International Energy Agency

Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation

AIVC Contributed Report 18

Energy in Buildings and Communities Programme

April 2019

EBC is a programme of the International Energy Agency (IEA)

International Energy Agency

Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation
AIVC Contributed Report 18

Energy in Buildings and Communities Programme

April 2019

Authors

W.R. Chan, Lawrence Berkeley National Laboratory

Y-S Kim, Lawrence Berkeley National Laboratory

B.D. Less, Lawrence Berkeley National Laboratory

B.C. Singer, Lawrence Berkeley National Laboratory

I.S. Walker, Lawrence Berkeley National Laboratory

Contributed Reports are reports produced by third parties but considered of relevance for the AIVC target audience.

Published by INIVE EEIG , Lozenberg 7, B-1932 Sint-Stevens-Woluwe, Belgium

ISBN 2-930471-55-6

EAN: 9782930471556

Participating countries in EBC: Australia, Austria, Belgium, Canada, P.R. China, Denmark, Finland, France, Germany, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Portugal, Singapore, Spain, Sweden, Switzerland, United Kingdom and the United States of America.

EBC Bookshop
C/o AECOM Ltd
The Colmore Building
Colmore Circus Queensway
Birmingham B4 6AT
United Kingdom
Web: www.iea-ebc.org
Email: essu@iea-ebc.org

Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the Energy in Buildings and Communities (EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the Energy in Buildings and Community Systems Programme, ECBCS.)

The research and development strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. The research and development (R&D) strategies of IEA-EBC aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five focus areas for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

The Executive Committee

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)

Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54: Integration of Micro-Generation & Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy & CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy & CO2 Equivalent Emissions for Building Construction (*)
Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling & Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building & Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings

Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Public Resilient Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables
Annex 76: EBC Annex 76 / SHC Task 59 Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO2 Emissions
Annex 77: EBC Annex 77 / SHC Task 61 Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings
Working Group - Cities and Communities

Foreword to AIVC Contributed Report 18

Although indoor air quality has been studies for many years there is a lack on comprehensive data on the contaminants found in homes combined with information on home air exchange rate and operation of ventilation systems. There are also questions regarding the efficacy of ventilation requirements: do they result in acceptable indoor air quality? This study aimed to provide a set of baseline contaminant data measured in homes that have mechanical ventilation to address these issues. This study was performed in California on new homes with operating mechanical ventilation systems intended to meet the ASHRAE 62.2 ventilation standard. This US national standard includes source control measures by exhausting from kitchens and bathrooms together with dwelling unit ventilation at a rate of approximately 0.3 Air Changes per Hour and is required in all new California homes. The study combined field measurements of contaminants in 70 homes together with a survey of Indoor Air Quality issues for over 2700 California residents as well as a simulation component to investigate energy impacts of airtightness requirements and mechanical ventilation systems across a wide range of climates, house types and occupancy.

The results of this study can be used by AIVC members to provide the rationale for having ventilation requirements. It also provides information on what contaminants are often present at levels of concern that allows for the application of ventilation and air cleaning solutions that target the most important contaminants. The study also provides insight on typical occupant thoughts about ventilation and indoor air quality that are useful for developing public information strategies. Lastly, the energy impacts of air tightening and ventilation in a range of climates can be used to prioritize different approaches to having low energy use homes that also maintain acceptable indoor air quality.

The key results are that formaldehyde and particles are reduced relative to homes without mechanical ventilation and that other contaminants were controlled to acceptable levels indicating that the ASHRAE 62.2 standard does provide acceptable indoor air quality in these new California homes[1]. However, when ventilation controls are unlabelled or are complex for uses, they are often turned off (only one quarter of systems were operating when the test homes were first visited). If we are going to allow occupant control of ventilation systems, better controls, labels and occupant awareness are essential. The dwelling unit ventilation and kitchen/bathroom exhausts almost always met the minimum required air flows, with dwelling unit ventilation about 50% greater than the minimum on average. The ventilation devices of greatest concern were microwave ovens integrated into kitchen range hoods that often failed to meet minimum flow requirements, or only did so at the highest, noisiest operating speed. Occupants seemed to recognize this fact and these kitchen ventilation systems were used the least. Because the ASHRAE 62.2 standard is based on a total ventilation requirement, additional mechanical ventilation is required as home

[1] We note that California also introduced legislation to reduce formaldehyde emissions from building materials in recent years and that these newer homes tended to have better air filters in their central forced air systems than have been seen previously. Both of these likely contributed to the reduction in formaldehyde and particles compared to previous studies in new California homes.

become more airtight there was very little energy savings associated with airtightening below the current levels (about 4 ACH50 or 3 L/s/m2 of floor area at 50 Pa) in mild California climates.

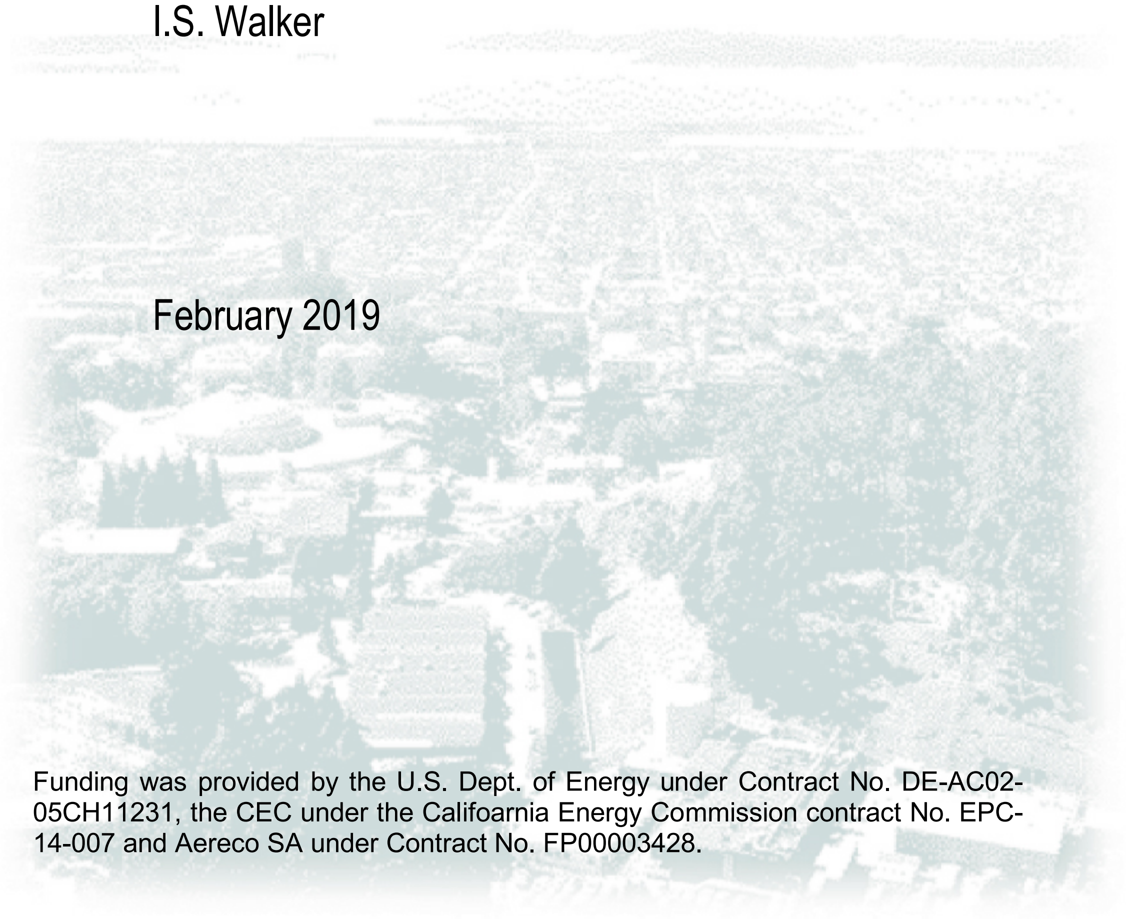
Iain Walker

Lawrence Berkeley National Laboratory

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation

W.R. Chan, Y-S Kim, B.D. Less, B.C. Singer, and I.S. Walker



February 2019

Funding was provided by the U.S. Dept. of Energy under Contract No. DE-AC02-05CH11231, the CEC under the Califoarnia Energy Commission contract No. EPC-14-007 and Aereco SA under Contract No. FP00003428.

Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or The Regents of the University of California.

Energy Research and Development Division
FINAL PROJECT REPORT

Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation

Prepared for: California Energy Commission
Prepared by: Lawrence Berkeley National Laboratory

MONTH YEAR
CEC-500-YYYY-XXX

PREPARED BY:

Primary Author(s):
Wanyu R. Chan
Yang-Seon Kim
Brennan D. Less
Brett C. Singer
Iain S. Walker

Lawrence Berkeley National Laboratory
1 Cyclotron Road
Berkeley, CA 94720
Phone: 510-486-6570
http://www.indoor.lbl.gov

Contract Number: PIR-14-007

Prepared for:

California Energy Commission

Yu Hou
Contract Manager

XXXXXXXXXXX
Office Manager
Energy XXXXXXXX Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

ACKNOWLEDGEMENTS

This work was supported primarily by the California Energy Commission through Contract PIR-14-007. Additional support was provided by the Department of Energy under Contract DE-AC02-05CH11231. The Southern California Gas Company (SoCalGas) provided direct financial support to the Gas Technology Institute (GTI) to purchase equipment and to conduct field data collection. Staff support was contributed by the Pacific Gas & Electric Company (PG&E) which funded Misti Bruceri & Associates (MBA) to provide a staff person to support the study, and by SoCalGas, which allocated engineering and technical staff to contribute to the field work in SoCalGas service territory under GTI direction. SoCalGas and PG&E also supported the project by allocating Gas Service Technicians to conduct gas appliance safety inspections in study homes.

The data presented in this report would not exist without the committed work of the field research teams in PG&E and SoCalGas service territories; the authors are deeply appreciative of their efforts. The field work for this project was conducted by Luke Bingham, Erin Case, and Shawn Scott of GTI; Guy Lawrence of MBA; and Eric Barba, Mary Nones, Ara Arouthinounian, and Ricardo Torres of SoCalGas; Randy Maddalena and Woody Delp of LBNL. Rick Chitwood also assisted with field data collection and provided guidance on measuring airflow rates in supply ventilation systems.

The authors would like to thank Max Sherman (now retired from LBNL) who was instrumental in project development and planning, was the original Principal Investigator for this project and provided valuable guidance and support. The authors note with appreciation the following contributions. Genese Scott of SoCalGas helped with online survey recruitment. Marion Russell of LBNL assisted with chemical analysis of samples. Xiong Mei, a visiting doctoral researcher at LBNL assisted with quality assurance review and cleaning of time-resolved pollutant data. Taylor Lyon, a student intern with support from Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI) program. Ji Gao, Samir Anbri, and Hao Fu, summer interns from Institut National Des Sciences Appliquees (INSA) Lyon contributed to preliminary data assessment. Kelly Perce developed online forms to enable easy entry of survey and activity log data from paper forms. The CalCERTS and CHEERS organizations provided Title 24 compliance records for many of the study homes. Neil Leslie, Larry Brand, and Rob Kamisky of GTI provided management support.

The authors thank Yu Hou at the Energy Commission for managing this project and Marla Mueller (retired) for helping to establish the project. Additional thanks go to Marshall Hunt of PG&E and Todd Sostek of SoCalGas for leading the efforts within their organizations to support the project.

The authors also thank the following members of the project advisory committee for their advice and reviews of draft documents: Bill Pennington, Brent Stephens, Eric Werling, Gregg Arney, Marla Mueller, Marshall Hunt, Maziar Shirakh, Michael Blanford, Mike Hodgson, Peggy Jenkins, Robert Raymer, Sarah Widder, Sarany Singer, Scott Kysar, Todd Sostek.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation is the final report for the Healthy Efficient New Gas Homes (HENGH) project (contract number PIR-14-007) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

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

ABSTRACT

Substantial energy is used to condition the air that enters California homes through leaks in the building envelope and ductwork - typically about a third of all heating and cooling. Reducing this through air sealing is essential to California achieving zero energy homes. However, this outdoor air also dilutes pollutants emitted inside homes and contributes to a healthy indoor environment and acceptable indoor air quality (IAQ). To address this IAQ issue, California's Title 24 Building Standards have required mechanical ventilation in new homes since 2008. This report presents a comprehensive study of the impacts of these requirements in recently constructed homes with natural gas appliances. The study included a survey about satisfaction and activities that impact IAQ; a field study of homes built to 2008 or later; and simulations assessing how various ventilation rates would impact chronic exposures to an indoor emitted pollutant as air tightness improves in California. The report focuses on the field study; the web-based survey and simulation elements are described in appendices.

