related work (Wray 2012). Full details of the literature search are available in Wray 2012. The focus was on metrics, norms, and diagnostics related to mechanical ventilation systems, which include:

- Airflow through and pressure rise across fans.
- Airflow through, pressure loss, and leakage of ducts and associated components.
- Ventilation controls.

A substantial amount of new information related at least peripherally to ventilation system commissioning has been published over the past decade. In particular, about 300 new documents were identified but only a limited number of documents were relevant to developing commissioning protocols for residences. .

The most advanced and relevant references are European: the eight parts of CEN 13141 (*Ventilation for buildings – Performance testing and installation checks of residential ventilation systems*.) related to "Ventilation for buildings – Performance testing of components / products for residential ventilation" and CEN 14134:2004.

Each of the eight parts of CEN 13141 describes methods specifically for *laboratory* performance testing of residential ventilation components and products. CEN 14134 describes *field* installation completeness checks and functional tests for commissioning installed mechanical and passive ventilation systems in dwellings. The rest of the literature reviewed remains relatively devoid of field-test-related information that can be used in isolation to commission residential ventilation systems. For example, ASHRAE Standard 111-2008, "Measurement, Testing, Adjusting and Balancing of Building Heating, Ventilation and Air-Conditioning Systems," describes many field diagnostic techniques for use in commercial building test and balance (TAB) activities. However, many of these diagnostics are not suitable for residential ventilation system commissioning because:

- the diagnostic is impractical or takes too long (e.g., pitot-static tube traverses of ducted airflows, where the ducts are often inaccessible, too short, or not straight enough),
- the information provided relates to flows that are much larger than those typically found in residential systems (i.e., it does not address increased inaccuracies at low flows), or
- the guidance is not applicable (e.g., suggestions that flow hoods cannot be relied upon for accurate measurements).

If relevant information from each of the reviewed references was combined together along with the European work and the results of our work described in Sections 3.3.3 and 3.4 of this report, it could be used as the basis to prepare a future stand-alone residential ventilation system commissioning guide for practitioners.

4.3.3 Assessing the Potential Value of Commissioning

4.3.3.1 Approach

To demonstrate the potential value of commissioning residential ventilation systems, computer simulations were used to assess energy use and IAQ for new homes in California over a range of climate zones. Turner et al. (2012) describes these simulations in detail.

In summary, the energy and airflow simulations used REGCAP; LBNL's in-house residential building energy and ventilation simulation tool with mass, heat, and moisture transport models. A key aspect of REGCAP is that it explicitly accounts for HVAC system-related airflows (including duct leakage and grille flows), as well as airflows attributable to the effects of weather and leak location, and the interactions of HVAC system flows with house and attic envelope tightness. Three houses were simulated based on Title 24 housing prototypes in three California climate zones (Oakland, Sacramento, and Blue Canyon). The small- and medium-sized houses were single-story and had occupied floor areas of 1,200 ft^2 and 2,100 ft^2, respectively; the large house was two stories with an occupied floor area of 2,700 ft^2.

As described in the bullets below, we considered two ventilation systems with various malfunctions that could be identified or rectified by commissioning: a whole-house exhaust system and a heat recovery ventilator (HRV) system.

- The ASHRAE 62.2 minimum airflow was used as a baseline for normal operation of the mechanical whole-house exhaust system. The airflow was then simulated at 25, 50, and 75 percent of this airflow to represent underperforming ventilation strategies with inadequate airflows. Airflows of 200 and 300 percent of the 62.2 flow were also simulated to represent malfunctioning intermittent fans, to determine if there were any advantages or disadvantages to over-ventilation compared to the 62.2 minimum.
- A balanced and stand-alone (i.e., not integrated into the central forced air heating and cooling system) HRV system was simulated as a baseline. The HRV was sized to twice the 62.2 airflow and operated for the first 30 minutes of every hour. Airflow restrictions were then applied to the supply side of 50 percent and 100 percent to simulate blockages in the HRV ducts or supply registers. For the 100 percent blocked case (0 percent supply side airflow rate), there was no heat exchange with the incoming and outgoing ventilation air.

A simple time-step mass balance approach was used to calculate indoor concentrations and occupant exposures over the course of a year as a function of building air change and pollutant emission rates. Because this analysis focused on commissioning airflows for whole-house ventilation systems, we only considered the impact of controlling two continuously emitted pollutants that are dominant contributors to the chronic burden of indoor health: formaldehyde and acrolein (emitted by materials, combustion, and cooking). Although particulate matter with an aerodynamic diameter of less than 2.5 microns ($PM_{2.5}$) is also a dominant contributor, it was not considered because it is not continuously emitted. For each of the three homes in each of the three climate zones, three levels of pollutant loading (low, medium and high) were used, as shown in Table 4.3.1. The low, medium, and high emission rate for formaldehyde represent the 5th, 50th (median), and 95th percentile of household emission rates found in the California new homes field study by Offermann (2009). The low, medium, and high emission rates for acrolein represent the 5th, 50th, and 95th percentile emission rates measured by Seaman et al. (2007) in homes.

Table 4.3.1: Emission Rates for Formaldehyde and Acrolein.

Pollutant	Emission Rate [μg/(h m²)]		
	Low	Medium	High
Formaldehyde	9.7	30.3	88.2
Acrolein	1.3	1.9	6.1

Energy and IAQ impacts were converted to monetary values using a Time Dependent Valuation (TDV) approach for energy and a Disability Adjusted Life Year (DALY) impact assessment approach for IAQ, assuming a discount rate of 3 percent. The monetary impacts were combined over a 30-year period to represent the net present value (NPV) in 2011 U.S. dollars of the fiscal cost/benefit to the endpoint user (not including the actual cost of commissioning).

The TDV approach is used by the Energy Commission to preferentially weight California energy saved during peak periods, while the distribution grid is operating at or close to capacity. It uses factors applicable for a 30-year time period.

DALYs are a measure of overall disease burden and incorporate both disease likelihood and severity. They are reported as the equivalent number of years lost from premature death and disability. To determine the NPV of changes in exposure for each simulation for 30 years (to allow comparison with the 30-year TDV energy NPV), we determined the annual cost of DALYs lost or gained relative to a system that was operating at the level specified by ASHRAE 62.2. For these analyses, we assumed a central cost of $100,000 per DALY lost. The projected values for DALYs are on the order of $50,000 - $160,000 US. References for this range are provided in Turner et al. (2012).

4.3.3.2 Energy and Air Quality Potential Values

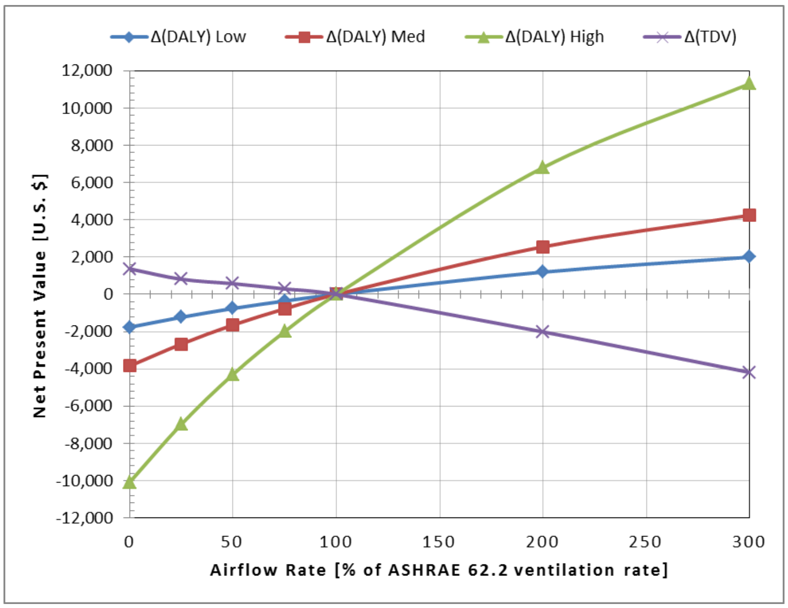
Results for the different house sizes and climate zones showed insufficient variability to justify independent discussion. As a consequence, the results described below are only for the medium-sized house in Sacramento and may be applied to other regions.

Figure 4.3.1 shows the monetized relationship between energy (represented by ΔTDV) and IAQ (represented by ΔDALY) at 0, 25, 50, 75, 100, 200, and 300 percent of ASHRAE 62.2 ventilation rates standard for three emission rates, low, medium and high (see Table 4.3.1). The net present value is set at $0 at the ASHRAE 62.2 ventilation rate standard. Figure 4.3.2 demonstrates the combined energy and IAQ benefit (i.e., the ΔTDV plus the ΔDALY from Figure 4.3.1) those three emission rates. A positive dollar value represents money saved (benefit), while a negative dollar value represents money lost (cost, or negative benefit). Under-ventilation represents an energy benefit from reduced mechanical ventilation energy and reduced heating and air conditioning loads, and an IAQ cost from higher contaminant levels. Conversely, over-ventilation represents an energy cost from higher fan energy use and increased space-conditioning loads, and an IAQ benefit from reduced contaminant levels.

As an example, consider the 50 percent airflow case in Figure 4.3.1 (whole-house exhaust delivering only half the ASHRAE Standard 62.2 flow). The TDV energy financial benefit is $576 over 30 years. This represents money saved on energy bills due to decreased ventilation. For the medium contaminant emission house with the same 50 percent airflow, the IAQ financial benefit is a *negative* $1,639 over 30 years. This represents money lost (or a cost) due to reduced air quality from increased exposure to indoor contaminants. When the energy and IAQ costs are combined in Figure 4.3.2, the net benefit is a *negative* $1,063, which represents an overall loss (the financial value of the energy saved is less than the financial value of life lost due to exposure to higher contaminant levels).

The worst case is a non-functioning (0 percent of the ASHRAE 62.2 airflow) whole-house exhaust system in the high-emission house. This will cost the occupants approximately $8,700 net over 30 years. Over-ventilating the same high-emission house with an airflow three times the 62.2 minimum will gain the occupant approximately $7,100 net (a $15,800 difference). In the latter case, fixing the system to meet the norm (ASHRAE 62.2) would actually be detrimental to the occupants because the value of the energy saved from reducing the system airflow rate is vastly outweighed by the benefit from improved IAQ.

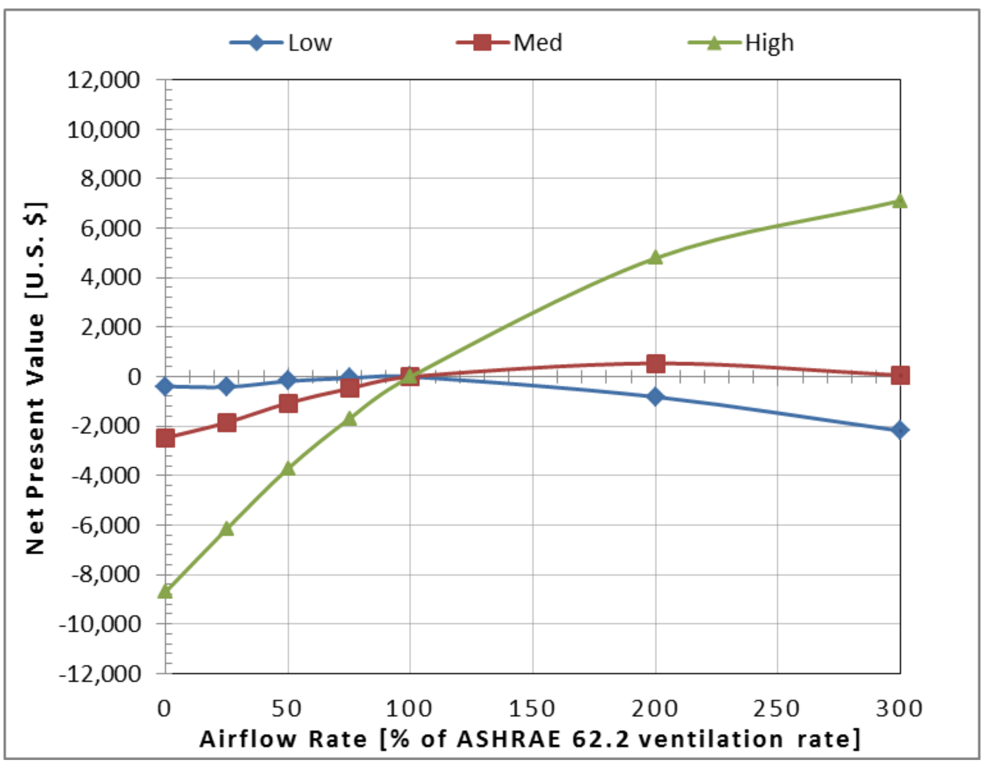
Figure 4.3.1: IAQ and Energy Components, Relative to 100 Percent ASHRAE 62.2 Airflow, for the NPV of Commissioning a Malfunctioning Title 24 Whole-House Exhaust System for Three Contaminant Emission Rates. Results Are for the Medium-Sized House in Sacramento.



However, the cost to the occupants of the low-emission house with a non-functioning whole-house exhaust system is approximately $390, which is comparatively small over a 30-year time period. The low-emission house sees a net loss of $2,200 from over-ventilating by 300 percent, due to increased energy consumption. In both cases, repairing the system to meet the norm would be beneficial.

Because HRV systems are less common, detailed results are not shown here (available in Turner et al. 2012). In summary, 0 and 50 percent supply-side airflow increase the TDV estimated energy cost due to reduced heat exchange between incoming and outgoing air, thus increasing the building heating load. The DALY estimated health cost also increases, due to reduced building air exchange rates (and higher indoor contaminant levels) from the imbalance in mechanical ventilation. As a result, there is no financial benefit to be had from an HRV system with blocked filters or supply registers relative to an HRV that operates as required by ASHRAE 62.2. A benefit might be seen if the HRV were to operate for longer than the intended time period each hour, but this was not simulated. Commissioning a blocked HRV would always be worthwhile, provided that the cost of commissioning is less than the combined cost of the energy used and life lost over 30 years (or some other acceptable payback period to the occupant).

Figure 4.3.2: Combined IAQ and Energy NPV from Commissioning Malfunctioning Title 24 Whole-House Exhaust System for Three Contaminant Emission Rates (Low, Medium, and High).Results Are for the Medium-Sized House in Sacramento.

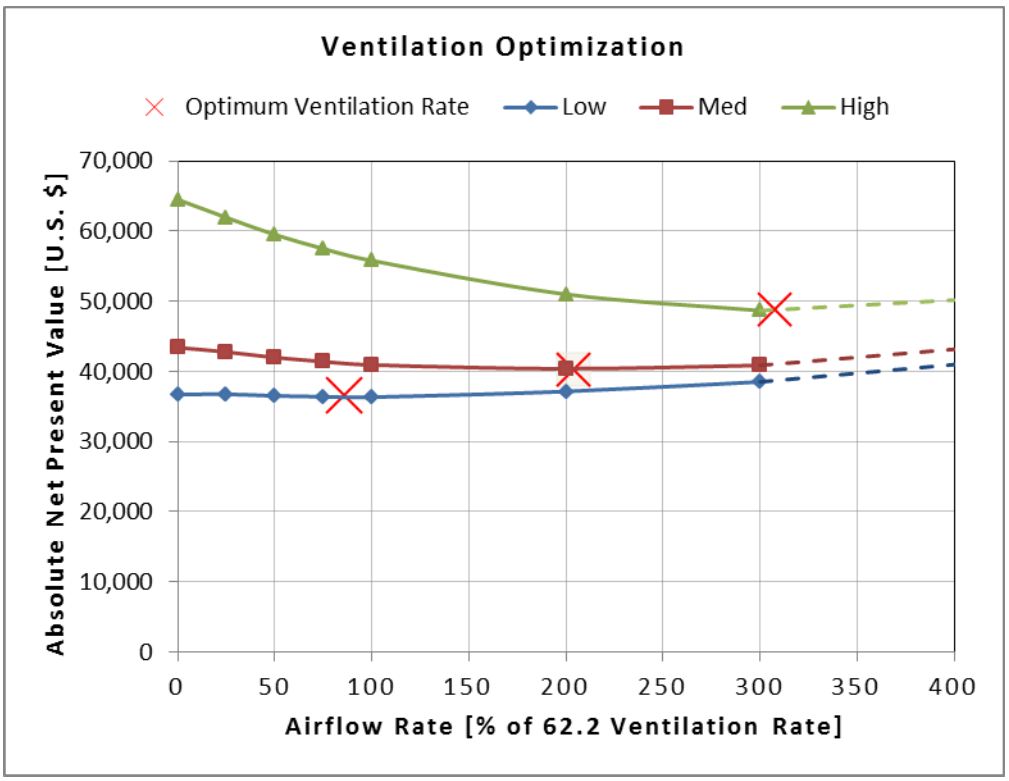


4.3.3.3 Ventilation Rate Optimization

Health benefits dominated energy benefits, and there was a strong dependence of IAQ on indoor contaminant emission rates. As a result, providing minimum airflow rates to comply with ASHRAE 62.2 alone was not a sufficient metric for commissioning whole-house ventilation systems. Instead, the metric should be net present value of the combined energy and IAQ benefits to the consumer, and commissioning cost decisions should be made relative to that value, even if that means ventilating to exceed the ASHRAE 62.2 minimum.

Using the results of these simulations, it is possible to attempt to optimize the ventilation rate to find the most cost-effective IAQ level. Assuming a binomial relationship, the curves in Figure 4.3.3 have been extrapolated past the 300 percent modeled ASHRAE 62.2 airflow.

Figure 4.3.3: Optimization Curves for IAQ and Energy. The Previous Graphs Show the Net Present Value (NPV) Relative to a Base Case of the Home Operating as Specified by Title 24. This Graph Shows the Absolute NPV.



The local minima are the points representing the minimum cost to the occupants.

As the ventilation rate increases, the NPV decreases, due to lower indoor contaminant concentrations. At higher airflows, energy costs begin to dominate and cause the NPV to increase. The optimum ventilation rates are at the local minima, or where the differentials of the curves are equal to zero. For the various emission rates considered, the optimum airflows were approximately 85 percent of the ASHRAE 62.2 minimum (low emission), 200 percent of the minimum(medium emission), and 310 percent of the minimum (). These results indicate that, for the medium- and high-emission houses, the minimum ASHRAE 62.2 airflow was not high enough. For the low-emission house, the minimum 62.2 airflow rate was slightly too high, suggesting over-ventilation. Clearly, this approach is highly dependent on emission rates, but the high and low emission rates used in this study should act as boundary conditions.

4.3.4 Benefits to California

Commissioning is performed in steps, and whether or not to perform each step should be evaluated along the way. The ideal commissioning process uses appropriate, calibrated diagnostic tools and standardized procedures to determine the total energy and IAQ cost or benefit for a given home as a function of system airflow, followed by identification of the tuning options for that home, cost analysis of those options, and then finally implementing those options dependent on the cost benefit to the homeowner.

Based on the home characteristics considered for this study, the first step of performing diagnostics appears to be justified in the majority of new homes. For low-emission homes, assuming the proper use of task ventilation, tuning the airflow will always be of value, so long as the price of tuning is less than the 30-year health and energy cost of an over-ventilating system. For homes with higher emission rates, currently, it would be difficult and potentially costly for a commissioning professional to perform the diagnostics required to estimate household emission rates for the pollutants of concern, especially as these are house-specific and subject to change, in part due to occupant behavior.

Identifying that diagnostics are needed to quantify emission rates will hopefully spur industry to develop appropriate tools and guidelines for the commissioning community. Our results suggest that controlling and limiting the levels of continuous emissions may also be an important tuning tool for residential ventilation systems. Labeling schemes now exist for products that meet low emission standards. Addressing emission rates in the commissioning process might be as simple as the auditor looking for labeled products in the house to help quantify the levels of continuous emissions.

4.3.5 Recommendations for Future Work

Relevant information in the references listed in our annotated bibliography should be combined with an energy and IAQ benefit assessment tool and the results of the diagnostic tool evaluations described in Section 4.4 of this report to develop a standardized commissioning process and a residential ventilation system commissioning guide for practitioners.