The field study characterized 70 homes built between 2011 and 2017. Each home was monitored over roughly one week with the dwelling unit mechanical ventilation system operating and windows closed. Pollutant measurements included time-resolved fine particulate matter ($PM_{2.5}$) indoors and outdoors, and formaldehyde, nitrogen dioxide (NO_2), and carbon dioxide (CO_2) indoors. Time-integrated measurements were made for formaldehyde, NO_2 and nitrogen oxides (NO_X) indoors and outdoors at all homes. Activity monitoring devices were installed on the cooktop, range hood and other exhaust fans, and the heating and cooling system. The field study found that most homes met most ventilation requirements and the dwelling unit ventilation fans on average moved 50% more airflow than the minimum specified in Title 24. Air pollutant concentrations were similar or lower than those reported in a study of recent construction California new homes conducted in 2007-08. Notably, the median formaldehyde level was 38% lower than in the prior study. Measured concentrations were below health guidelines for most pollutants, indicating that IAQ is acceptable in new California homes when dwelling unit mechanical ventilation is used. However, the dwelling unit mechanical ventilation fans were only operating in one quarter of the homes when first visited and the control switches in many homes did not have informative labels as required by the standards. Corrective action needs to be taken to improve labeling and controls for ventilation systems.

Keywords: Airtightness, Cooking, Formaldehyde, Healthy buildings, Nitrogen dioxide, Particulate matter, Range hood, Title 24

Please use the following citation for this report:

Chan, Wanyu R.; Kim, Yang-Seon; Less, Brennan B.; Singer, Brett C.; Walker, Iain S. (Lawrence Berkeley National Laboratory). 2018. ***Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation.*** California Energy Commission. Publication number: CEC-500-YYYY-XXX.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Many California homes waste energy to condition excessive outdoor air that enters via uncontrolled infiltration through the building envelope. Though energy inefficient, outdoor air infiltration has traditionally served to dilute indoor-generated air pollutants. Thus, while reducing infiltration saves energy, these measures also increase the risk of negative health impacts as indoor air pollutant concentrations and exposures could increase. Previous California Energy Commission research studies found that windows are not a reliable source of ventilation, measured ventilation rates in many homes were below target minimum levels and formaldehyde and $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 micrometers) exceeded health guidelines.

In 2008, ventilation requirements were added to the California Title 24 Building Energy Efficiency Standards (Title 24) to address adverse impacts that could potentially result from air sealing envelopes to reduce air infiltration. Previous work in California has highlighted contaminants of concern and documented their levels, but this was done in homes that were built before building standards required dwelling unit mechanical ventilation. Prior to the study reported here, it was not known if the ventilation requirements resulted in acceptable levels of contaminants or how the ventilation requirements are being met in the state. The study reported here was designed to measure the indoor air quality (IAQ) in California homes built to meet these requirements and to determine if the requirements are having the desired effect: i.e., ensuring acceptable IAQ for California residents. In addition to IAQ measurements collected over a one-week period, the study measured installed ventilation system operation characteristics together with other home parameters related to airflows between the house and outside, such as envelope and duct leakage. The field study also collected data about ventilation practices and indoor air quality and comfort satisfaction of the home's occupants. The field study focused on homes with natural gas appliances with gas service provided by California's investor-owned utilities. The field study obtained data from 70 homes. Prior to the field study, the project implemented a web-based survey to obtain data on IAQ satisfaction and ventilation practices in a much larger sample of homes. The web-based survey aimed to collect data from homes built both before and after the 2008 standards, starting with homes built in 2002; but mostly obtained data from homes built before the 2008 Standards were in effect. Participants in the field study homes also completed the survey. Another major element of the project was a simulation-based analysis of potential energy benefits and indoor air quality implications of reducing infiltration and modifying ventilation requirements. The body of this report focuses on field study data and analysis. The survey and simulation studies are described in appendices.

Project Purpose

The Healthy Efficient New Gas Homes (HENGH) project aimed to study the impacts of new home mechanical ventilation requirements included in the 2008 Title 24 Building Energy Efficiency Standards. The goals of the HENGH project were: (a) to assess whether the mechanical ventilation systems that have been required starting with California's 2008 Title 24 Building Standards are effectively providing acceptable IAQ, and (b) to provide recommendations on how to achieve adequate ventilation while reducing infiltration and associated energy consumption.

Methods

A field study protocol was designed and overseen by Lawrence Berkeley National Laboratory (LBNL) and LBNL conducted all data analysis. The study included measurements of indoor air quality (IAQ), home characteristics, mechanical ventilation, and occupant activities in 70 occupied new California homes with natural gas appliances. The IAQ measurements were performed over a period of one week and included time-resolved concentrations of particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), carbon dioxide (CO_2), and formaldehyde, together with time-integrated concentrations of formaldehyde, NO_2 and total nitrogen oxides (NO_X); the concentration of NO was estimated as the difference between NO_X and NO_2. Diagnostic tests were conducted to measure air leakage of the envelope and heating and cooling duct systems and the airflows of all ventilation fans including those used to satisfy local exhaust in kitchens and bathrooms. Occupant activities were monitored for cooking, use of range hood and other exhaust fans.

HENGH field teams, one led by the Gas Technology Institute (GTI) with technical support from the Pacific Gas & Electric Company (PG&E) and the other comprising Southern California Gas Company (SoCalGas) researchers and gas service technicians working under GTI guidance, completed field data collection in 70 homes (48 homes in PG&E territory, and 22 homes in SoCalGas territory), between July 2016 and April 2018. LBNL obtained human subject approval for this study, recruited study homes, provided technical oversight of data collection, and performed data analysis. LBNL also performed chemical analysis of all time-integrated formaldehyde and NO_2/NO_X samples, and quantification of PM filters.

Project Results

The web-based survey results from 2648 respondents indicate that the homes sampled in the field study were typical of new California homes in terms of house size and occupancy. About 90% of occupants rated IAQ neutral or better and were generally more satisfied with IAQ than outdoor air quality. Other key results from the web-based survey include the following: range hoods that were vented to outside were used more often than recirculating hoods (suggesting that occupants are aware of the difference in efficacy of these devices) and while most occupants are satisfied with IAQ, there are some indications that increased bathroom exhaust venting and fewer occupants are correlated to reductions in complaints of mustiness/odor. In addition, households with sensitive occupants (at least one person diagnosed with asthma or allergy; all answers are self-reported) were much more likely to use air cleaning devices. Homes with mechanical ventilation system that the survey respondents identified as providing fresh air are correlated with higher IAQ satisfaction.

Most of the field study homes (N=55, out of 70) met the dwelling unit ventilation requirement with a continuous exhaust fan that was either in the laundry room or a bathroom. Three homes

— all in the same development — used a continuous exhaust fan in the attic that was connected to all three bathrooms to meet both the dwelling unit and local exhaust ventilation requirements. The other dwelling unit mechanical ventilation system identified were intermittent exhaust fan(s) with operation interval controller (N=9), supply fans connected to the central forced air system operating continuously (N=4), and supply ventilation provided intermittently by central fan integrated system with a motorized damper (N=2). In most cases, the measured airflow of the exhaust fan exceeded the required dwelling unit ventilation needs. However, the field teams found the dwelling unit mechanical ventilation system operating in only one in four homes during the first visit. The systems were not operated because occupants were unaware that the system existed and did not understand the control that was typically not labeled. Only 12 homes had a label that identified the control switch for the dwelling unit mechanical ventilation system. Field teams also found that fan runtime was set to run intermittently in half of the homes with a programmable controller. In the two homes where the thermostat is used as the controller, the fan was turned off in both cases.

The kitchen ventilation equipment in many homes appears to meet most but not all of the Title 24 requirements: moving ≥100 cfm at a setting with a certified sound rating of ≤3 sones. While most homes had a range hood or over-the-range microwave exhaust fan (OTR) that met the 100 cfm minimum airflow requirement, many of the range hoods and most of the OTRs did so only at medium or high speed that is often louder than 3 sones, and some OTRs did not meet the airflow requirement even at the highest speed setting. An important caveat to this finding is that the OTR airflows could be biased low based on the measurement method, which required taping over the air inlets provided at the front top of some OTRs.

Comparisons of indoor formaldehyde, NO_2, and $PM_{2.5}$ with a prior study of new homes in California (conducted in 2007-08) suggest that contaminant levels are lower in recently built homes. California's regulation to limit formaldehyde emissions from composite wood products appears to have substantially lowered its emission rate and concentration in new homes. Formaldehyde levels are still above California guidelines, but lower than other national and international guidelines. Lower outdoor $PM_{2.5}$ can only explain part of the substantially lower indoor $PM_{2.5}$ levels measured in the HENGH study compared to the prior study. Other contributors to lower indoor $PM_{2.5}$ are the use of higher efficiency air filters in central forced air systems (MERV8 or better in almost all homes and MERV11 or better in about a quarter of homes); filtration of outdoor particles by the building envelope, as occurs when ventilation is provided with an exhaust fan; and possibly lower particle emission rates inside the home. The finding of relatively low time-averaged NO_2 concentrations in this study is significant, given that all HENGH homes had natural gas cooking appliances. It suggests that the mechanical ventilation systems in HENGH homes may be contributing to lower NO_2. CO_2 concentrations were highest overnight in bedrooms. Indoor CO_2 concentrations measured in the main living space were not substantially different from the prior study.

Our results suggest that unless occupant pollutant exposure is allowed to increase by 5-10% relative to target rates, then an airtightness limit will have very marginal savings of roughly 1% of annual HVAC energy. If exposure is allowed to increase (by about 5-24%), then savings of 3-5% are possible through airtightening. On average, the adopted 2019 fan sizing method for Title

24 performed similarly to ASHRAE 62.2-2016 method under current airtightness conditions. The 2019 Title 24 fan sizing method gave weighted average exposure very near to 1.0 under both current and hypothetical airtightened scenarios, though exposure would increase roughly 5% under a hypothetical airtightness requirement in the energy code. The 2019 Title 24 fan sizing approach was found to give consistent results for occupant exposure across a wide range of climates and airtightness with the exception that it over-ventilates leaky homes (3 and 5 ACH50), with increased site energy consumption ranging from 70 to, 1,400 kWh/year. The other Title 24 fan sizing methods from 2008 and 2013 did not have this consistency, and had exposures 30-40% worse than the 2019 Title 24 method.

When the energy savings are normalized to give the same exposure the weighted average energy savings were reduced to less than 1% for all fan sizing methods. In practice, the effects of the higher minimum mechanical airflow requirement on home energy use may be less than the estimates presented above because the field study found that many recently constructed homes already have ventilation equipment that would meet the new fan sizing requirements.

Project Benefits

The field study of 70 homes that were built to meet the 2008 Title 24 mechanical ventilation requirements found acceptable indoor air quality in the homes when the mechanical systems were operating and windows were generally closed. Therefore, we conclude that these, or similar requirements should continue to be included in Title 24 to ensure healthy indoor environments for California ratepayers. The finding that roughly three quarters of the homes did not have their ventilation systems operating and many of those homes did not have code-required labels on ventilation controllers suggests that indoor air quality may not be adequately protected in many homes. Corrective actions to mediate the widespread prevalence of non-operation of mechanical ventilation in new homes will benefit occupants by reducing their exposure to indoor generated pollutants. At a minimum, the requirement to label switches controlling ventilation systems needs to be enforced. Even better would be to have a standardized label used in all homes in the state and indicators to show system operation.

There is little energy benefit associated with implementing a maximum air leakage requirement for new California homes on a statewide basis, unless exposure to indoor generated contaminants is allowed to increase by 5-10%. Estimated energy savings were higher in climate zones (CZ1 and CZ16) with the harshest weather, but the number of new homes being constructed in those climate zones is small compared to other parts of California.

CHAPTER 1: Introduction

1.1 HENGH Study Overview

The Healthy Efficient New Gas Homes (HENGH) project aimed to study the impacts of new home mechanical ventilation requirements included in the 2008 Title 24 Building Standards (CEC, 2008). The ventilation requirements were added to the standards to address adverse impacts that could potentially result from air sealing envelopes to reduce infiltration and improve energy efficiency. The field study component of the project aimed to characterize installed ventilation system designs and rated airflows, to measure airflows, and to monitor ventilation equipment use and indoor air quality (IAQ) over a one-week period in a diverse sample of homes built to meet the 2008 or subsequent versions of the standards. The field study also collected data about ventilation practices and indoor air quality and comfort satisfaction of the home's occupants. The field study obtained data from 70 homes with natural gas appliances and service provided by one of California's investor-owned gas utilities.

Many California homes, including some that have been built in recent decades, waste energy to condition excessive outdoor air that enters via uncontrolled infiltration through the building envelope. Air leakage to and from forced air heating and cooling system ducts in unconditioned attics and garages results in additional energy losses. Though energy inefficient, the infiltration of outdoor air has traditionally served to dilute air pollutants emitted inside the building. Thus, while reducing infiltration and duct leakage saves energy, these measures also increase the risk of negative health impacts as indoor air pollutant concentrations and exposures could increase.

Starting in the mid-2000s, the California Energy Commission funded several research studies (e.g., Price et al., 2007, and Offerman, 2009) that aimed to evaluate the potential IAQ impacts associated with envelope air sealing, and the potential to mitigate these through the use of mechanical ventilation systems. These studies found (a) that a majority of the households in new California homes reported not opening windows regularly for ventilation in some seasons, and a substantial minority of households reported not using windows to ventilate during any season; (b) that actual, measured ventilation rates in many homes were below target minimum levels; and (c) that the median measured formaldehyde concentration across study homes was four times the chronic reference exposure level set by the California Office of Environmental Health Hazard Assessment (OEHHA).

To address this issue, the 2008 California Building Energy Efficiency Standards[1] included requirements for mechanical ventilation to maintain acceptable IAQ, and ventilation requirements have been included in all subsequent versions of the standard. The first ventilation requirement was based on a version of ASHRAE Standard 62.2 that was specifically

[1] In this document we use the term "Title 24" to refer to California Title 24, Part 6, Building Energy Efficiency Standards.

developed for California and set a minimum continuous mechanical airflow along with an option to ventilate intermittently at rates determined to provide equivalent dilution of indoor sources. The standards also include requirements for kitchen and bathroom ventilation.

The Energy Commission funded the HENGH study to evaluate the impacts of the mechanical ventilation system requirements that started in 2008. The intent was for HENGH results to inform considerations of ventilation requirements as California transitions to a building standard requiring all new homes to be zero net energy.

1.2 Prior Studies of Ventilation and IAQ in New California Homes

1.2.1 Mailed Survey of Ventilation Behavior and Household Characteristics

In the mid-2000s, the Energy Commission funded, via contract CEC-500-02-023, a study of ventilation behaviors, IAQ perceptions, and related household characteristics in recently built California homes. The study, reported in Price and Sherman (2006) and Price et al. (2007), had the following objectives:

- Determine how occupants use windows, doors and mechanical ventilation
- Determine occupants perceptions of and satisfaction with IAQ in their homes
- Determine the relationships among ventilation practices, perceived IAQ and house and household characteristics
- Determine barriers that prevent or inhibit the use of windows, doors, and mechanical ventilation systems.

The study was conducted using a paper survey form that was mailed to a statewide, stratified random sample of 4972 single-family detached homes in 2003 with 1448 responses received. The data were supplemented with 67 completed interviews from a "builder" (convenience) sample of 230 houses known to have mechanical ventilation systems. The data from the sample were analyzed for the entire state and also by region; associations between behaviors and household characteristics were investigated.

The results of this study showed that window opening was not a reliable method to ventilate homes. Windows were not used for a wide range of reasons including inclement outdoor weather, noise and security issues. Even among homes that did open windows, the use was generally sporadic and inconsistent.

1.2.2 Field Study of Ventilation and IAQ in California Homes Built 2002–2004

As a follow-up to the mailed survey, the Energy Commission and Air Resources Board jointly supported a field study of ventilation and IAQ performance in recently built California homes as described in Offermann (2009). Throughout this report the Offermann study is referred to as the California New Home Study or CNHS. The CNHS characterized ventilation equipment and relevant performance aspects of the home – such as envelope air leakage and garage to house air leakage – and measured air exchange rates, ventilation equipment use, and a suite of IAQ parameters over a 24-h period in each home. The CNHS used the mailed survey database from the earlier mail out survey and supplementary procedures to recruit 108 homes, with most built in 2002-2004. At the time of the research team visits in the summer of 2007 through winter 2008, the homes ranged in age from 1.7 to 5.5 years. The study measured CO_2, CO, temperature, and relative humidity with time resolution. Formaldehyde, acetaldehyde, and 20 other volatile organic compounds (VOCs) were measured in 24-h integrated samplers inside all homes and outside of 40 homes. Measurements of time-integrated $PM_{2.5}$ and NO_2 were made inside 29 homes and outside at 11 homes. Time-integrated air exchange rates were measured in all homes over the 24-h sampling period and in a subset of 21 homes over a two-week period. Use of windows and ventilation equipment was monitored over a weeklong period in almost all study homes. Twenty of the homes were visited in both summer and winter seasons. Day-to-day variability was assessed by measurements conducted on three successive days in four of the study homes.

The air exchange rate (AER) of a home describes the rate of airflow in and out of the home as a fraction of the volume of air in the house. For the CNHS, the median AER was 0.26/h (i.e., about one quarter of the air in the home was exchanged with outside each hour) among the 107 homes with data from the main monitoring day and 0.24/h for the 21 homes with AER measured over a 2-week period. Approximately 2/3 of the homes had air exchange rates below the implicit target of 0.35/h. Thirty-two percent of study homes had no window or door use for ventilation during the 24-h monitoring period and 15% had no use during the preceding week. There were a total of 48 seasonal measurements (winter and/or summer) for 26 homes that had provided data through the prior mailed survey. In 52% of homes, the actual week-average window use exceeded the high end of the usage estimated during the survey. And in another 10% of cases, there was measured usage in homes that estimated no use of windows.

The two contaminants with measured indoor air concentrations that exceeded health guidelines were formaldehyde and $PM_{2.5}$. Indoor formaldehyde concentrations exceeded the OEHHA chronic reference exposure level (CREL) of 9 $\mu g/m^3$ in 98% of study homes and the median level of 36 $\mu g/m^3$ was four times the OEHHA CREL. While none of the homes had indoor $PM_{2.5}$ above the guideline exposure level of 65 $\mu g/m^3$ considered by Offermann, we believe the US EPA national ambient air quality annual standard of 12 $\mu g/m^3$ is a more relevant benchmark for in-home, time-averaged $PM_{2.5}$. The Offermann study reported a 75th percentile indoor $PM_{2.5}$ concentration of 14 $\mu g/m^3$ and a 50th percentile of 11 $\mu g/m^3$. Outdoors, the 75th and 50th percentile concentrations were 9.5 and 8.7 $\mu g/m^3$. Overall, these results suggest that a substantial minority of the homes in the Offermann study may have had indoor $PM_{2.5}$ above the NAAQS threshold and high indoor $PM_{2.5}$ was not solely due to high outdoor concentrations. A large fraction of the homes studied by Offermann also exceeded the Proposition 65 Safe Harbor Levels of acetaldehyde (93%). Concentrations of VOCs other than formaldehyde were lower than OEHHA CRELs in all cases, though several VOCs were present in at least some homes at levels that exceeded the Proposition 65 Safe Harbor Levels: trichloromethane (8%), tetrachloroethene (8%), 1,4-dichlorobenzene (12%), naphthalene (27%), benzene (63%).

1.2.3 Field Studies of Mechanical Ventilation System Performance

Published data on installed ventilation system performance suggest uneven implementation of code and standard requirements across states. A study of 29 homes in the state of Washington (Eklund et al., 2015) found that most had systems that were set, or that could be set to comply with the state standards for general mechanical ventilation. However, many of the systems were not operating at these design conditions as found. There were problems with incorrect settings (mostly systems not set to operate continuously or with adequate frequency) and maintenance issues, including some that required substantial expertise to resolve. A 21-home study conducted in Florida (Sonne et al., 2015) found that only 12 of the installed general ventilation systems were capable of operating and many of those had airflow rates well below design conditions. These two studies reported the following problems:

- Installation problems, e.g., disconnected duct, blocked vent, poorly hung ducts, inadequate duct insulation, inoperable outdoor air exhaust duct damper, ERV/HRV system installed backward.
- Operational problems, e.g., fan turned off, dirty filters, inadequate operation runtime.
- Difficult access to on/off controls, inaccessible intake/discharge vents (e.g., on roof) with screens that require routine maintenance.

In contrast, a study of 15 new homes in California (Stratton et al., 2012) – including six which were occupied – found installed exhaust ventilation systems that exceeded the minimum airflow requirements (by 40% on average) and only 2 homes failed to meet the minimum dwelling unit ventilation requirement. About one third of the kitchen and bathroom exhaust systems failed to meet minimum requirements.

1.3 Title 24 Ventilation Requirements

Dwelling unit mechanical ventilation has been required in new homes and in additions of more than 1,000 ft^2 since the 2008 California Title 24 Building Energy Efficiency Standards. The standard also requires exhaust ventilation in each bathroom and either a venting range hood or an exhaust fan in the kitchen.

The local exhaust requirements can be met by continuously operating fans or "demand controlled" fans that are either operated manually or using a sensor, e.g. based on occupancy or humidity level. The fans must have certified airflow ratings or must be field verified to move a specified minimum amount of air at a rated maximum sound level. Bathroom fans must move at least 20 cubic feet per minute (cfm) or 10 liters per second (l/s) if continuous or 50 cfm (25 l/s) if demand-controlled. Enclosed kitchens can have a continuous exhaust fan moving air equivalent to at least 5 kitchen air volume per hour. Non-enclosed kitchens must have a range hood that moves at least 100 cfm (50 l/s) or an exhaust fan that moves at least 300 cfm (150 l/s) or 5 kitchen air volumes per hour. Continuously operating exhaust fans – used either for dwelling unit or local exhaust – must be rated at 1 sone or lower and demand-control exhaust fans must be rated at 3 sone or lower at the required airflows.

Initially, the only compliance path for dwelling unit ventilation was the Fan Ventilation Rate method (FVRM), as described in Section 4.6.2 of the 2008 California Title 24, Part 6 Building Energy Efficiency Standards Residential Compliance Manual. This calculation requires 1 cfm of mechanical airflow for every 100 ft^2 of conditioned floor area and an additional 7.5 cfm for each occupant (typically bedroom count + 1). This calculation and the kitchen and bathroom venting requirements are taken from ASHRAE Standard 62.2-2007. Required airflows calculated using the FVRM do not vary by location or airtightness, but only by house size and occupancy. The FVRM is currently used to size dwelling unit ventilation fans for the prescriptive reference homes used to demonstrate Building Standards compliance in CBECC-Res. While not explicitly stated in the Standard, this calculation assumes 2 cfm of natural infiltration per 100 ft^2 of conditioned floor area (per the ASHRAE Standard), which is a reasonable assumption for homes in the 5-7 ACH50 range of airtightness. For more airtight homes (particularly in mild California climates), this infiltration assumption is too high, leading to dwelling unit ventilation rates that are below current targets. Recognizing the incompatibility of the FVRM with low-infiltration, airtight new homes, the CEC added a parallel compliance path in the 2013 standard cycle called the Total Ventilation Rate method (TVRM), calculated as follows. First, a Total Required Ventilation Rate is calculated (Q_{total}) similarly to the FVRM, but with a 3 cfm per 100 ft^2 conditioned floor area requirement (based on more recent versions of ASHRAE Standard 62.2 from 2013 onwards). Next, the Effective Annual Infiltration Rate is estimated based on the home's normalized leakage (as measured by blower door), geometry and geographic location (Q_{inf}). Finally, the Required Mechanical Ventilation Rate (Q_{fan}) is calculated as the difference between the Total Required Ventilation Rate and the Effective Annual Infiltration Rate. For airtight homes, this sizing method results in larger mechanical fan airflow requirements than the FVRM. For leaky homes, fan size can be reduced. Dwelling unit ventilation fan airflows differ by airtightness, house geometry and climate zone. The new 2019 Title 24 Building Energy Efficiency Standards have eliminated the FVRM for demonstrating compliance, and also adjusted the TVRM such that all homes will receive a dwelling unit ventilation fan sized as if the home were 2 ACH50. If air leakage is measured and is less than 2 ACH50, then the lower leakage rate is used in fan sizing calculations.