Further work is specifically needed to identify diagnostics for quantifying emission rates, which could be as simple as the auditor looking for labeled products in the house to help quantify the levels of continuous emissions. The guide should include guidance regarding these diagnostics, as well as related norms. Where needed, an emissions database also should be developed and made available to support such assessments.

As a consequence of combining energy costs with monetized IAQ costs, we now have the beginnings of an approach to optimize ventilation rates for homes. Future work should be carried out to further develop this method and to incorporate it into standards such as ASHRAE 62.2.

4.4 Airflow Diagnostics

Although ASHRAE Standard 62.2 and Title 24 require homes to have minimum ventilation airflows, they specify neither the device nor the procedure that is to be used to measure these flows. Devices for measuring ventilation (or space conditioning) airflows in buildings are generally referred to as flow capture hoods, or "flow hoods" for short. Typically, these hoods capture the flow entering or exiting a terminal and funnel it through some kind of measurement mechanism. Most flow hoods purportedly can measure flows in either direction (both inlet and outlet), and many have the capability to perform time averaging.

There is a wide range of residential mechanical ventilation flows. In homes with fully ducted heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs), the flows at each terminal can be as low as 10 cubic feet per minute (cfm). At the high end, flows from commercial-style residential range hoods can exceed 1,200 cfm. However, most residential ventilation flows are in the range of 15 to 200 cfm, so this is the range used for this study.

Acceptable measurement accuracy differs depending on the intended use for the results. Previous LBNL studies have described measurement accuracy requirements in terms of evaluating residential heating and cooling systems. For those studies, the required minimum accuracy ranged from a broad ±50 percent for identifying large leaks and disconnected ducts to a narrow ±3 percent for determining total system leakage. Currently, there is no accepted accuracy range for ventilation airflows required by residential building standards, and there is no minimum accuracy required for measuring ventilation flows. To evaluate residential ventilation airflows, we decided on a minimum required accuracy of ±5 cfm or ± 10 percent of measurement reading, whichever was greater.

4.4.1 Laboratory Calibration and Evaluation of Field Measurement Techniques and Technologies for Ventilation Airflow Measurement

There is currently no standard for calibrating flow hoods that reflects their use in realistic field measurement situations. ASHRAE standards 41.2 and 51 discuss how to use a specific laboratory apparatus to perform laboratory evaluations of airflows through conditioning and ventilation equipment, but they do not establish how to calibrate devices that are used to make flow measurements in the field. This situation has left each device manufacturer to develop its own calibration procedure. Flow hoods are often calibrated in a laboratory using an apparatus that produces an approximately uniform flow field that covers the entry of the flow hood. These calibration procedures do not necessarily account for the primary causes of measurement inaccuracy, the non-uniform flow fields common in residential buildings. Therefore, a new standard for flow hood calibration needs to be developed, along with a new measurement standard to address field use of flow hoods. These standards would help to ensure that flow hoods are capable of measuring all flows to an acceptable accuracy, so that homes receive the proper ventilation rates.

For the laboratory calibration (Stratton et al. 2012), we evaluated seven flow hoods that represent a range of types, manufacturers, sizes, weights, measurement mechanisms, complexity, and price. Six were commercially available hoods, and one was a research-grade powered hood constructed by LBNL. This LBNL hood is referred to in this study as "EPB" and has a previously determined accuracy of ±2 percent. The other six hoods were: a powered flow hood from The Energy Conservatory (TECFB), a powered flow hood from Europe (DIFF), a passive exhaust-only device from The Energy Conservatory (TECEFM), a rotating vane anemometer (testo417), and two traditional flow hoods from TSI/Alnor: ABT701 and EBT721.

Our laboratory experiments were designed to ascertain each flow hood's accuracy for measuring various outlet and inlet ventilation airflows under controlled conditions where a well-known reference measurement could be employed. The test apparatus combined an inline fan with two calibrated reference airflow measurement devices that were connected to a baffle into which was inserted a range of air inlets and outlets that are used with ventilation systems. A total of nine inlets and outlets were used, including both exterior and interior terminals. Sensitivity to flow hood placement over the terminals was evaluated by first centering the flow hood, then placing the terminal along one edge ,and finally placing the terminal in the corner of the flow hood.

In general, the three powered hoods yielded more reliable and accurate measurements than did the non-powered hoods. The average mean absolute difference for the three powered hoods was 4.2 percent, versus 11.6 percent for the four non-powered hoods. Two of the non-powered hoods—the ABT701 and the TECEFM—had overall results that were comparable to the powered hoods in terms of mean absolute difference.

The overall accuracy difference between the powered and non-powered hoods is due primarily to their respective abilities to measure outlet flows. The overall mean absolute differences of the inlet flow measurements for the powered hoods (5.1 percent) and non-powered hoods (2.9 percent) were similar, with the non-powered hoods overall yielding slightly more accurate results for inlet flows. However, the powered hoods were much more accurate when measuring outlet flows. For outlet flows, the powered hoods' mean absolute difference was 3.6 percent and the non-powered hoods' was 20.8 percent.

The type of terminal being used, which determines the angle of the flow relative to the mounting face, affected the accuracy of outlet flow measurements more than it affected inlet flow measurements. The standard deviation of mean average differences for all inlet flow terminal measurements was 0.5 cfm, versus 3.0 cfm for outlet flow terminal measurements. For comparison, the standard deviation of the mean average differences of flows sorted by flow location (middle, edge, and corner) was 1.8 cfm. The standard deviation of the mean average differences of flows sorted by flow direction (inlet, outlet) was 4.2 cfm. This reinforces our finding that the direction of flow has a greater effect on measurement accuracy than does the flow location.

Most of the hoods are relatively unaffected by the location of the flow relative to the face of the hood. Two exceptions are the testo417 and the EBT721, both of which are noticeably less accurate the farther the flow is from the center of the hood face. In the case of the testo417, this sensitivity to flow location is especially pronounced; its mean absolute difference is 7.8 percent for middle flows, 11.4 percent for edge flows, and 17.5 percent for corner flows.

In this laboratory study, we did not evaluate insertion losses: that is, the effect the hood has on the flow it is measuring. In particular, we did not compare the flow measurements from hoods to the reference flow as measured *before* the terminal was covered by the hood, because the test apparatus does not represent the system response of an actual ventilation system. Future studies could evaluate the effect of hoods on the flow they are measuring. One way to quantify this effect could be to measure the static pressure within the duct near the terminal before and then during the measurement.

4.4.2 Field Measurements of Whole-House and Local Exhaust Ventilation Air Flows in 15 New California Homes

The goal of this component of the study was to evaluate compliance with the ventilation requirements of ASHRAE Standard 62.2-2007 and Title 24. ASHRAE Standard 62.2 requires mechanical ventilation for both whole-building and local exhaust. ASHRAE 62.2-2007 states that whole-building and local exhaust flows can be measured or can meet prescriptive ducting and fan labeling requirements that use ratings provided by the Home Ventilating Institute. The 2013 version of the Title 24 will refer to ASHRAE 62.2-2010, which requires that whole-building airflows be measured. To show compliance with the ASHRAE Standard, we need a reliable way of measuring ventilation system airflows. This study (Stratton, Walker and Wray 2012) evaluated ASHRAE 62.2 compliance for fifteen California homes, both for whole-building ventilation flows and for local exhaust flows. It also evaluated the accuracy of six commercially available flow hoods, based on our experience using the devices to take field measurements of ventilation flows.

The homes included in the study were all within a 100-mile radius of LBNL. Nine were unoccupied new homes in Manteca and Napa, in new housing developments. Two of the fifteen homes studied were built prior to the implementation of Title 24 2008 (which made ASHRAE 62.2 mandatory) but were designed to be compliant with ASHRAE 62.2. Twelve of the fifteen homes used the exhaust fan in the laundry room for whole-building ventilation. The remaining three homes used a fully ducted ERV to provide whole-building ventilation. In addition to an ERV, one home also has a hole-in-the-return ventilation system. Thirteen of the fifteen homes had range hoods vented to outdoors. Two of the three homes with ERVs had recirculating range hoods. The recirculating range hoods do not count as kitchen exhaust for compliance with ASHRAE 62.2. Instead, these kitchens need to comply with the alternative to local exhaust ventilation, which is five kitchen air changes per hour that would be provided by the ERVs that have pickups in the kitchen.

The airflows were measured using the same flow hoods that were evaluated in the laboratory calibration and evaluation part of the RESAVE study (described in Section 4.4.1).

4.4.3 Summary of Results of Compliance with Title 24/ASHRAE 62.2 Ventilation Requirements in 15 New California Homes

Thirteen of the fifteen homes met or exceeded the minimum whole-house airflow rates required by ASHRAE 62.2 and Title 24. The two homes that did not meet the requirements failed substantially—by 20 cfm (36 percent) and 38 cfm (54 percent). It should be noted that both these homes were built prior to ASHRAE 62.2 being adopted by Title 24. The homes that exceeded the minimum airflow rates did so by a significant margin—averaging an additional 28 cfm (50 percent excess) over the minimum requirements.

There was less consistency for the local exhaust requirements. A key issue is that some exhausts were difficult to measure—in particular kitchen range hoods. The hardest to measure from inside the house are combined microwave/range hoods that have multiple air entry points for exhaust air—often on more than one face of the range hood. These kitchen exhausts need to be measured at their outlets, and that can lead to access-related safety issues, e.g., high exterior wall mounts or roof mounts.

All four of the homes for which kitchen range hood flows were measured met or exceeded the relevant ASHRAE 62.2 requirement. Some kitchens had no range hood, so that they need to meet a continuous kitchen exhaust airflow rate based on kitchen volume. The kitchens without flow hoods were not able to meet this whole kitchen exhaust requirement.

Of the 44 bathroom exhaust fans evaluated for this study, 23 (52 percent) met or exceeded the ASHRAE 62.2 required flow rates for local exhaust. The continuous bathroom exhaust fans used in some homes (with ERV) were required to be 20 cfm, rather than the 50 cfm required for the other homes' intermittent bathroom exhaust fans. Two of the three ERV systems met this requirement.