1.4 HENGH Field Study Objectives

The HENGH field study aimed to collect data on indoor air quality and ventilation system characteristics, installed performance and usage in California homes built to the 2008 or more recent version of the Title 24 Building Energy Efficiency Standards. The overarching goal of the field study was to collect data to improve understanding of whether the ventilation equipment being installed to meet the recent Title 24 requirements is effectively providing acceptable IAQ in new California homes. The study had the following specific data collection objectives:

- Collect field data from a diverse sample of homes that covers the areas of the state with substantial new home construction and including a range of climate zones;
- Characterize the dwelling unit/dwelling unit mechanical ventilation systems and measure their airflows for comparison to Title 24 requirements;

- Characterize all other mechanical systems (e.g., bathroom exhaust fans) that may contribute to outdoor air exchange in the home and measure their airflows as feasible;
- Collect data on the use of kitchen and bathroom exhaust fans in relation to activities that release pollutants and moisture into these rooms;
- Measure concentrations of air pollutants inside and outside of the homes, including as feasible, time-varying monitoring of pollutants that are impacted by occupant activities;
- Obtain information about occupant activities and use of controls that may impact IAQ during the in-home monitoring period;
- Obtain monitoring data over a period of a week in each home to capture the cycle of activities that happen over this interval;
- Collect data on occupant satisfaction with IAQ and comfort conditions in the field study homes;
- Examine the relationships among ventilation equipment and use, measured and perceived IAQ, and house and household characteristics; and
- Evaluate how to provide adequate ventilation in homes while reducing infiltration beyond the 2008 Title 24 standard, while still providing acceptable IAQ.

Since the focus of the study was to investigate whether the current requirements for mechanical ventilation provide sufficient protection, and it was known that a substantial fraction of California households do not routinely open windows for ventilation during at least some parts of the year, the study protocol was to measure IAQ in homes while windows were generally kept closed and with dwelling unit ventilation systems operating.

Prior to the field study, the project implemented a web-based survey to obtain data on IAQ satisfaction and ventilation practices in a much larger sample of modern California homes. The survey aimed to collect data from homes built both before and after the 2008 Building Energy Efficiency Standards, starting with homes built in 2002. However, almost all the data were from homes built to pre-2008 versions of the standard. Details about the web-based survey are provided in Appendix A.

1.5 Simulation Study Objectives

Another major element of this project was a simulation-based analysis of potential energy benefits and indoor air quality implications of reducing infiltration and modifying ventilation requirements. This element of the study is described in Appendix B. The main goals of this simulation effort were to quantify the energy, ventilation and IAQ impacts of airtight residences under current and proposed IAQ compliance paths available in the Title 24 Building Energy Efficiency Standards and the ASHRAE 62.2 ventilation standard. Specifically, we examined how different levels of envelope airtightness and methods of sizing dwelling unit ventilation fans would affect HVAC energy use and time-averaged concentrations of a theoretical, continuously emitted pollutant (as an IAQ indicator). The results of this work are designed to inform the questions of whether an airtightness requirement should be included in the Title 24 standard, and if so, should ventilation requirements be modified to compliment this requirement, to avoid causing harm.

The main objectives of the simulation study were (1) to evaluate the IAQ and energy impacts of different dwelling unit fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH50 airtightness requirement in the Title 24 Building Energy Efficiency Standards. Energy, ventilation and IAQ performance were simulated in two prototype homes compliant with the 2016 prescriptive provisions of the Title 24 Building Energy Efficiency Standards, across a subset of California climate zones (CZ 1, 3, 10, 12, 13 and 16), reflecting the variety of climate conditions in the state. Airtightness was varied between 0.6 and 5 ACH50, and dwelling unit ventilation fans were sized according to seven currently available or proposed compliance paths in Title 24 or ASHRAE Standard 62.2. Fan sizing methods either accounted for infiltration and fan type (i.e., balanced vs. unbalanced), or they used a fixed airflow approach, with no variability in the fan sizing by airtightness, climate zones, geometry and fan types. The simulations used the ASHRAE 62.2 relative exposure framework to assess IAQ. This framework considers IAQ by calculating the time-integrated concentration of a generic contaminant emitted at a constant rate under some alternative ventilation approach and compares that to the time-integrated concentration that would occur with a continuous, fixed airflow – in this case the target dwelling unit airflow required by ASHRAE Standard 62.2. This metric is described in the 62.2 framework and subsequently in this report as relative exposure. The results for individual cases were combined using a weighting based on the fraction of new homes constructed in the state's climate zones to get statewide estimates of performance.

CHAPTER 2: Methods

2.1 Field Study Overview

2.1.1 Overview of Data Collection Approach in Homes

The HENGH field study was designed by the research team from Lawrence Berkeley National Laboratory (LBNL) to achieve the objectives of obtaining measured IAQ and ventilation equipment usage data over a weeklong cycle of household activity, characterizing the installed ventilation equipment and measuring airflows, and obtaining information on perceptions and activities from the participant, in each study home. The detailed protocol is provided in a report (Chan et al., 2016, LBNL-1005819) that is available via the LBNL Energy Technologies Area (ETA) publications web site (https://eta.lbl.gov/publications). The final protocol was developed in part based on a pilot study conducted by LBNL in two homes in Northern California. The pilot study protocols and results are described in Appendix C, which is also published as a separate report (Chan et al., 2016, LBNL-1005818). Both the pilot study and final field study protocols were reviewed and approved by the LBNL institutional review board.

Each home in the HENGH field study was visited three times.

During the first visit, the research team obtained written consent from the study participant, checked that the home had the basic ventilation equipment required by the Title 24 Building Energy Efficiency Standards, and confirmed that the equipment was operable. If the dwelling unit ventilation fan was not operating, the researcher obtained consent from the participant to activate the system. The team confirmed that the participant met and understood all study requirements including the expectation that the dwelling unit ventilation system would operate throughout the week and the use of windows and doors would be limited to dealing with acute IAQ challenges (e.g. during major cleaning) and not opened for extended periods to provide extra ventilation beyond the mechanical system. The participant was asked about potential hazards and any locations within the home that the researcher should not enter, and potential indoor and outdoor locations for siting of air quality measurement stations were discussed. Characterization of the house, gas appliances, and ventilation equipment was also started on the first visit. The characterization included marking the locations of ventilation equipment and appliances on a house floor plan; photographing appliance and ventilation equipment as installed; and recording make, model, and performance ratings such as gas appliance burner fuel use rates and airflow rates for ventilation fans. A detailed list of parameters recorded in the characterization is provided in the LBNL report about the protocol. Each home also received a standard gas appliance safety inspection (NGAT) by a utility field service technician who performs this test routinely for utility customers. In a few homes, the inspection identified an issue that the gas service technician was able to fix on the spot, at the homeowner's request. Three homes failed NGAT because of a venting non-conformity identified for a fireplace or water heater. In two cases, a follow up visit was scheduled with a gas technician, and one-week monitoring was rescheduled at a later date. In the third case, the gas technician determined that the appliance could be used and monitoring could safely proceed without rescheduling. A few homes had problems with mechanical ventilation systems that were corrected prior to monitoring. In one home, the exhaust fan providing the dwelling unit ventilation was not connected to the terminal fitting at the roof; the homeowner contacted the builder and this was resolved before the next scheduled visit. In two other homes, exhaust fans providing the dwelling unit ventilation were unplugged. These were referred to the owner, who contacted the builder. In one of these homes, the builder simply came to plug-in the fan. In the other, the builder found that the fan was not working and replaced it with a new fan. At the request of two of the homeowners, air filters in the forced air heating and cooling systems were replaced by the research team prior to the one-week monitoring period in these homes. In addition, air filters were missing from both of the filter slots in one home. At the request of the homeowner, air filters were installed prior to the one-week monitoring period.

During the second visit, the team conducted equipment performance measurements, installed devices to measure indoor air quality and record equipment use over the week, and finished the house and equipment characterization. The performance measurements included a "DeltaQ" test to determine air leakage through the building envelope and through the HVAC and duct system, and airflow measurements of the following exhaust fans: kitchen range hood, exhaust fans in the three most used bathrooms, and exhaust fans in any toilet rooms. Air quality monitors and samplers were placed outdoors, at a central indoor location (usually the great room), in the master bedroom, and in up to three additional bedrooms. Monitors were installed to record the usage history for kitchen, bath and laundry exhaust fans and the clothes dryer, and temperature sensors were placed on the cooktop and an HVAC supply register to record their operation. Photographs were taken of the installations. Detailed descriptions of the measurement methods and devices and a complete list of the parameters monitored are provided in subsequent sections of the Methods. The research team provided the participant with a printed survey and a set of daily activity logs (see appendix D) and explained how to complete the forms. The survey included a subset of the questions from the online survey conducted as an earlier research task of HENGH, focusing only on perceptions and activities and excluding questions about equipment that the research team could determine themselves while on site. A few days into the monitoring period, a researcher called the participant to check if they had any issues or discomfort related to the research operating in the home or any questions.

During the third visit, the research team removed all equipment monitors and air quality samplers, collected the survey and activity logs and did an exit walkthrough with the participant to verify that all equipment was removed. The incentive – a $350 gift card to a national home improvement store – was provided to the participant upon completion of this visit and a signed record of incentive payment was obtained.

2.1.2 Research Team

The field study was a collaboration involving LBNL, the Gas Technology Institute (GTI), the Pacific Gas & Electric Company (PG&E), the Southern California Gas Company (SoCalGas), Misti Bruceri & Associates (MBA), and Chitwood Energy Management. LBNL designed the overall study and recruitment plan; developed the specific data collection protocols; conducted recruitment; analyzed IAQ samples; and compiled, reviewed and analyzed the data. GTI managed all elements of the field study including scheduling visits, preparing equipment, conducting quality assurance checks of the equipment, managing staff working in homes to implement data collection, and providing data to LBNL in electronic format. SoCalGas provided staff members from their engineering and technical services departments to collect data under GTI direction in homes in SoCalGas service territory, and also provided gas service technicians to conduct safety inspections in those homes. PG&E provided financial support for MBA to commit a technical staff person to work with the GTI field team in PG&E territory; PG&E also arranged for their gas service technicians to conduct safety inspections in these homes. Chitwood Energy Management worked as a subcontractor to GTI, providing technical support and guidance.

2.1.3 Eligibility

To be accepted into the study, the following criteria had to be met by the participant, the building and the household. The participant had to be 18 years of age and speak English sufficiently well to understand the consent form. The building had to be a single-family detached structure, located in California, and built in 2011 or later. The home had to have gas appliances and mechanical ventilation, suitable locations and electrical outlets for study instruments, and not have highly unusual filtration or ventilation systems. The household had to prohibit smoking and at least one adult resident had to be available to grant access to the study for each in home visit. The home had to be occupied by the owner and the participant had to agree to allow the study team access to the home to recover measurement devices if they decided to stop participating before the week of in-home measurements was complete.

The "built in 2011 or later" requirement was used as a proxy for homes built to comply with the 2008 version of Title 24. The study team assumed it would be difficult for potential participants to determine which version of Title 24 was applicable when their home was permitted. Records were obtained from CalCERTS/CHEERS for 23 homes to verify that they were certified to meet the 2008 or more recent standards. Even though Title 24 compliance documents were not available for the other homes, the presence of mechanical ventilation equipment in all 70 homes indicates that they were built to the 2008 or more recent standards.

2.1.4 Recruitment

The study was advertised and homes were recruited via several mechanisms.

The initial plan was to identify eligible and interested field study participants via the online survey (see Appendix A for details). After they completed the online survey, respondents who had indicated that their home was built 2011 or later and was a single-family detached structure were asked if they were interested in learning about "a follow-up study of indoor air quality and ventilation" that "involves research teams visiting homes to measure the performance of ventilation equipment, and to set up air quality and ventilation monitoring devices that will remain in place for a one-week period." Twenty-eight online survey homes built 2011 or later indicated interest in learning more about the study, but none of them ultimately participated.