Without further investigation, it is not possible to say with any certainty why the failing fans failed. It is worth noting that in several instances the same fan model in the same house provided flow rates that differed by as much as a factor of four. This suggests that duct type, length, and installation change flow rates considerably, and that design and installation quality is a factor that determines the flow of an exhaust assembly as much as the fan's HVI-rated airflow.

4.4.4 Recommendations for Measurement Techniques to Be Used in Building Codes in California

At present, there is no industry consensus standard for assessing flow hood accuracy. For several of the hoods, there was little resemblance between the manufacturer's claimed accuracy and the accuracy that we determined in the course of our measurements. This would suggest that the accuracy evaluation protocols that manufacturers use are both different from our own protocol and from each other's. To ensure that hoods are evaluated uniformly on their ability to measure flows in the field, there needs to be a standard method of test for accuracy evaluation that incorporates "actual use" considerations, such as terminal type, flow direction, and flow location.

Included in this standard, or perhaps in a separate rating standard, should be acceptable accuracy ranges for each flow hood application. Based on results from the standard accuracy evaluation, a hood could then be rated and listed for certain flow measurement applications. In turn, codes might state, for example, that "a rated and listed hood with an accuracy of ±5 cfm or 10 percent shall be used to measure ventilation flows to evaluate a home's compliance with ASHRAE Standard 62.2."

The compliance testing indicated that, although compliance with whole-house ventilation was generally good, the kitchen and bathroom exhaust airflow rates were below requirements about half the time. This indicates that more attention needs to be paid to these intermittent fans and that field measurements need to be performed as part of a commissioning process to show compliance with build codes and standards (Title 24). Kitchen range hoods—particularly those with integrated microwave ovens—present a significant challenge for field verification, due to the complexity of airflow entering the range hood and location of building exhausts in hard to access places. In addition, some flow hoods had openings that were too small for typical exhaust fan inlets. Such a misfit leads to large errors in measurement that will have to be addressed through product development or commissioning specifications that disallowed such measurements.

The field testing did not cover as wide a range of terminals as the laboratory studies, so the comparisons between different flow hoods showed less variability. However, two of the tested devices (both passive hoods) had significant errors. The testo417 had average errors greater than 20 percent and only was acceptable (±10 percent or 5 cfm) in about half the tests. The EBT 721 only had poor results when measuring flows entering the flow hood, for example when measuring kitchen exhausts on the exterior of the home.

Until a new testing standard is completed, we can only give broad recommendations for acceptable methods of showing compliance:

1. For inlet flows, use any hood except one with a rotating vane anemometer
2. For outlet flows, use only powered flow hoods

If range hood flows are to be measured to verify compliance with the local kitchen exhaust requirements, guidance needs to be established with regard to the methods and flow hoods that are to be used to make these measurements.

Because they are usually installed on the face of continuous flat surfaces such as walls and ceilings, flows at terminals for bathroom exhaust fans and fully-ducted HRV/ERV systems tend to be more readily measureable than range hood flows. However, these terminals present their own measurement challenges. Tight spaces or obstructions immediately in front of the terminal face can make flow measurement difficult or impossible. If the wall or ceiling surface surrounding the terminal is inadequately sized or irregular, it may not be possible to create a seal with the flow hood and make an accurate measurement.

Given that ASHRAE 62.2 requires measurement of the ventilation flows at these terminals, it is imperative that efforts are made to ensure that flows at these terminals are in fact measurable. Possible strategies for ensuring the measurability of these flows may include a building code stipulation requiring an adequately-sized flat surface bordering the terminal and a requirement that flow hoods have an adjustable flow capture mechanism that can establish a good seal under a range of common terminal conditions.

CHAPTER 5: Dissemination and Partnering

The RESAVE program devoted a significant amount of effort to making sure its research is relevant to end users and the results achieved find their way into codes and standards, and to industrial partners.

5.1 Partners

RESAVE had two industrial partners who participated in project planning, the work of various tasks, and output review. In addition, these partners could make use of RESAVE results directly as they sought to improve their building products.

5.1.1 DuPont

DuPont Building Innovations participated as an industry partner with LBNL on the RESAVE program. As a producer of air barrier, water-resistive barrier, and flashing products, DuPont Building Innovations was primarily interested in aspects of the program concerning the air-tightness of the building envelope.

DuPont partnered with the RESAVE program in two areas:

- understanding the complexity of energy retrofit air sealing in existing homes, and
- working within ASTM to initiate new test standards or test standard revisions.

The most common ways of increasing the air-tightness of existing homes is either by using sealants at cracks, such as those around windows, or to install an air barrier as part of a cladding replacement. The prevalence of stucco construction in California limits the number of re-cladding opportunities. With this in mind, DuPont supported the work of the RESAVE program to identify the air-tightening potential from sealing of leakage between the living space and buffer zones such as an attached garage, attic, or crawlspace. The interface between the living space and these buffer zones is often ignored during the installation of traditional air barriers. DuPont continues to develop air barrier installation details for both new and retrofit construction.

Theresa Weston, the DuPont Building Innovations representative on the RESAVE team, is the chair of the ASTM Sub-Committee (E06.41) on the Performance of Buildings – Air Leakage and Ventilation. As such she was able to initiate ASTM work items to use the results of the RESAVE program to upgrade existing standards and to develop new standards:

1. Upgrades to ASTM *E779 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, incorporating the results described in Chapter 2 of this report, including the revision of multizone leakage measurement section and updating precision and bias of single and multi-point methods.

2. New standard *Test Method for Measuring the Capture Efficiency of Residential Kitchen Range Hoods* initiated. The task group developing this potential new standard will use the information discussed earlier in this report and thus build on RESAVE results.

This standards work continues beyond the completion of the RESAVE program.

5.1.2 Panasonic

Don Stevens has represented Panasonic Home and Environment Company (PHEC) as an industry partner with LBNL since the first discussions of this program in 2007. PHEC became Panasonic Eco Solutions North America (PESNA) in April 2012. Don is the National Research and Development Manager of PESNA responsible for ventilation and IAQ product and code development in North America. Figure 5.1.1 shows some example products.

PHEC/PESNA has used information from the RESAVE program to help in the design of several products for the North American market and California in particular. Data from the range hood study by Brett Singer has gone into Panasonic's range hood designs. Data from the filtration studies has influenced the development of a family of through-the-wall supply fans with Minimum Efficiency Reporting Value (MERV) 8 filters specifically targeted to California weatherization programs and to other products. Research projects have provided feedback on several products related to installation, sizing, and operation, including a recessed light/fan combination unit and small ERV that can be installed in the ceiling or exterior wall. All of these products can be used in new construction and existing homes and apartments.

Figure 5.1.1: Examples of a (a) Through-the-Wall Supply Fan, (b) Recessed Light/Fan Combo, and (c) Ceiling- or Wall-Mount ERV.

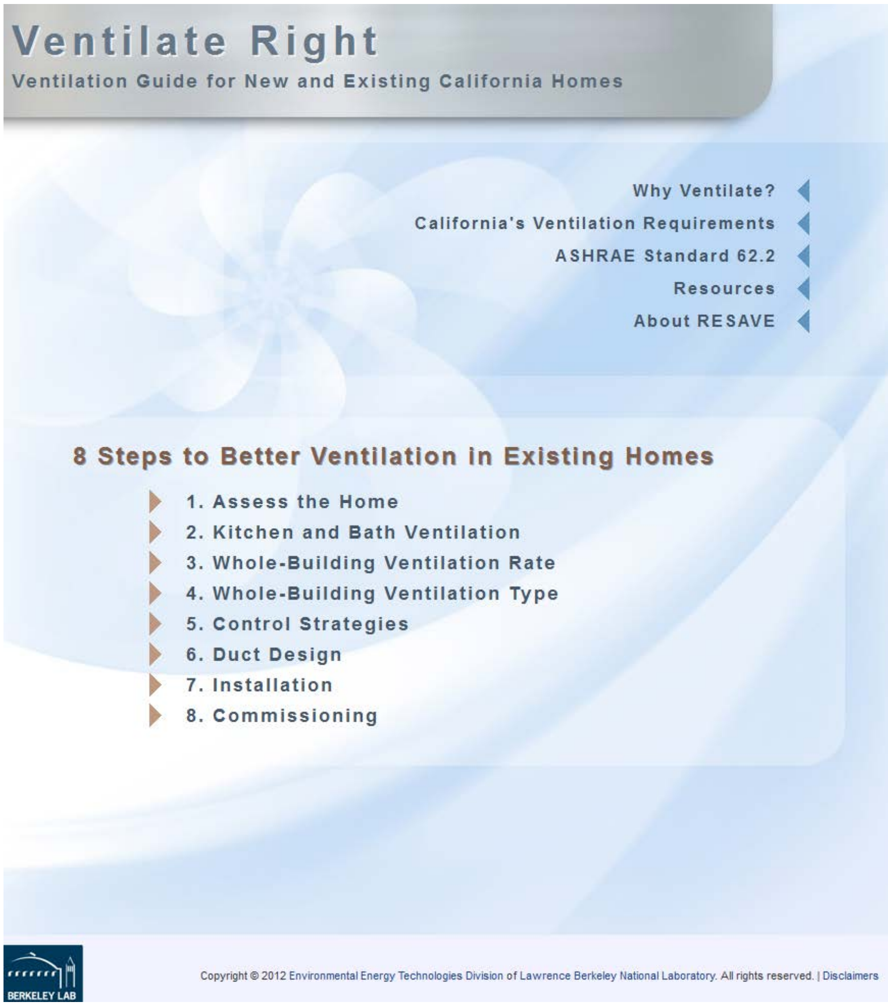
(a)  (b)  (c) 

The RESAVE program has also helped in the development of controls for ventilation devices, ranging from switches and timers to the development and commercialization of a condensation-potential controller that measures the relative humidity and temperature of the room and then calculates if there is a potential for condensation using the psychrometric chart from the ASHRAE Handbook of Fundamentals. Panasonic is using lessons learned from RESAVE to transition between lighted fans from compact fluorescent lamps to light-emitting diode technology.

5.2 Existing Homes Ventilation Guide

The Existing Homes Ventilation Guide sprang from an idea to help homeowners achieve proper ventilation in existing homes as they were weatherized or had major energy upgrades. It began as a written guide booklet, but it became obvious that the building community would be better served if it were moved to the RESAVE and/or Energy Commission websites so it was accessible and simple to update. Because it was targeted to contractors but accessible to owners and occupants, a Guide Advisory Panel (GAP) was established to provide input and review drafts for clarity. The GAP included industry, weatherization programs, and Energy Commission staff, to ensure the broadest review. The final product is currently located at http://resaveguide.lbl.gov under the title "Ventilate Right." Figure 5.2.1 shows the landing page. Don Stevens of PESNA (and Chair of ASHRAE SSPC 62.2) was the primary author of the Existing Homes Ventilation Guide, and Karol Stevens of Stevens and Associates was the technical editor.

Figure 5.2.1: The First Page of the RESAVE Ventilation Guide.



This page allows users to get as little or as much information as they want or need to design and install a proper ventilation system. It includes both spot ventilation in baths and kitchens as well as whole-building ventilation for IAQ for the entire house or apartment. The material is organized based on the eight-step process on the landing page.

The designs and recommendations are all compliant with ASHRAE Standard 62.2. Guidance is provided for the current requirements found in the 2007 edition of 62.2, (as required by the 2008 Title 24 for new construction) that apply to current new construction and energy upgrade projects. In addition, it addresses the requirements of the 2010 edition of 62.2 with the 2012 published addenda as adopted by the Energy Commission for the 2013 Title 24. "Best Practice" recommendations are provided for users who want to go beyond code requirements. Because ASHRAE 62.2 is a "high profile" standard, it is constantly being revised. These differences are called out through-out the 100-plus pages of information. Many terms are linked, to allow users to access other sections when more information or clarity is needed. Energy Upgrade California program could also use this guide.

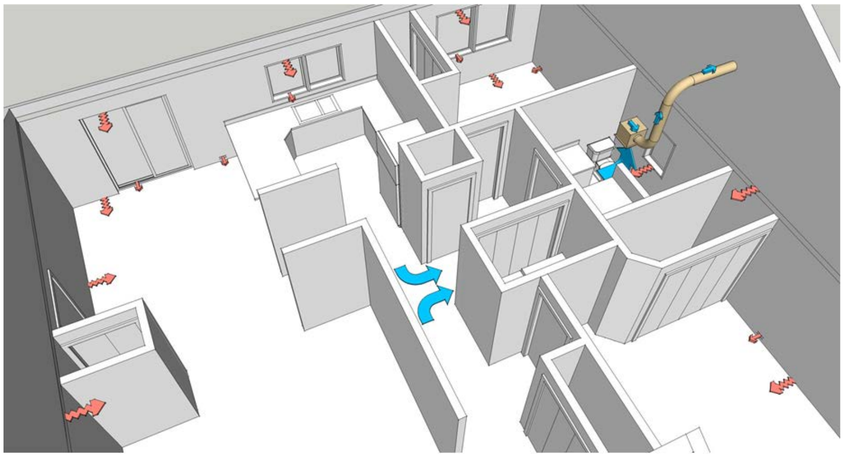
The guide includes various informative tables and charts, including one that compares 16 different ventilation strategies with a relative ranking of first cost range, an energy use range (expressed in kWh/year), a range of ventilation fan efficacy, and maintenance. Figure 5.2.2 shows a subset of the guide for exhaust-only systems.

Figure 5.2.2: Example Guide Section for Exhaust Systems.

Exhaust-Only Systems				
Name / Description	Cost	Energy (kWh/year)	Fan (cfm/watt)	Maintenance
E1: Single Point Exhaust-Only System One fan exhausts stale air from one location. Wall vents or air leakage through the building envelope provide make-up air.	$ – $$	35 – 438	1 to 15	Clean 1 fan grille
E2: Two Point Exhaust-Only System Two fans (or one inline fan with two pickups) exhaust stale air. Wall vents or air leakage through the building envelope provide make-up air.	$ – $$$	70 – 701	1 to 15	Clean 2 fan grilles
E3: Multiple Point Exhaust-Only System Multiple fans (or a multi-port fan ducted to several rooms) exhaust stale air. Wall vents or air leakage through the building envelope provide make-up air.	$$ – $$$$	70 – 876	1 to 15	Clean 3 or more exhaust grilles

As shown in Figure 5.2.3, each ventilation system features a graphic showing a generic system installed in a house, as well as common points of outdoor air entry or indoor air exit based on that system.

Figure 5.2.3: Example Illustration of Air Flow Paths.



5.3 National Standards

5.3.1 Air Leakage Standards

5.3.1.1 Summary of Current Ventilation Standards and How They Relate to California Standards

The two important ASTM ventilation standards are E779 for measuring air leakage of homes and E1554 for measuring duct leakage. Neither have changed substantially in recent years; however, it is likely that E779 will be rewritten in 2013 or 2014 to remove some of the superfluous test elements that are impractical and to add single-point testing and a wider range of test result metrics such as ACH_{50}, Q50, normalized leakage area (NLA), and specific leakage area (SLA). The specific addition of SLA would be of interest, as this is the metric used in Title 24.

The most important ASHRAE standard is the one that has already been discussed— ASHRAE 62.2, for residential indoor air quality. However, other ventilation- and infiltration-related standards, such as ASHRAE 119 and ASHRAE 136, also pertain. Over the past couple of years these standards have been incorporated in ASHRAE 62.2, so that all the calculation procedures required for natural infiltration contributions to ventilation are in one place—in Standard 62.2. Therefore, adoption of more recent versions of 62.2 will incorporate the key parts of standards 119 and 136.

EPA's current ENERGY STAR program has the following prescriptive requirements for envelope leakage:

- 5 ACH_{50} in Climate Zones (CZs) 1 and 2
- 5 ACH_{50} in CZs 3 and 4
- 4 ACH_{50} in CZs 5, 6, and 7
- 3 ACH_{50} in CZ 8

California has CZs 2, 3, 4, 5, and 6—indicating a wide range of requirements for the state to match ENERGY STAR. This wide variation is justified because of California's wide range of climates—in the same way that Title 24 prescriptive requirements currently have climate variation.

The current Title 24 does not set limits for air leakage—but it does give credit for homes tighter than the defaults of SLA of 4.3 for homes with ducted unsealed HVAC systems, 3.8 for homes with ducted and sealed HVAC systems, and 3.2 for homes without ducted HVAC systems (approximately corresponding to 8.6, 7.6, and 3 ACH_{50}, respectively). There is also the requirement in Title 24 for balanced ventilation (or additional added leakage) if a home has an SLA below 1.5.

The 2012 IECC has prescriptive requirements for envelope leakage that would require homes in California to be 3 ACH_{50} or less. This seems a reasonable requirement to add to future Title 24 requirements.

The Canadian R2000 standard limits envelope leakage to 1.5 ACH_{50} or less. In extreme Canadian climates this might be reasonable, but in the majority of California, our moderate climates make this level of leakage unnecessary in a minimum performance code such as Title 24.

Passive House requirements are even tighter, at 0.6 ACH_{50} for new homes and 1 ACH_{50} for retrofits. As with the Canadian R2000 standard, these low levels of leakage produce diminishing returns in mild California climates, and it is not necessary to go this low as a baseline for a minimum performance code in California.

The U.S. Green Building Council's LEED Residential requirements give both an upper limit and credit for limiting air leakage. The upper limits are:

- 7 ACH50 for IECC Climate Zones 1 and 2
- 6 ACH50 for Climate Zones 3 and 4
- 5 ACH50 for Climate Zones 5, 6, and 7
- 4 ACH50 for Climate Zone 8

The maximum LEED points for air leakage reduction are awarded at the level of:

- 3 ACH_{50} for IECC Climate Zones 1 and 2
- 2.5 ACH_{50} for Climate Zones 3 and 4
- 2 ACH_{50} for Climate Zones 5, 6, and 7
- 1.5 ACH_{50} for Climate Zone 8

California contains IECC Climate Zones 3, 4, 5, and 6.

5.3.2 RESNET and BPI

5.3.2.1 Summary of Ventilation-Related Changes in RESNET and BPI Standards

During the course of this project both the Residential Energy Services Network (RESNET) and the Building Performance Institute (BPI) changed their requirements to match those of California by requiring compliance with ASHRAE Standard 62.2. However, they refer to the

2010 version of the standard and not the 2007 version referenced in Title 24. It is recommended that California update its requirements to the 2010 version of Standard 62.2.

5.3.2.2 Summary of Future Ventilation Issues at RESNET and BPI, Including Whole-House/Local Ventilation and Combustion Safety

The process of training contractors and agencies to use ASHRAE 62.2 is ongoing, and it is not clear that all contractors are yet following the new standard. Within RESNET there is the feeling that we should stick with the ASHRAE 62.2-2010 standards for the next few years so that contractors get used to using them before changing to the 2013 version. In January 2013 BPI decided to only refer to the 2010 version of 62.2 for a very brief transitional period and to refer to 62.2-2013 as soon as it is published. There is a major change between 2010 and 2013 in that contractors will need to use substantially larger fans and flow rates, unless they measure the house leakage with a blower door in order to get credit for natural infiltration. RESNET and BPI might find the changeover from 2010 to 2013 easier than other institutions, as they already require blower door testing for envelope leakage.

The other related issue for RESNET and BPI is combustion safety testing. Both organizations are currently rewriting their combustion safety testing procedures, and LBNL is participating with both organizations to ensure that a good technical approach is used and that the two organization's procedures are as similar as possible. In addition to this harmonization, both organizations are examining the combustion appliance depressurization limit testing, due to the time it can take to do the testing and the lack of reliability associated with the results noted by LBNL and others. Representatives of the gas industry are strong advocates for simply referring to national gas codes. However these codes (primarily NFPA 54) give little or no guidance on how to carry out testing. RESNET and BPI are both reaching out to the National Fire Protection Association (NFPA) so that whatever procedures they adopt might also be transferred into the NFPA document to improve its utility to contractors.

5.3.2.3 RESNET, BPI, and ANSI Certification

Both RESNET and BPI are pursuing ANSI certification for their standards. This is leading to some conflicts between the two organizations and other organizations, such as Air Conditioning Contractors of America (ACCA) who are also publishing a suite of ANSI standards related to residential HVAC and home performance. It is likely that there are sufficient differences between the approaches and specific test procedures that all groups will have their own ANSI approved documents within the next 12 months. Some of which may be useful references for Title 24.