The low yield from these homes may have resulted from the long delay between the time when they completed the survey and indicated their interest (in 2015), and the time that the field study started to visit homes in SoCalGas service territory (in second half of 2017).

The second major approach was to advertise the study through various mechanisms and direct potentially interested individuals to visit a website that provided information about the study along with eligibility and participation requirements. The website had a page for interested individuals to provide their contact information. The online survey and an early version of the website noted that participants could receive an incentive valued at up to $230 for completing all elements of the study. Prior to the start of field monitoring, the incentive was increased to a $350 gift card to a home improvement store if they completed all study elements including the occupant survey and all daily activity logs. Participants also were offered a report summarizing the results of ventilation and IAQ measurements in their home. This report was prepared and provided to study participants by LBNL.

The most successful mechanism used to advertise the study was direct mailing of postcards to addresses of qualifying homes identified by searching the Zillow.com website for recently-sold, single-family homes built in 2011 or later. The postcards provided the basic study requirements, noted the incentive, and provided the study project website. Postcards were sent in several batches, each time targeting a different area with the study domain. During the last phase of recruitment, a $50 referral was offered to participants in order to meet the target number of study homes. Another mechanism that was tried without success was to offer incentives to home energy raters for any referrals that led to a consented study participant.

2.1.5 Screening and Selection

An LBNL researcher attempted to call each person who indicated interest through the survey or website. When a connection was made, the researcher first confirmed eligibility, then provided key information about the study and answered questions. During this call, study participants were informed that the field team could, in some cases, determine on site that a home is unsuitable for the field study. For example, this would occur if the field team could not clearly identify a dwelling unit mechanical ventilation system or not confirm that it is operable. If the ventilation system was merely turned off or if the runtime was improperly set, the field team would ask permission of the study participant to make a repair or adjustment. The potential participants were also informed that the research team would arrange with their local utility to conduct a safety inspection of their gas appliances and venting. Any critical safety issues would need to be resolved before proceeding. If a home were determined to be unsuitable by the research team or the participant decided to stop after the first visit, the participant would receive a $75 gift card.

If, at the end of the screening call, the person was still interested and both they and their home appeared to be eligible, LBNL provided the person's contact information to GTI to schedule the first visit. In total, LBNL recruited 103 homes. In the majority of the homes referred by LBNL to GTI that did not complete the study, there were no house visits, either because the formerly interested person did not respond to three attempts by the GTI team to make contact or the person decided to not participate before the first scheduled visit. One consented participant withdrew after the first visit and prior to the scheduled second visit. One home was excluded when it became clear on the first visit that the home was built before 2011.

2.2 Field Data Collection Procedures

2.2.1 House, Mechanical Equipment and Appliance Characterization

Prior to the visit, the research team typically was able to obtain a floor plan from the builder's website; sometimes this was a mirror image plan or a basic plan that could have small modifications among constructed homes. If the floor plan was not obtained prior to the visit, a basic floor plan was sketched on site. The team used a paper form to record basic information about the house: floor area and ceiling heights; number of stories, bedrooms, full and half baths, and other rooms on each floor; attached garage and number of parking spots, etc. Photos were taken of the connecting walls and ceilings between the garage and house, attic, backyard, gas appliances and mechanical ventilation equipment, general layout and exterior of the house.

The following equipment was identified, characterized and located on the floor plan, and photos were taken to document the details of the installation and typically also the nameplate information:

- Dwelling unit mechanical ventilation system. Noted basic design (exhaust, supply, or balanced); type of control; make, model and rated flow; and fan settings.
- Other ventilation equipment: bath and toilet room exhaust fans, kitchen range hood, and any laundry exhaust fans. Noted make, model and rated flow, type of control for each fan; and for kitchen note if range hood is microwave or simple range hood.
- Heating and cooling system(s). Noted type of system (all were forced air), make and model, capacity (in tons and Btuh) and whether system was zoned. Noted dimensions and location of each return and locations of filter(s) if not at the return air grille. Noted location(s) and types of thermostats. For each filter in a forced air heating or cooling system, recorded make, model and performance rating and visually assessed condition of filter; also took photo. Identified and characterized thermostat and marked location on floor plan.
- Attic. Noted whether it was vented or unvented and the type of insulation. Photographed ductwork, gas furnace, exhaust fans, and vents.
- Gas-burning appliances. Noted make, model and firing rates of all burners or photographed nameplate. Noted locations on floor plans.

2.2.2 DeltaQ Test to Determine Air Leakage of Envelope and Forced Air System

Air leakage of the building envelope and forced air system was measured with the DeltaQ test (Method A of ASTM-E1554-2013) using a TEC Minneapolis Blower Door System with DG-700 digital manometer (energyconservatory.com). The DeltaQ test provides the air leakage associated with the forced air system at its normal operating conditions. The TEC system includes software to perform the DeltaQ test in an automated manner. This software operates the blower door fan, records airflow rate and envelope pressure difference and calculates the resulting envelope and duct leakage. The software also automatically checks to see if the results are adequate to compute the building envelope and duct system air leakage. The software allows the user to repeat the whole test or part of the test if necessary, such as if someone stepped on a pressure tube during the test or a door was inadvertently opened.

The DeltaQ test was developed as an efficient alternative to the traditional duct leakage measurement method, which uses a duct blaster fan connected to the HVAC distribution system (per ASTM Standard E1554), and measures the airflow required to achieve a specified, arbitrary pressure relative to the house (typically -25 Pa), while all supply and return registers are tightly sealed off. Measuring duct leakage to outside requires further use of a blower door to zero-out pressure differences between the ducts and occupied space. In contrast, the DeltaQ duct leakage test (also in ASTM E1554) measures the duct leak airflows to outside at normal HVAC system operating conditions, using only the blower door fan and requiring no sealing of registers. The DeltaQ test builds on the standard envelope tightness blower door measurement techniques by repeating the tests with the HVAC system air handler turned off and on. The DeltaQ test requires several assumptions to be made about duct leakage and its interaction with the duct system and building envelope in order to convert the blower door results into duct leakage at system operating conditions. DeltaQ repeatability testing has shown the duct leakage measurement to be accurate within 1% of the air handler total flow. Accuracy may be reduced under windy conditions. We chose to use the DeltaQ test because it is more useful in considering the duct leak effects on IAQ as it gives the supply and return airflows at operating conditions. The metric used for duct leakage compliance is a total leakage airflow (supply + return) at a fixed pressure that does not give us the flow we need for IAQ assessments.

2.2.3 Measurement of Ventilation Equipment Airflows

Airflows of bath and laundry exhaust fans were measured using a TEC Exhaust Fan Flow Meter (The Energy Conservatory). Range hood airflows were measured using a balanced-pressure flow hood method described by Walker and Wray (2001). A calibrated and pressure-controlled variable-speed fan (TEC Minneapolis Duct Blaster, The Energy Conservatory) was connected to either the exhaust inlet (preferred approach) or outlet. The Duct Blaster was connected at each site using a transition piece that was adapted onsite to cover the entire underside of the range hood. Using a pressure sensor, the Duct Blaster fan was controlled to match the flow of the exhaust fan while maintaining neutral pressure to the room at the exhaust inlet. The pre-calibrated speed versus flow relationship of the Duct Blaster provided the flow through the exhaust fan. For microwave range hoods, the top vent was covered with tape to ensure that the airflow measured at the bottom inlet represented the entire flow through the device.

Supply fan flow rates were not measured directly because the air inlets – at the attic level – could not be quickly and safely accessed by the field teams. It was also not feasible to measure flows using in-duct velocity probes because the supply ducts were encased in spray foam insulation in the attic in all four of the HENGH homes that used supply ventilation.

Natural infiltration airflow was calculated over the same period and mechanical airflow was summed using sub-additivity, as described later in the Methods, to estimate the overall house air exchange rate.

2.2.4 Equipment Usage Monitoring

Cooktop and oven use were monitored using iButton temperature sensors attached to the surface of the cooktop, generally with one iButton adjacent to each burner. The temperature data were analyzed to find rapid increases in temperature that signal use of the cooking appliance.

Operation of exhaust fans, range hoods, clothes dryers, and the central forced air system were determined using one of the following methods: motor on/off senor, air velocity anemometer, or power meter. The field team determined which method to use depending on the accessibility and configuration of the appliances. Fans with multi-speeds (e.g., range hood) were monitored using a vane anemometer to discern use at varied settings and to enable use of the setting-specific airflow (measured separately) to be used when calculating the overall airflow through the home.

State sensors that discern open vs. closed condition were used to monitor the most often used exterior doors and windows. Although study participants were asked to keep these openings closed during the one-week study period, it was deemed valuable to monitor as any extended natural ventilation could impact pollutant measurements.

Temperature and relative humidity were monitored at the supply air registers as an indicator of heating/cooling use.

2.2.5 Air Quality Measurements

Air pollutant concentrations and environmental temperature and relative humidity were measured at several locations indoors and also outdoors on the premises. The central indoor air quality station was generally in the great room, a large open room on the first floor of the house that includes the kitchen and family room, or in a dining room that was openly connected to the other rooms on the first floor. The parameters measured at each location are noted below.

IAQ parameters and measurement equipment at outdoor station

- $PM_{2.5}$, 1-min resolved, MetOne ES-642 photometer
- Formaldehyde, 1-week integrated, SKC UMEx passive sampler
- NO_2 and NO_X, 1-week integrated, Ogawa passive sampler
- Temperature and humidity, 1-minute resolved, Onset HOBO U23 Pro v2

IAQ parameters and measurement equipment at central indoor station

- $PM_{2.5}$, 1-min resolved, MetOne BT-645 photometer

- Formaldehyde, 30-minute resolved, GrayWolf Monitor FM-801[2]
- NO_2, 1-minute resolved, Aeroqual Series 500
- CO_2, temperature and RH, 1-minute resolved, Extech SD-800
- Formaldehyde, 1-week integrated, SKC UMEx passive sampler
- NO_2 and NO_X, 1-week integrated, Ogawa passive sampler
- Temperature and humidity, 1-minute resolved, Onset HOBO UX100-011

IAQ parameters measured and measurement equipment in master bedroom

- Formaldehyde, 30-minute resolved, GrayWolf Monitor FM-801
- CO_2, temperature and RH, 1-minute resolved, Extech SD-800
- Formaldehyde, 1-week integrated, SKC UMEx passive sampler

IAQ parameters and measurement equipment in other occupied bedrooms

- CO_2, temperature and humidity, 1-minute resolved, Extech SD-800

The measured IAQ parameters are summarized in Table 1. Specifications of the time-resolved monitoring equipment, as advertised by the nameplate manufacturers, are provided in Table 2.

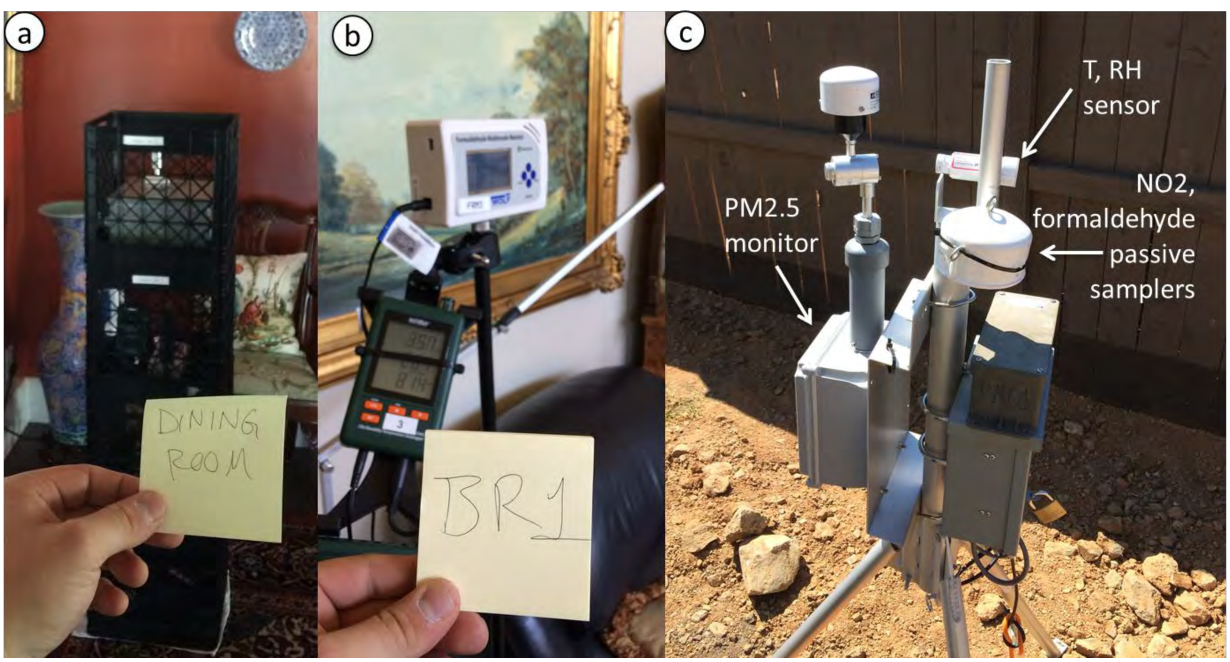
The central indoor monitoring equipment was deployed using a stacked crate system that protected the measurement equipment but allowed free airflow (Figure 1). The outdoor monitoring station was mounted on a tripod with air sampling occurring at roughly 2 m height. The target location for the outdoor station was at least 3 m from the nearest exterior wall of the house and any local sources such as a fire pit or grill. The ES-642 photometer was housed in a weatherproof enclosure designed and sold by the manufacturer (Met One Instruments, Inc.) that incorporates a sharp-cut cyclone to exclude particles larger than 2.5 µm aerodynamic diameter. The formaldehyde and NO_2/NO_X passive samplers were placed inside a 10 cm diameter PVC cap. This configuration is shown in Figure 1.