5.3.3 ASHRAE Standard 62.2

5.3.3.1 Summary of Changes to ASHRAE 62.2 Since Adoption in Title 24

There have been substantial changes since the 2007 version of ASHRAE 62.2 that was adopted by the Title 24. The following changes were made for the 2010 version of 62.2:

1. Removed the climate zone 3B and 3C exceptions to whole-house ventilation requirements (providing allowed to do so by the authority having jurisdiction).

2. Required measurement of whole-house and local exhaust airflow.
3. Changed the effective ventilation for intermittent fans.
4. Replaced the "transfer air" requirements with air sealing for adjacent spaces and an added section on multifamily buildings.
5. Added more requirements for air sealing of attached garages, and the measurement of HVAC system air leakage was revised to refer to Method D of ASTM E1554 as well as California Title 24.
6. Added the new U.S. DOE climate zone map.
7. Added a normative annex for existing buildings that allows additional whole-house ventilation to compensate for lack of kitchen and bathroom exhaust.

The following additional changes have more recently been made for 2013. They are from currently approved addenda:

1. Added an option for minimum filtration referring to Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 680 as well as ASHRAE MERV ratings.
2. Clarification of test pressure requirements for sound ratings.
3. Added a requirement that system designs include the pressure drop from the filters.
4. Removed limits on net exhaust flows that depended on climate and the associated climate map.
5. Clarified the existing buildings appendix.
6. Expanded and revised the section for intermittent fans that introduced the concept of equivalent dose (as used in the RIVEC controller studied in this project).
7. Added a requirement for carbon monoxide alarms.
8. Added a new section for multifamily buildings.
9. Changed the core of the standard to incorporate the default infiltration rate of 2 cfm/100 ft^2 directly into the fan sizing equation and uses tables that have many more entries in the range of houses sizes that are normally built (increments of 500 ft^2) and has better resolution for smaller homes. The required relationships and data from ASHRAE standards 119 and 136 were incorporated directly into 62.2 for the infiltration calculations. New weather factors were calculated for all the current Typical Meteorological Year (TMY)2 data sites that included better assumptions about wind shelter that led to slightly reduced infiltration rates. Unlike the 2007 version, the full credit for infiltration is now allowed. Unless a blower door test is performed to estimate infiltration and take credit, the fan sizing will be approximately doubled compared with the value from the 2007 version. There was an intermediate version of the standard that

allowed the old relationships to be used for fan sizing only, with no infiltration credit allowed, but a new addendum removed this approach.

10. The standard will require that mechanical systems be operated in order to comply with the standard.

5.3.3.2 Current ASHRAE 62.2 Activities That May Affect Future Title 24

The most important current ASHRAE 62.2 activity is the investigation of filtration effects and consideration of the addition of minimum filtration levels: either for outside for mechanical supply systems and/or for air recirculation systems (either as part of the ventilation system or a central forced air heating or cooling system). The impact on Title 24 would be that there would be a requirement for a minimum filter level on forced air heating and cooling systems, and on supply sir systems. Houses without central forced air heating and cooling systems would require the addition of a central forced air filtration system to remove indoor-generated pollutants; in other words, it would not be sufficient to supply filtered outdoor air, as this does not remove indoor pollutants. This latter effect would be minor in terms of additional equipment in California because almost every home has a central forced air system, but it could add substantially to energy budgets if central forced air fans operate either continuously, or, at the very least, for many more hours of the year.

The operation of central forced air systems for filtration would require that:

- ducts not leak,
- ducts be in the conditioned space (or be very well insulated—much more so than current standards), and
- energy requirements for the forced air blowers be introduced (because there are substantial fan energy savings available for systems that use Brushless Permanent Magnet blowers, lower continuous air flows, and low air flow resistance duct systems).

These would all be issues for Title 24.

Chapter 6: Conclusions and Recommendations

The RESAVE program has been very successful from an RD&D perspective. This can be judged by the three dozen technical products listed in this report. This number far exceeds the number that could be generated by the RESAVE resources alone and was accomplished by leveraging RESAVE resources with industry and federal programs as described above.

The list of technical products RESAVE can take credit for is not complete, because at the time that this report is being written, continuing work (supported by cost-share partners) will result in additional technical products. To see the most recent set of technical results, please consult the RESAVE website, at http://resave.lbl.gov.

6.1 Key Findings

Each section and each technical product discusses specific research findings. Below are some key findings.

6.1.1 Industrial Cooperation

A key enabling (rather than technical) finding is that partnering with industry has led to a more rapid development and adoption of technology and related R&D than would have been accomplished without such collaborations. Working with Panasonic, for example, has led to more rapid update of RESAVE products in the market, and well as more rapid advancement of ASHRAE Standard 62.2. Working with DuPont has led to improved air leakage standards and clarified the value of air-tightness.

6.1.2 Air Leakage

6.1.2.1 Residential Diagnostics Database

Analysis of the data for both the United States as a whole and for California allows us to determine tendencies and correlations of the air-tightness of building envelopes with building properties. These findings are needed to estimate energy demand associated with heating and cooling, and also the potential energy savings from air-tightening. Some important findings are summarized below:

- Homes that were built (or retrofitted) to be energy efficient (in some sense) are generally 30 percent tighter than conventional homes.
- Low-income homes, (such as those that qualify for the Weatherization Assistance Program (WAP), are generally 50 percent leakier than conventional housing.
- A typical air-tightening retrofit reduces leakage by 20 percent for conventional housing and 30 percent for low-income housing.
- Coastal homes (e.g., California climate zone 2) are leakier than most homes, correcting for all other factors. Houses in California climate zones 13 and 14 are over 20 percent tighter than coastal homes.
- Houses built over the past five years (since 2008) are over 20 percent tighter than those built a decade earlier.

6.1.2.2 Multizone Leakage

Simulation and field analysis of multizone, blower-door base, air-leakage techniques have enabled us to identify different methods for measuring residential leakage, both to the outside and to adjacent spaces. The methods considered are applicable to both multifamily homes and single-family homes with an attached garage. The important results are summarized below:

- It is possible to measure all the appropriate leakages with multiple configurations using a single blower-door. It can be done with an accuracy as good as 20 percent, but only if the proper configuration is used. The configuration most often used in the field is not optimal.
- Reduced uncertainty and more robust measurement options are possible when two blower-doors are used. Ideal configurations can reduce the uncertainty to 16 percent, but poor experimental design can also lead to very poor results.
- Use of a single pressure station (e.g., 50 Pa) generally fails to produce reasonable results. It is possible to get acceptable results with a single-pressure station in special cases and when the relative leakage values are known in advance.
- From limited field measurements it appears the house-garage leakage is small by a significant fraction (e.g., 15 percent) of the total house leakage.

6.1.2.3 Energy Benefits of Air Sealing

By applying our simplified ventilation-energy model to the California housing stock it was possible to determine the impact that tightening programs would have and where the optimum level may likely to be. The analysis showed a clear trend with diminishing returns for more extreme tightness levels (i.e., $ACH_{50} < 1.5$) (or, equivalently, a California SLA of 3), which is likely to cost more to achieve. The exact optimum is different for each climate and cost structure, but it is clear that the stock could be profitably tightened. The extreme tightness required for the passive house is unlikely to be cost-effective. A practical rule of thumb is that the current stock could be profitably tightened to the level of the best 10 percent of the stock.

6.1.3 Indoor Contaminants

6.1.3.1 Prioritizing Contaminants for Health-Based Ventilation Standards

One of the most significant outputs of the RESAVE program is the prioritized listing of chronic indoor contaminants of concern. The study results showed that fine particulate ($PM_{2.5}$) has the most significant chronic health impact even in non-smoking households. In such households, formaldehyde is the next most important indoor contaminant. Following that are the products of combustion taken as a whole, with the chemical acrolein being the most significant. Ozone and radon can be important, but will be limited by the locations for which the outdoor ozone levels are high or where there is radon in the soil. These results were obtained by developing an approach which converts exposures to Disability Adjusted Life Years (DALYs), which in turn can be monetized and compared with related costs and benefits.

6.1.3.2 Ventilation Control of Formaldehyde

Emission from materials is often the most important formaldehyde source within the home. Our analysis of concentrations has shown that these emissions vary with a variety of environmental parameters and most importantly with air change rate. Because emission varies with air change rate, ventilation is not as effective at reducing short-term formaldehyde concentrations as it is for more generic contaminants. It can, however, be as effective at reducing long-term exposures because a higher air change rate depletes the formaldehyde in the stored material faster.

By applying the DALY approach to formaldehyde control, this study found that even if the reduced effectiveness of ventilation is considered, reducing the long-term exposure of formaldehyde using ventilation can be cost effective. Of course, it may be even more cost effective to eliminate the source in the first place by not having materials that emit formaldehyde.

6.1.3.3 Source Control for Cooking Burners

Because particles and products of combustion have been identified as the most important indoor contaminants, cooking is the single most important source related to occupant activity. Unvented or poorly vented cooking appliances are thus substantial health hazards. Use of a range hood to capture these contaminants can substantially reduce these hazards. Our analysis shows that even a conventional range hood *can* reduce the fraction of time concentrations by 70 percent, but most range hoods perform substantially worse than that because they are not well utilized.

6.1.4 Optimized Ventilation

6.1.4.1 Optimized Mechanical Ventilation

Standard mechanical ventilation systems involve a constantly operating (or cycling) fan to provide continual ventilation regardless of the time of day or operation of exogenous ventilation systems. This study’s simulations showed that by applying a smart control algorithm to any of the standard ventilation approaches, one can save 30 to 50 percent of the energy required for ventilation.

Such smart algorithms also allow a substantial reduction of demand by shifting ventilation away from peak period. They also allow a reduction of outdoor pollutants that are brought inside during periods when outdoor air quality is poor or, in principle, when the space is unoccupied.

6.1.4.2 Sustainable Ventilation

The most sustainable way to ventilate is without a fan at all. Many parts of the world use passive or hybrid ventilation strategies, which could be useful in a mild climate like California, but these have not been adopted. This study used simulation tools and the equivalent ventilation approach to determine if using sustainable ventilation approaches make sense in California. The results show that passive and hybrid approaches can perform nearly as well as traditional mechanical approaches. For them to perform well, they must be well designed, and include some flow control products to minimize over-ventilation.

6.1.4.3 Ventilation Commissioning

A thorough review of the literature shows that commissioning of residential ventilation systems is not a common practice in California, but is being adopted in other countries. It also found that the literature is relatively devoid of field-test-related information that can be used in isolation to commission residential ventilation systems. When appropriate diagnostic methods were used, this study's field results showed that many systems being installed (e.g., almost half of the bathroom exhaust fans) do not meet the intended requirements.

Energy and IAQ simulation and DALY approaches were used to determine the value of residential ventilation system commissioning. We concluded that adjusting system airflows will always be of value in homes with low emission rates, as long as the price of tuning is less than the 30-year health and energy cost of an over-ventilating system. Our simulation results also suggest that controlling and limiting the levels of continuous emissions may be an important tuning tool for residential ventilation systems (i.e. if sources of a pollutant are removed, the ventilation rate can potentially be reduced). An interesting result of our simulations is that the economic optimum ventilation rate may be well above the current requirements of ASHRAE Standard 62.2, especially for homes with elevated emission rates.

6.1.4.4 Airflow Diagnostics

This study showed that there is great diversity in the performance of different products that contractors might use to measure airflow in ventilation-related systems for California homes. Some of this diversity is logistical because it can be practically impossible to attach an airflow measurement system to certain appliances (e.g., range hoods). Even when connection of the airflow diagnostic system is not an issue, different types of equipment may perform poorly because of insertion losses and asymmetric airflow. The study found, for example, that unpowered flow hoods are not very reliable for measuring outlet flows. In general, powered flow hoods were the most robust class of air-flow diagnostic equipment.

6.2 Benefits to California

As California seeks to reduce the environmental impact of homes while protecting the indoor environment, it must improve the energy efficiency of homes, and tightening homes to reduce infiltration is a straightforward means of doing so. The amount of energy saved depends on both the home's baseline energy use and what must be done to mitigate any negative impacts from tightening. Air sealing and tightening of the building envelope reduces air infiltration and its attendant energy costs in California homes, but doing so also reduces the total air exchange with outdoor air. California currently requires that new construction comply with ASHRAE Standard 62.2 to provide sufficient ventilation, but ASHRAE 62.2 is not an energy standard, and therefore allows many means of compliance which may not be optimal for energy efficiency.

6.2.1 Title 24 and ASHRAE Standard 62.2

California Title 24 is a key means for the State to implement energy efficiency in buildings. Because Title 24 references ASHRAE Standard 62.2, the RESAVE team has been very active in advancing this standard to improve its ability to provide acceptable IAQ while allowing the flexibility to do so energy-efficiently. A key benefit to California residents from the adoption and continued improvements in ASHRAE 62.2 is the improved health that goes along with improved IAQ, which can result in better school attendance and less productivity lost to IAQ-related illness. The 2013 version of Title 24 will reference most of the 2013 version of ASHRAE Standard 62.2. The RESAVE team has worked with ASHRAE to improve the version that will be adopted by California, and the team had several improvements implemented. Some of those that benefit California are listed below.

6.2.1.1 Equivalent Ventilation

Equivalent ventilation is the general principle that enables innovative ventilation systems to be shown as equivalent to the continuous ventilation specified in the standard. This enabling principle would allow the Energy Commission to determine if some future proposed ventilation technologies (such as the passive ventilation technologies investigated in RESAVE) comply.

While the general principle of equivalent ventilation is not yet operationally defined for the general case, there are two special cases that are explicitly described in the standard: one that looks at the impact of intermittent ventilation and one that looks at the impact of air leakage.

6.2.1.2 Intermittent Ventilation

One may wish to cycle a fan because outdoor air is undesirable at certain times, either because of the cost to condition or because it is contaminated (e.g., with high ozone concentrations). One may also wish to decrease the ventilation and attendant load during peak utility demand periods or when utility prices (or TDV) are high. The simplest way to cycle a fan is on a timer.

The intermittent ventilation approach of Standard 62.2 specifies how a ventilation fan may be cycled to be considered equivalent. A cycled fan, must be larger in capacity than a minimally compliant continuous fan, and overall will exchange more air per day, but it may result in less energy consumption and peak demand to do so.

6.2.1.3 Air Leakage Credit

Air leakage causes infiltration, which contributes to the home's overall ventilation rate. An airtight home requires more mechanical ventilation than a leaky one to achieve the same indoor air quality. The mechanical ventilation rate may be adjusted downward to account for air leakage, but that air leakage must be measured (using a blower door). California already requires a certain level of air-tightness testing, and that measured value may be used to reduce the energy needed for mechanical ventilation.

The ASHRAE 62.2-2013 version will not assume any default level of air leakage, but the California 2013 version will have a default infiltration credit. Either way, it is expected that adoption of 62.2-2013 will lead to many more homes being diagnostically tested for air leakage, and this represents a significant advance in quality assurance and control procedures for California housing that will benefit Californians. It will also lead to better quality construction—representing a long-term investment in California's infrastructure and allowing the California construction industry to become national leaders.

6.2.1.4 Existing Buildings

Understanding California's need to reduce energy by retrofitting existing homes, the RESAVE team was instrumental in updating the 2010 version of ASHRAE Standard 62.2 (which was principally focused on new construction) to accommodate the practical issues associated with existing homes. The current version of 62.2 has an existing buildings appendix and additional requirements that enable it to be used for both deep and conventional retrofit applications.

6.2.1.5 Multifamily Buildings

ASHRAE Standard 62.2 is principally focused on single-family homes, but it has been updated for use in multifamily buildings.

6.2.2 Envelope Air Leakage

6.2.2.1 Residential Diagnostics Database

The air leakage database work benefits California in several ways: The analyses performed for the study help policy and other decisions makers to prioritize targets of opportunity by characterizing the stock of target homes in California that would benefit the most from air-tightening of the building envelope. These data can be used in simulation or forecasting models to determine the likely outcome energy savings of different programmatic air-tightening targets. Additionally the online database, http://resdb.lbl.gov, enables anyone from homeowners to policy makers to analyze envelope leakage for any subset of California homes that interests them. Finally, the data from this study's leakage database is being included in U.S. DOE's Home Energy Saver (http://hes.lbl.gov). Thus, when Californians use any of the Home Energy Saver suite of tools, they will benefit from the best information on air-tightness.

6.2.2.2 Multizone Leakage

The ability to make multizone leakage measurements is not yet a standardized process. It is far more complicated than a standard blower-door test, but as the need to address house-garage leakage or leakage among apartments in multifamily buildings grows in California, the need for such techniques grows. While the techniques evaluated or developed by RESAVE are not yet ready for widespread use in California, they are suitable for expert and research community use. Such use could lead to standardized test methods needed in retrofit and new construction programs.

6.2.2.3 Energy Benefits of Air Sealing

The ability to have a simplified physical model to predict the energy impacts of air sealing allows population-level simulation and forecasting to be done on the impacts of programmatic or policy-level decisions. In particular, this work has shown that there is likely an optimal air-tightness level for California climates that balances the energy savings, cost to tighten, and negative operational consequences of very tight envelopes. More work is needed to refine this estimate, but it is likely in the vicinity of 2 ACH_{50} (or a California SLA of 1), with variations by climate.

6.2.3 Contaminants and Their Control

6.2.3.1 Prioritizing Contaminants for Health-Based Ventilation Standards

Having a prioritized list of contaminants of concern allows researcher and policy makers to focus their resources on key contaminants. This impacts the health of Californians, but it also supports the design of programs that can save energy while improving health. In the longer term, this prioritization has the potential to put the IAQ aspects of Title 24 and other standards on a health basis, rather than just a ventilation basis. This will most likely be done by working to modify the next version of ASHRAE Standard 62.2.

6.2.3.2 Ventilation Control of Formaldehyde

Formaldehyde levels exceed California standards in most homes around the State, but as the DALY approach has shown, it is not the most important contaminant indoors. While source control is the preferred option and is being pursued in California, ventilation is still a cost-effective strategy for reducing formaldehyde exposure. Our results suggest that it would be beneficial to improve California standards for not only formaldehyde exposure but also for testing and rating of formaldehyde-emitting products.

6.2.3.3 Source Control for Cooking Burners

This study's results indicate that well-designed range hoods with adequate flow rates can effectively remove cooking-related pollutants before they mix into the home. Widespread use of even moderately effective hoods would dramatically reduce pollutant exposures in California households. Energy-efficient control of IAQ requires that more emphasis be placed on this source. The area of ventilation controls should be considered in future energy and IAQ standards in California. For example: requiring that range hoods operate automatically or that all local exhaust fans operate at a low level even when "off" and can be turned to higher air flows by occupants when necessary. Some aspects of this were observed already in the new homes that were part of the ventilation commissioning part of the RESAVE program, where the bathroom and laundry room exhaust fans were operated automatically by humidity sensors.

6.2.4 Ventilation Systems

6.2.4.1 Optimized Mechanical Ventilation

This study's results showed that it is possible to optimize important State policy objectives at reduced energy costs through smart control of ventilation. These objectives go beyond the minimum ventilation standards, include protection from outdoor contaminants, and reduce peak demand while saving 40 percent of ventilation energy. By adopting the new version of ASHRAE Standard 62.2 in the next version of Title 24, the use of such optimized control technologies will be allowed in principle.

6.2.4.2 Sustainable Ventilation

RESAVE has shown that the use of sustainable ventilation can be very helpful in California homes, particularly in retrofit programs. It can sometimes be cost-prohibitive to install mechanical ventilation as part of a retrofit package. Passive ventilation can facilitate economic energy reductions while protecting the indoor environment if appropriate controls are used to prevent over-ventilation. By adopting the new version of ASHRAE Standard 62.2 in the next version of Title 24, the use of sustainable ventilation will be allowed in principle.