[2] This monitor is a rebranded Shinyei Multimode Formaldehyde Monitor

Table 1. Measured Air Quality Parameters

Parameters	Measurement Device	Sampling Locations	Sampling Resolution
$PM_{2.5}$	MetOne ES-642	Outdoor	1-minute
	MetOne BT-645	Indoor (central)	1-minute
CO_2. T, RH	Extech SD-800	Indoor (central, master & other bedrooms)	1-minute
NO_2	Aeroqual NO_2 Monitor	Indoor (central)	1-minute
	Passive Ogawa Samplers	Outdoor Indoor (central)	1-week
Formaldehyde	GrayWolf FM-801 (Shinyei Multimode)	Indoor (central, master bedroom)	30-minute
	Passive SKC UMEx-100	Outdoor Indoor (central, master bedroom)	1-minute
T, RH	Onset HOBO U23 Pro v2 Onset HOBO UX100-011	Outdoor Indoor (central)	1-minute

Figure 1. Examples of air quality monitors.



Air quality monitors deployed at indoor central station (a), master bedroom (b), and outdoors (c).

Table 2. Specifications of air pollutant monitoring equipment

Parameter	Device make and model	Range and Resolution	Accuracy	Other
Temperature	Onset HOBO UX100-011	Range: -20° to 70°C. Resolution: 0.024°C at 25°C	±0.21°C from 0° to 50°C	Response time: 4 min in air moving 1 m/s Drift: <0.1°C per year
Temperature	Extech SD800	0 to 50°C	±0.8°C	
Relative humidity	Onset HOBO UX100-011	Range: 1% to 95% (non-condensing); Resolution: 0.05%	±2.5% from 10% to 90%; up to ±3.5% at 25°C including hysteresis	Response time: 11 sec to 90% in airflow of 1 m/s Drift: <1% per year typical
Relative humidity	Extech SD800	Range: 10-90%	±4%RH below 70%; 4% of reading + 1% for 70–90% range	
Particulate matter, $PM_{2.5}$	MetOne ES-642 MetOne BT-645	Range: 0-100 mg/m^3. Resolution: 0.001 mg/m^3.	± 5% traceable standard with 0.6um PSL	
Carbon dioxide, CO_2	Extech SD800	Range: 0-4000 ppm; Resolution: 1 ppm	±40 ppm under 1000 ppm; ±5% (>1000ppm)	
Nitrogen Dioxide	Aeroqual 500 Series	Range: 0 to 1 ppm	± 0.02 ppm within 0 to 0.2 ppm range	
Formaldehyde	GrayWolf (Shinyei) Multimode Monitor	20 to 1000 ppb	± 4ppb for <40ppb, ± 10% of reading for ≥40ppb	30 min resolution; 20 ppb is lowest reliable value with stated accuracy

The standard software for the GrayWolf (Shinyei) formaldehyde monitor reports readings below 10 ppb as “<LOD”. By special arrangement, GrayWolf provided modified software to provide readings below the nominal detection limit of the instrument.

The MetOne Instruments ES-642 and BT-645 are aerosol photometers that quantify the light scattered by the ensemble of particles passing through the measurement cell and translate that to an estimated $PM_{2.5}$ concentration based on a device-specific calibration relationship developed in the laboratory using a traceable reference of 0.6 µm diameter polystyrene latex (PSL) spheres. Since photometer response varies with aerosol size distribution and chemical composition, the accuracy of these devices for ambient (outdoor) or indoor $PM_{2.5}$ can vary substantially as the qualities of the aerosol vary. The recommended practice when using a photometer is to measure an environmental aerosol sample is to collect a filter sample in the same environment, preferably at the same time, and determine a location specific gravimetric $PM_{2.5}$ adjustment factor. In this study, we sought to both check the mass calibration factor and the time-response of the primary photometers by deploying Thermo pDR-1500 photometers with onboard filter sample alongside the MetOne monitors indoors and outdoors at 8 homes. Due to power interruptions, data are available for only 5 of the outdoor deployments.

2.2.5.1 Calibrations and Quality Assurance for Time-Resolved Measurement Devices

All of the monitors used to collect time-resolved air quality data were purchased new at the start of the study, and thus were expected to conform to the manufacture specification for accuracy. The following additional procedures were implemented to check instrument cross calibrations.

The indoor and outdoor $PM_{2.5}$ monitors were co-located for roughly one hour during the instrument deployment visit at each home. In most cases the co-location was outdoors at the location of the outdoor monitor. Co-located comparisons were available from 45 homes. In two of the homes, the two monitors measured very different concentrations likely because the outdoor monitor had a heated inlet that was set to activate when relative humidity reached above 60%, and the indoor monitor did not. The heated inlet prevents condensation that could damage the instrument. The indoor monitor did not have a heated inlet because high humidity is generally not a concern when sampling indoor. At the two homes during the one-hour co-location test, the outdoor monitor measured high concentration of $PM_{2.5}$ (51 and 60 µg/m^3 at Home 063 and 068, respectively). Without the heated inlet, the co-located indoor monitor measured 111 and 78 µg/m^3, respectively. The two homes were sampled in winter (January 2018) in Tracy and Manteca CA, where high humidity condition in the morning likely explained this difference between the co-located indoor and outdoor $PM_{2.5}$ monitors. Excluding these two cases, the co-located indoor and outdoor $PM_{2.5}$ monitors agreed to within 1.9 µg/m^3 on average (median = 0.9 µg/m^3). In the remaining 43 homes, the outdoor monitor read somewhat lower concentration than the indoor monitor when the two were co-located more often (79%) than not (21%). This is likely because the heated inlet intended to prevent condensation resulted in some volatilization of the outdoor particles.

The Extech CO_2 monitors were co-located for 1 hour at each home or at a warehouse where the field team used for setup before the visit. The Extech were also calibrated at LBNL midway through the field study. During a break in the field study, the calibrations of all Extech CO_2 monitors were checked at LBNL by deploying the monitors in a well-mixed chamber with CO_2 concentrations varying between 400 and 1700 ppm. CO_2 concentrations were measured concurrently using an EGM-4 gas analyzer (PP systems, Amesbury, MA, USA). The EGM-4 was separately calibrated using standard gas of known CO_2 concentrations between 0 and 2500 ppm. CO_2 concentrations measured by the Extech were compared minute by minute against the EGM-4 data. On average, the difference in readings between the Extech monitors and EGM-4 was 7% of the CO_2 concentrations being measured by the EGM-4.

The Aeroqual 500 NO_2 monitor was calibrated before each visit with zero gas and a 1 ppm NO_2 standard gas. Monitor response was adjusted to match those values following manufacturer instructions.

2.2.5.2 Quality Assurance for Passive Samplers

Ogawa samplers were prepared according to manufacturer protocols. Prior to assembly for field deployment, all parts of the samplers were washed thoroughly with deionized water and allowed to dry thoroughly in a laboratory at LBNL. Sample pads were stored in the refrigerator in their original packaging until they were inserted into samplers. After samplers were assembled with new sample pads, they were placed in sealed amber plastic bags (Ziploc) and shipped to the field team in an insulated box with ice packs to keep them cool.

Four Ogawa samplers were deployed at each study home: one outdoors, two at the central indoor station (duplicates), and one field blank. The field blank was opened either at the indoor or outdoor station, then packaged and stored in a refrigerator for the monitoring week.

At least four UMEx 100 formaldehyde samplers were deployed at each study home: one outdoors, two in the central indoor station (duplicates) and one in the bedroom. In most of the sampled homes, a fifth formaldehyde sampler was opened indoors and packaged immediately to serve as a field blank. The formaldehyde blanks were stored in a refrigerator during the monitoring week.

2.2.5.3 Analysis of Passive Samplers

All passive samplers were shipped to LBNL for analysis. To avoid damage to the chemical samplers from extreme temperatures, samplers were mailed in an insulated shipping container with ice packs to keep them cool. The samples were extracted and analyzed following the protocols provided by each company (Ogawa & Company 2017; SKC, Inc. 2017). All Ogawa samples were extracted for analysis within 30 days from when the samplers were assembled.

For each NO_X and NO_2 sample we subtracted the mass determined from the field blank at the same home before calculating the sample period concentrations of NO_X, NO_2 and NO as the difference between the adjusted NO_X and NO_2 concentrations. Analysis of 64-paired duplicates of indoor samples found that agreement in NO_2 concentrations was within 0.6 ppb on average (median = 0.3 ppb). When available, duplicates were averaged to provide a better estimate of the indoor concentrations of NO, NO_2, and NO_X.

The formaldehyde concentration determined by passive sampler at each home also was adjusted by the effective sample period concentration determined from the field blank at the same home. For the eleven homes that did not have a formaldehyde passive sample field blank, we subtracted 0.15 micrograms, which is the mean mass determined from all available field blanks (and corresponds to 0.6 ppb for a 7-day collection period). Sixty-six paired indoor formaldehyde samples agreed to within 1.0 ppb on average (median = 0.7 ppb). When available, duplicates were averaged to provide a better estimate of the indoor concentrations.

The UMEx contains an internal blank within each sampler that can potentially be used for convenience instead of deploying a separate field blank sampler. However, analysis of the internal blank suggested that even it was not directly exposed to the sampling air, some formaldehyde was collected, possibly because the compartment isolating the internal blank was not completely airtight. The average analyte mass determined from internal blanks of indoor samples was 0.6 micrograms; this is 4 times the field blank value noted above.

Formaldehyde indoor emission rates E (μg/m^3-h) were calculated using a simple mass-balance equation assuming well-mixed, steady state condition. The same method was applied by Offermann (2009) to estimate indoor emission rates of formaldehyde and other VOCs.

$$E = (C_i - C_o) \times AER \quad (1)$$

Outdoor formaldehyde concentration (C_o, μg/m^3) was subtracted from the indoor concentration (C_i, μg/m^3) measured at the central location, assuming that there is no loss in formaldehyde as the outdoor air enters through the building envelope. Air exchange rate (AER, 1/h) is assumed to be the only mechanism that removals formaldehyde from the indoor air. Air exchange rate was estimated from natural infiltration airflow and mechanical airflow using sub-additivity, as described later in the Methods.

2.2.5.4 Weighing of Filters for Gravimetric $PM_{2.5}$ Determination

The filters used for gravimetric analysis were 37 mm diameter, 2.0 micron pore size Pall Teflo filters with ring. Prior to deploying to the field, each filter was preconditioned for 24 hours at controlled temperature and humidity conditions (47.5 +/- 1.5 % RH and 19.5±0.5 ºC), according to EPA guidance for gravimetric measurements. The filters were passed over a deionizing source to remove any static charges and each filter was weighed twice using a Sartorium SE2-F balance. After pre-weighing, filters were loaded into the two pDR-1500 photometers and the devices were shipped to GTI prior to the scheduled deployment. At the conclusion of the week of side-by-side monitoring, GTI shipped the two pDR monitors back to LBNL. LBNL removed the filters, and repeated the preconditioning and weighing procedures noted above. The collected mass was determined as the difference in mass, post-sampling versus pre-sampling. The sample air volume was taken from the pDR software and the sample concentration was calculated as collected PM mass / sample air volume.