6.2.4.3 Ventilation Commissioning

This work demonstrates that it would benefit California to require commissioning of residential ventilation systems as part of a compliance program and as required by ASHRAE Standard 62.2. Uncommissioned systems should be presumed to work poorly compared to commissioned ones based on observations of ventilation fan actual versus required flow rates in homes as shown in Stratton 2012, and penalized severely in energy and IAQ standards. With respect to VOCs like formaldehyde, the current study results show that Californians would be better off increasing their ventilation rates above the minimum required by code, but care must be taken to control particle concentrations. This is only a preliminary result, and a more thorough analysis needs to consider ozone and particle impacts when the air change rate is increased.

6.2.4.4 Airflow Diagnostics

The laboratory and field work on airflow diagnostics has indicated that most California homes would be expected to meet the whole-house ventilation requirements, but many would not meet the local exhaust requirements.

Products available for measuring flows in the California market have a wide range of performance and cannot be counted on to meet manufacturer specifications in all the reasonable configurations typically found. Until suitable industry standards have been developed, we find that only powered flow hoods meet California needs for all residential airflow, and that some passive flow hoods may be adequate for bathroom exhaust flow measurements.

6.3 Recommendations

Based on the results from this study, the California Energy Commission should consider the following actions and investments.

6.3.1 Title 24 2013

The RESAVE program has shown several technologies to be valuable. Some of these technologies are allowed under ASHRAE Standard 62.2-2013, but are not described or not enabled in the 2013 version of Title 24. It would be advantageous to California to invest in some enabling work to facilitate innovation in the following areas:

- Advance ventilation control systems, such as RIVEC, are allowed in principle in Title 24, but there is insufficient description to determine compliance. In such cases, innovative designers will not be able to take advantage of this technology. We recommend that research be conducted to develop a usable protocol for determining compliance.
- Sustainable, and particularly passive, ventilation approaches would facilitate advanced retrofit. Similar to optimized mechanical systems that are allowed but not enabled, the equivalency principle of ASHRAE standard 62.2 does not describe how to do sustainable ventilation. Performance specifications need to be developed to determine how to show compliance for such systems

6.3.2 ASHRAE Standard 62.2-2016

In the future, Title 24 will likely reference the next version of ASHRAE Standard 62.2, which is nominally scheduled to be published in 2016. The Energy Commission should provide research and technical support to the committee to make sure that changes and evolutions of the standard meet California needs. This will be particularly important as California seeks to achieve the goal of zero energy homes.

We recommend that the Energy Commission (perhaps with appropriate co-funding from the California Air Resources Board, CARB) undertake some specific research that will advance State interests for inclusion in 62.2:

- Contribution of cooking to indoor air quality: It may be much more energy efficient to improve the extraction of cooking contaminants than to increase whole-house ventilation rates. Understanding this trade-off may allow reduction in whole-house rates if other requirements are met, and this could reduce costs. Research is necessary to understand this trade-off and to ascertain the role of the acute exposures. Technologies for controlling exposure to cooking contaminants automatically need to be demonstrated and evaluated.
- The most important indoor contaminant is fine particulate, and it has both indoor and outdoor sources. Technologies exist to remove it, and the industry is continuing to advance these technologies, but research is necessary to facilitate trading off improved particle filtration for air flows or other contaminant control. Practical methods for including particle filtration in a ventilation standard need to be developed and demonstrated.
- Formaldehyde is the compound that exceeds California chronic standards the most. Research is necessary to put the exceedances of this contaminant in context with other contaminants, to allow energy use to be optimized without harming indoor air quality. Methods need to be developed, demonstrated, or evaluated to cost-effectively reduce formaldehyde concentrations, including ventilation, source control, and air cleaning.

6.3.3 Consensus Test Methods

The RESAVE program has shown that there are innovative techniques for evaluating energy performance and IAQ, but that in many cases there are not appropriate test methods or diagnostics that can be used in the field. For California programs, codes, or standards to be able to require or allow new techniques, appropriate test methods must be developed and made available.

To develop and demonstrate these test methods, some research is necessary, and standards development effort is required. We recommend that the Energy Commission, in conjunction with appropriate federal agencies (e.g., U.S. DOE), work with the appropriate industry or consensus body to develop the following test methods or diagnostics:

- Multizone Leakage Test Method: ASTM E779 is the industry standard for using a blower-door in a single zone. RESAVE demonstrated that test methods could be developed for making multizone measurements, such as those that would be needed in multifamily buildings or for determining leakage of attached garages in single-family homes. Research is needed to determine the optimal protocols and then to work with ASTM (or another appropriate organization) to develop the standard.
- Capture Efficiency: Currently range hoods are rated by their flow rate, but that is only an intermediate to the desired metric, which is capture efficiency. One cannot specify capture efficiency in a code or standard because there is no test method for it. RESAVE (and other Energy Commission projects) have demonstrated that there are good ways to measure capture efficiency. Expanded research is needed to refine these methods and then to work with an appropriate industry or consensus body to adopt a test method suitable for adopting in a code or standard.

- Airflow Diagnostics: As demonstrated in this study, flow hoods have quite a wide performance range. If commissioning or similar field verifications are to be done on California homes, it is necessary to have methods of certifying performance of the airflow diagnostic equipment that will be used. A test method suitable for determining field performance of these devices does not yet exist, and one needs to be developed.

6.3.4 Stock Characterization

The RESAVE program has improved our knowledge of the state of air-tightness, ventilation, and indoor air quality in California, but it has also exposed data gaps. To develop better programs and codes to cost effectively save energy and improve indoor air quality, it is necessary to understand the stock of homes better. Therefore, Energy Commission should undertake field data collection and research to address the following issues:

- Aging of Building Envelopes: The envelope air leakage data created by RESAVE characterizes the stock of homes and shows that older homes tend to be more leaky. The database does not have sufficient data to separate out the effect of aging (that is buildings getting leakier as they age) from improvements in construction over time. Such data are necessary to understand the persistence of air-tightness savings, as well as to design better programs. Addressing this issue requires additional data from homes that have repeated air leakage measurements over time.
- Duct Leakage: In building the envelope air leakage database, incidental data were collected on duct leakage in California homes, but no systematic effort was conducted to disaggregate substantial or representative duct leakage data. Since duct leakage can reduce HVAC efficiencies substantially, it is as important, if not more important, to understand the trends in duct leakage as it is to understand envelope leakage.
- Contaminant Exposures and Sources: RESAVE identified the contaminants of concern in California homes, but it is not known how these contaminants are distributed in different regions, house types, and seasons. A tailored expansion of the California New Homes Study would allow a better understanding of that distribution.
- Compliance Methods and Performance: California houses built since 2009 are required to meet ventilation requirements. It is not known which compliance options have been chosen, nor whether the intent of the requirements was actually met.

6.3.5 Technology Development

RESAVE was not primarily focused on the development of new technology, but its research results indicate areas where future technology development could be productive.

- New air leakage testing approaches and equipment will be needed to measure leakage in more complex building systems. Additionally, quick, low-cost air leakage test methods would help to improve audits of existing houses.
- Innovative air-sealing systems need to be developed if California intends to substantially improve the energy efficiency of existing homes.
- Improved sensors for the contaminants of concern such as particles, formaldehyde, acrolein, and others are required to enable the transition from a ventilation rate basis of IAQ to a health basis.

- Low-cost, high-efficiency air cleaning equipment could be part of an energy-efficient IAQ control strategy, but outside of particle filtration none yet exist for the residential environment.
- Since cooking is typically the largest single indoor source of contaminants in a non-smoking household, improved range hoods and other cooking source control measures would facilitate improved IAQ and reduced energy costs.
- The principle of equivalence allows ventilation loads to be shifted in time or to vary with loads and activities. Further development of smart ventilation (and ultimately IAQ) controllers would enable both energy and peak power savings.
- Passive ventilation strategies, particularly in retrofit environments, have the potential to be a low-cost, moderate efficiency technology, but require further development for use in California.
- Low-cost, reasonably accurate commissioning diagnostic equipment (and associated test methods) need to be developed to be able to realize energy savings from commissioning.

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GLOSSARY

ACCA	Air Conditioning Contractors of America
ACH	air changes per hour
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
BPI	Building Performance Institute
CAAQS	California Ambient Air Quality Standards
CARB	California Air Resources Board
CE	capture efficiency
CFIS	central fan integrated supply
cfm	cubic feet per minute
CI	confidence interval
CRI	Carpet and Rug Institute
CZ	climate zone
DALY	Disability Adjusted Light Year
DIFF	A powered flow hood from Europe
EPA	U.S. Department of Energy
ERV	energy recovery ventilator
ft^2	square foot
GAP	Guide Advisory Panel
HRV	heat recovery ventilator
HUD	U.S. Department of Housing and Urban Development
HVAC	Heating, Ventilation, and Air-Conditioning
IAQ	indoor air quality
IECC	International Energy Conservation Code
IMC	International Mechanical Code

IRC	International Residential Code
IVE	Incremental Ventilation Energy
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
MERV	Minimum Efficiency Reporting Value
NAAQS	National Ambient Air Quality Standards
NFPA	National Fire Protection Association
NL	normalized leakage
NO_2	nitrogen dioxide
NPV	net present value
OEHHA	California Office of Environmental Health Hazard Assessment
OSHA	U.S. Occupational Safety and Health Administration
PESNA	Panasonic Eco Solutions North America
PHEC	Panasonic Home and Environment Company
PIER	Public Interest Energy Research
PM	particle mass or particulate matter
R&D	research and development
RD&D	research, development, and demonstration
REGCAP	REGister CAPacity model
RESAVE	Residential Energy Savings from Air-Tightness and Ventilation Excellence
ResDB	Residential Diagnostics Database
RESNET	Residential Energy Services Network
RIVEC	Residential Integrated Ventilation Energy Controller
SHS	secondhand tobacco smoke
SLA	specific leakage area
SSPC	ASHRAE Standing Standard Project Committee
TAB	test and balance
TDV	Time-Dependent Valuation

TECEFM	A passive exhaust-only device from The Energy Conservatory
TECFB	A powered flow hood from The Energy Conservatory
TMY	Typical Meteorological Year
USGBC	U.S. Green Building Council
U.S. DOE	U.S. Department of Energy
VIAQ	Ventilation and Indoor Air Quality study
VOC	volatile organic compound
WAP	weatherization assistance program

APPENDIX A:
RESAVE Products Not Cited in the Report

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