2.2.6 Survey and Activity Log

Participants were asked to complete a daily activity log, provided in Appendix D.

Field study participants also were asked to complete a survey that was adapted from the online survey conducted earlier in the project; the complete survey is provided in Appendix D. The field study survey reduced the number of questions about the mechanical equipment in the home as these data were collected already during the characterization work of the field team.

2.2.7 Data Compilation

Following the visits to homes, GTI researchers uploaded data files from all measurement devices, photos, and completed home characterization data forms to a secure server at GTI. The LBNL team copied these data onto a secure server at LBNL for compilation and analysis. The compiled LBNL database includes only de-identified data and may be made available to other researchers as specified in the approved IRB protocol.

2.2.8 Total Ventilation Rate Calculation

The total ventilation rate (Q_{total}) from mechanical fans and air infiltration was calculated following the procedure described in ASHRAE Handbook Fundamentals (2017). The calculation assumed that during the monitoring week, occupants followed instructions to keep windows and doors closed, so natural ventilation was negligible.

First, airflow rates from mechanical fans were added to calculate balanced ($Q_{balance\_mech}$) and unbalanced ($Q_{unbalance\_mech}$) airflow rates by comparing minute by minute the amount of exhaust and supply air from usage data collected from each home. Next, air infiltration ($Q_{infiltration}$) was calculated using the flow coefficient and pressure exponent of the building envelope, determined as part of the DeltaQ Test. Wind data were obtained from the nearest weather station[3]. Indoor and outdoor temperature were monitored onsite. Typical shelter class of 4 (urban building on larger lots where sheltering obstacles are *more than* one building height away) and 5 (shelter produced by buildings or other structures that are *closer than* one house height away) was used, as determined by reviewing photos of the house in relation to its surrounding. The total ventilation rate was calculated following Equation 2, which uses a superposition adjustment (∅) to account for the sub-additivity of unbalanced mechanical airflows with air infiltration.

$$Q_{total} = Q_{balance\_mech} + Q_{unbalance\_mech} + \emptyset Q_{infiltraiton} \quad (2)$$

$$\emptyset = \frac{Q_{infiltration}}{Q_{unbalance\_mech} + Q_{infiltration}}$$

2.3 Assessing Title 24 Fan Sizing and Airtightness Requirements for New California Homes using Simulations

The main objectives of the simulation study were (1) to evaluate the IAQ and energy impacts of different dwelling unit fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH50 airtightness requirement in the Title 24 Building Energy Efficiency Standards. The results for individual cases were combined using a weighting based on the fraction of new homes constructed in the state's climate zones to get statewide estimates of performance. The simulations included several fan sizing methods: the new requirements in 2019 Title 24, the fan ventilation rate method from the 2008 Title 24, the total ventilation rate method introduced in the 2013 Title 24 (with and without natural infiltration), the ASHRAE 62.2-2016 approach, and

---

[3] Data obtained from www.wunderground.com. During periods when wind was reported as "calm", 1 mph (mile per hour) was assumed for calculating air infiltration rate.

current builder practice based on the installed fan sizes found on the field testing part of this study.

The following discussion outlines the approach used on the simulation of fan sizing and air tightness requirements. More details are provided in Appendix B.

2.3.1 IAQ and Relative Exposure

IAQ impacts are assessed using the metric of relative exposure. The simulations used the relative exposure approach to assess IAQ where the concentration of a generic, continuously-emitted contaminant under some alternative ventilation approach is compared to the concentration that would occur with a continuous, fixed airflow – in this case the dwelling unit target airflow required by ASHRAE Standard 62.2 (Qtotal). The ratio of the exposure under the alternative ventilation scenario to the continuous fixed flow is the relative exposure. The metric of relative exposure is now the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard.

At a given time, a relative exposure equal to 1 means the two ventilation rates lead to identical pollutant concentrations. When averaged over a period of time (e.g., annually), a value of 1 means the two rates provide equivalent chronic pollutant exposure. A relative exposure of one-half suggests the real-time ventilation rate is double the reference ventilation rate, and a relative exposure of two indicates a real-time ventilation rate that is half the reference rate. The annual average relative exposure during occupied hours must be less than or equal to one in order to satisfy ASHRAE 62.2-2016 requirements.

The relative exposure can be interpreted as a multiplier that could be applied to any generic contaminant emitted uniformly and at a constant rate from only indoor sources. For example, a value of 1.2 reflects a 20% increase in pollutant concentration relative to the concentration that would occur if the home's actual ventilation (Q_i) was at the target ventilation rate (Q_{total}). Or a value of 0.66 would reflect a 34% reduction in the pollutant concentration, relative to the concentration at the target ventilation rate.

In general, the pollutant concentration is inversely related to the ventilation rate. As a result, the increased airflow required to reduce the concentration by some fixed amount is much greater than the reduction in airflow needed to result in a similar increase in the concentration.

2.3.2 Airtightness, IAQ and Energy Consumption

Overall, reducing air leakage while mechanically ventilating to maintain equivalent IAQ is expected to save energy for two reasons: (1) it reduces the variability in the ventilation rate throughout the year, shifting airflows to milder weather conditions, and (2) this reduction in variability means the same exposure can be maintained with a lower total airflow. Both of these effects reduce the heating and cooling loads associated with ventilation, even when the same relative exposure is maintained.

2.3.3 Simulation Tool

The REGCAP simulation tool is used to predict the ventilation and energy performance. It combines detailed models for mass-balance ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. Two zones are simulated: the main house and the attic. REGCAP is implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance.

2.3.3.1 Prototype Descriptions

Two CEC prototype homes were simulated: one- and two-story, referred to throughout as "med" (or "medium") and "large", respectively. These were made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 Building Energy Efficiency Standards. Thermostat schedules were set to meet those specified in the 2016 Title 24 Alternative Calculation manual (ACM). Heating and cooling equipment was sized using Air Conditioning Contractors of America (ACCA) Manual J load calculation procedures. Current deviations from the Title 24 prescriptive path prototypes include no economizer fans, internal gains based on RESNET calculation method, HVAC equipment efficiencies and elimination of duct leakage to outside. Equipment efficiency was increased beyond prescriptive minimums to SEER 16 A/C and 92 AFUE gas furnaces in order to align with standard new construction practice.

The climate zones were chosen to capture a range of heating and cooling loads. The airtightness levels used in the simulations were 0.6, 1, 2, 3 and 5 ACH_{50}. The ventilation fan for Title 24 compliance was sized according to seven different calculation methods. Each case was simulated with both balanced and unbalanced dwelling unit ventilation fans. A baseline case with no dwelling unit ventilation fan operating was simulated for each combination of prototype, airtightness and climate zone. The ventilation energy use was the difference in total annual HVAC consumption between the fan and no fan cases, which includes changes in fan energy and thermal loads from air exchange.

2.3.3.2 Weighted Average Calculations

To scale these individual cases up to statewide estimates, weighting factors were developed that represent our best estimate of the current distribution of parameters, including climate zone, envelope airtightness, house prototype and ventilation fan type. A second series of weighting factors were developed to represent a proposed envelope leakage requirement of 3 ACH_{50}. The weighting factors are discussed further in Appendix B. Even though this is an imperfect approach to characterizing the entire new California single-family building stock, it provides a way to generalize and summarize our results, with a focus on where and how new homes are built in the state. For example, this method gives greater weight to results from the mild climate zones in Southern and Central California where most new home development occurs in the state, and it reduces the effect of the larger energy impacts in sparsely populated zones, like CZ1 (Arcata) or 16 (Blue Canyon).

2.3.3.3 Energy Use Normalization with Relative Exposure

When assessing energy savings from an airtightness requirement, the results conflate changes in airtightness with changes in the ventilation rate and relative exposure. To isolate the energy associated with ventilation and infiltration from other envelope loads, we simulated cases with no fan operation and no envelope leakage. The energy use for these cases was subtracted from the total to get the ventilation-only component. We used these ventilation-only energy use estimates to determine estimates of energy savings normalized by relative exposure. This is achieved by simply multiplying the ventilation-only energy estimates by the relative exposure in this case. E.g., a relative exposure of 1.2 would lead to a 20% increase in energy use to correct to a relative exposure of 1. While this assumed linear relationship my not be exactly true in all cases it is the only way to achieve comparisons at the same relative exposure without considerable manual iteration. The total HVAC energy use was then calculated for each case by adding the adjusted ventilation energy use back onto the envelope-only HVAC energy use to provide an estimate of energy use for each case when they are forced to provide the same exposure.

2.3.3.4 Dwelling unit ventilation fan Size Calculation With Fixed Natural Infiltration

We assessed three fan sizing methods that have fixed assumptions for natural infiltration and do not include variability in house leakage. Their calculated fan airflows do not vary by the factors that affect infiltration: airtightness, house geometry and climate zone. These methods were chosen to reflect the most common approaches in California construction: two are directly from the Title 24 Building Energy Efficiency Standards and the third is based on field observations of installed systems (Builder Practice).

Fan Ventilation Rate Method (T24_2008)

The Fan Ventilation Rate method (referred to as ***T24_2008***) was added as a requirement in the Title 24 (2008) Residential Compliance Manual Section 4.6.2. It calculates dwelling unit ventilation fan airflow from conditioned floor area and occupancy, as shown in Equation 3. This was the fan sizing equation in the version of ASHRAE 62.2 at the time the Title 24 requirement was written. This fan sizing approach implicitly assumed a background infiltration rate equivalent to 0.02 cfm per ft^2 of conditioned floor area. This is an appropriate natural infiltration rate assumption for homes in the 5-7 ACH_{50} range, but it is inadequate for substantially more airtight homes. The ***T24_2008*** method results in fan sizes that do not vary by either airtightness or location. This fan sizing method continues to be available in the current 2016 Title 24, and it is the default sizing method for IAQ ventilation in the prescriptive and performance path homes.

$$Q_{fan} = \frac{A_{floor}}{100} + 7.5 \times (N_{br} + 1) \quad \textbf{(3)}$$

Q_{fan} = calculated dwelling unit ventilation fan airflow, cfm
A_{floor} = conditioned floor area, ft^2
N_{br} = number of bedrooms

Total Ventilation Rate Method (Qtotal)

In 2013, the Total Ventilation Rate method was added to the Title 24 Building Energy Efficiency Standards as an alternative IAQ compliance path for airtight, low-infiltration homes. Homes using the Total Ventilation Rate method would typically calculate a fan size by subtracting an infiltration estimate from a dwelling unit target airflow. This is based directly on changes to ASHRAE 62.2 that explicitly changed the basic equations from fan sizing (based on an assumed natural infiltration airflow of 2 cfm/100 sq. ft. of floor area) to a total ventilation target. In this no-infiltration sizing method (referred to as ***Qtotal***), we simply set the dwelling unit fan airflow equal to the dwelling unit ventilation airflow target, as in Equation 4, where the fan airflow is equal to Q_{tot}.

$$Q_{tot} = 0.03\ A_{floor} + 7.5 \times (N_{br} + 1) \quad (4)$$

Current Builder Practice Method (BuilderPractice)

Field studies, including preliminary feedback from the HENGH field study, suggest that current builder practice in California homes is to install a dwelling unit ventilation fan that is oversized relative to the T24_2008 airflow requirement by roughly 40%[4]. We refer to this fan sizing as ***BuilderPractice*** and use a 40% oversized fan in the simulations.

2.3.3.5 Dwelling unit ventilation fan Size Calculation with House-Specific Natural Infiltration

Four dwelling unit fan sizing methods are examined that include house-specific natural infiltration estimates with varying levels of sophistication, all of which are based on the methods in the ASHRAE 62.2 ventilation standard. ASHRAE 62.2-2016 is structured to help ensure that all compliant homes have similar dwelling unit airflows that are consistent with the target airflow set by the standard (Q_{tot}). We begin by outlining the general process of calculating a dwelling unit target airflow (Q_{total}), a house-specific infiltration estimate (Q_{inf}), and the resulting requirement for the dwelling unit mechanical ventilation system (Q_{fan}). We then highlight where specific fan sizing methods diverge from this general approach.

Total Ventilation Rate Method Including Infiltration (T24_2013)

Here we take the Total Ventilation Rate method, above, and account for natural infiltration in the dwelling unit fan sizing; it is henceforth referred to as ***T24_2013***.

The target total ventilation airflow, comprising the combined natural and mechanical flows, is calculated using Equation 4. The natural infiltration airflow is estimated from blower door air leakage, house geometry and climate data using the procedures from ASHRAE 62.2-2016 (see Appendix B for more details).

[4] The 70 homes in the current study had an average measured fan flow 50% above the minimum requirement. However, all these data were not available at the time of performing the simulations and a 40% value was used based on the initial field study results and the results of Stratton et al. (2012) in 15 California homes.

ASHRAE 62.2-2016 Ventilation Standard Method (ASH622_2016)

The current ASHRAE 62.2-2016 ventilation standard (referred to as ***ASH622_2016***) builds on the T24_2013 calculation approach, but it adds a superposition adjustment (∅, see Equations 5 and 6) to account for the sub-additivity of unbalanced mechanical airflows with natural infiltration. Inclusion of superposition reduces the effective infiltration airflow, as explained earlier in Equation 2.

$$\emptyset = \frac{Q_{inf}}{Q_{total}} \quad \textbf{(5)}$$

where ∅ is the sub-additivity factor, having a value of 1 if the dwelling unit fan is a balanced system.

$$Q_{fan} = Q_{total} - \emptyset(Q_{inf}) \quad \textbf{(6)}$$

2019 Title 24 Method (T24_2019)

This fan sizing procedure is identical to the ASH622_2016 method, except envelope leakage is treated differently. IAQ fans in homes with envelope leakage greater than 2 ACH50 are sized using a default 2 ACH_{50} envelope leakage value. Homes with reduced envelope leakage below the 2 ACH_{50} limit use the actual leakage rate in fan sizing calculations. For very airtight homes, the calculated IAQ fan sizes are identical to those using the ASH622_2016 sizing procedure, while leakier homes have larger fan airflows, because of lower natural infiltration estimates resulting from the default leakage rate of 2 ACH_{50}.

2.4.3.6 Calculation of Relative Exposure

The relative exposure for a given time step is calculated from the relative exposure from the prior step (R_{i-1}), the target ventilation rate (Q_{tot}) and the current ventilation rate (Q_i) using Equation 7, unless the real-time or scheduled ventilation is zero, then Equation 8 is used.

$$R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t/V_{space}} \quad \textbf{(7)}$$

R_i = relative exposure for time-step i
R_{i-1} = relative exposure for previous time-step i-1
Q_{tot} = Total ventilation rate from ASHRAE 62.2-2016, cfm
Q_i = Ventilation rate from the current time-step, cfm
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, ft^3

$$R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}} \quad \textbf{(8)}$$

The real-time ventilation rate (Q_i) is the combined airflow of the dwelling unit ventilation fan and natural infiltration, predicted by the REGCAP mass balance model.

CHAPTER 3:
Results

3.1 Characteristics of Field Study Homes

3.1.1 House Characteristics

Figure 2 shows the locations of the sampled homes. Forty-eight of the sampled homes were in PG&E service area and the other 22 were in SoCalGas service area.

Figure 2: Sampled Homes Locations

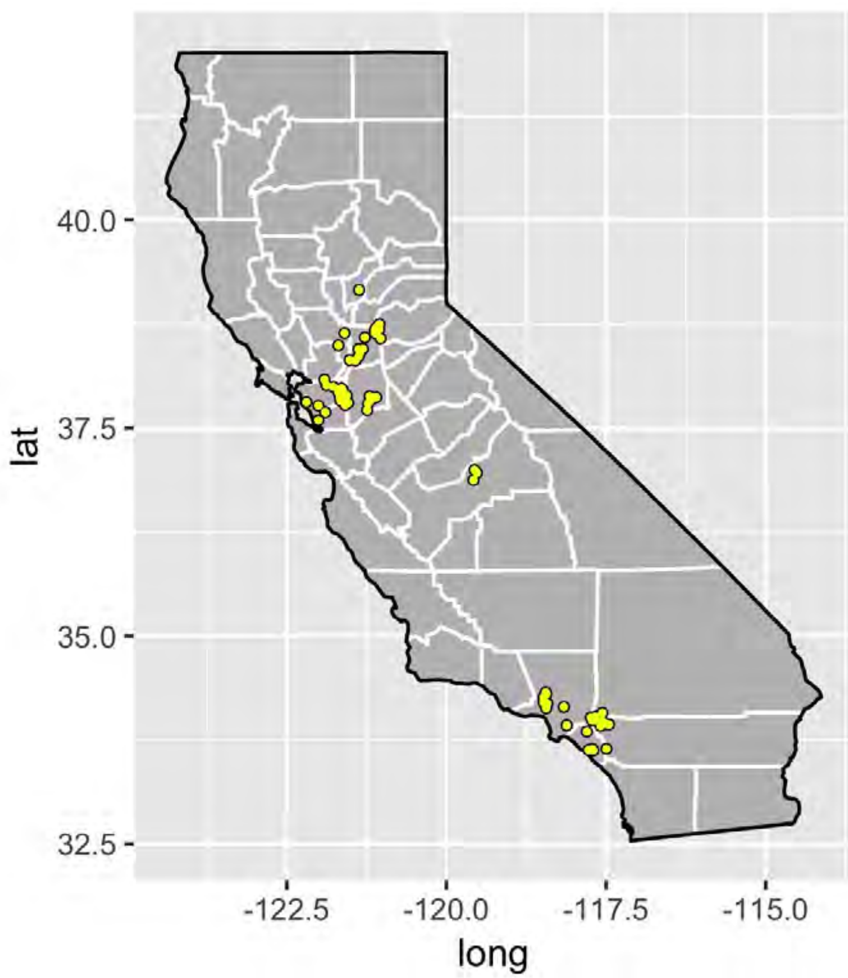


Table 3 shows the cities and climate zones where HENGH study homes were located. About 70% of new home construction in California is located within one of the 7 represented climate zones, based on the projected new housing by the CEC Demand Analysis office for 2017 (the same data was used to calculate weighing factors for the simulation analysis, see Appendix B).

Sampling occurred throughout the year, with summer (June through September) having the most samples, as shown in Table 4.

Table 3: Sampled Homes by Cities and Climate Zones (N=74)

IOU	Climate Zone	Cities (Number of homes)	Number of Homes	Total
PG&E	3	Discovery Bay (2), Hayward (2), Oakland (1)	5	48
	11	Marysville (1)	1	
	12	Brentwood (12), El Dorado Hills (10), Elk Grove (6), Manteca (4), Mountain House (2), Pittsburg (2), Davis (1), Dublin (1), Sacramento (1)	39	
	13	Clovis (3)	3	
SOCALGAS	8	Irvine (2), Downey (1), Lake Forest (1), Yorba Linda (1)	5	22
	9	Van Nuys (5), Alhambra (1)	6	
	10	Jurupa Valley (5), Chino (4), Corona (1), Eastvale (1)	11	

Table 4: Sampled Homes by Seasons

Season	Months	Number of Homes
Winter	Dec-Feb	16
Spring	Mar-May	13
Summer	Jun-Sep	27
Fall	Oct-Nov	14
Total		70

The earlier study by Offermann examined homes built between 2002 and 2004 and collected data from summer 2007 through winter 2008. This study sampled homes roughly a decade later, with most homes built between 2012 and 2016, and visited in fall 2016 through March 2018. The distribution of HENGH homes' construction years is shown in Table 5.

Table 5: Sampled Homes by Year Built

Year Built	Number of Homes
2011	1
2012	7
2013	13
2014	17
2015	15
2016	14
2017	3
Total	70

Tables 6 and 7 summarize the distribution of bedrooms and bathrooms. Almost all the homes had between 3 and 5 bedrooms.

Table 6: Sampled Homes by Number of Bedrooms

Bedrooms	Number of Homes
1	1
2	3
3	20
4	28
5	17
6	1
Total	70

Table 7: Sampled Homes by Number of Bathrooms

Bathrooms	Number of Homes
1–1.5	1
2–2.5	24
3–3.5	39
4–4.5	8
5–5.5	2

This study included a mix of one-story and two-story houses with a solitary three story home as summarized in Table 8.

Table 8: Sampled Homes by Number of Stories

Stories	Number of Homes
1	23
2	31
3	1

Most of the homes had floor areas in the rage of 2000 to 3500 ft^2, as shown in Table 9. The distribution of home sizes in the new study was very similar to homes in the Offermann study. For HENGH the Mean / Median / Interquartile (IQ) range were: 2657 / 2767 / 2096–3102 ft^2. In the Offermann study the Mean / Median / IQ range were: 2669 / 2703 / 2166–3152 ft^2.

Table 9: Sampled Homes by Floor Area

Floor Area (ft^2)	Number of Homes
<1500	4
1500–1999	8
2000–2499	12
2500–2999	12
3000–3499	13
≥3500	6

Offermann reported that homes were 1.7 to 5.5 years old when monitored in the CNHS study. HENGH homes were visited when slightly newer, with the majority being between 1 and 3 years at the time of monitoring (Table 10).

Table 10: Age of Homes When Sampled

Age of Home When Sampled	Number of Homes
<1	2
1	14
2	32
3	14
4	4
5	2
No Response	2
Total	70

All homes in the current study had gas cooktops. This is different from the Offermann study, in which 2% were gas and 98% were electric. The HENGH sample included many homes with electric ovens and/or clothes dryers.

Table 11: Appliance Fuel Use in Sampled Homes

Appliance	Number of Homes – Gas	Number of Homes – Electric
Cooktop	70	0
Oven	30	40
Clothes Dryer	42	28
Water Heater	70	0
Heating	69	1

Twenty-six of the 70 homes had a gas fireplace in the main living space and all were vented to outside (as required in California). One home had a second gas fireplace inside the master bedroom. Three homes had a gas fireplace outdoors, and three in an indoor/outdoor space, e.g., a California Room.

3.1.2 Household Demographics

Data on household demographics were obtained via the survey. Table 12 shows that the most common household sizes were two or three residents and there were only three homes with a single resident. Summary data on the number of homes with occupants from each age group are provided in Table 13. Among the 70 homes sampled, 41 had no youths and 49 had no seniors, whereas only 8 homes had no (traditionally defined) working age adults.

Table 12: Number of Occupants in Sampled Homes

Number of Occupants	Number of Homes
1	3
2	29
3–4	23
5–6	9
7 or more	3
No response	3
Total	70

Table 13: Number of Occupants in Sampled Homes by Age Group

Number of Occupants Within Age Group	Number of Homes with Designated Number of Occupants in Designated Age Group		
	Age 0–17	Age 18–65	Age 65+
0	41	8	49
1	7	7	10
2	14	41	9
3	3	8	0
4	2	2	0
5	1	2	0
No response	2	2	2
Total	70	70	70

Table 14 indicates that the study sample comprised mostly college-educated heads of household, with about half having graduate degrees. The household earnings (Table 15) were also skewed toward higher earners, which is not surprising given the high cost of real estate in California.

Table 14: Education Level of Head of Household in Sampled Homes

	Number of Homes
Completed high school	1
Some college	5
Associate's degree	2
College degree	23
Graduate or professional degree	36
No response	3
Total	70

Table 15: Total Household Income in Sampled Homes

	Number of Homes
\$35,000–\$49,999	1
\$50,000–\$74,999	2
\$75,000–\$99,999	5
\$100,000–\$150,000	29
Greater than \$150,000	29
No response	4
Total	70

Study participants were the first owners in most of the homes, as indicated in Table 16. Many had their floor plans and appliance user manuals, and shared them with the research team.

Table 16: Responses to Survey Question: Are you the first owner of the property?

Survey Response	Number of Homes
Yes	53
No	9
No response	8
Total	70

3.1.3 Understanding of Mechanical Ventilation System Operation

Study participants answered two survey questions about their understanding of the operation of their own mechanical ventilation system. The responses are summarized in Table 17 and Table 18. A little more than half of the study participants responded that they understand how to operate their mechanical ventilation system, with 31 not knowing or not being sure. Only 29 said the system was explained to them at the time of purchase.

Table 17: Answer to Survey Question: Do you feel you understand how to operate your mechanical ventilation system properly?

Survey Response	Number of Homes
Yes	38
No	12
Not sure	19
No response	2
Total	70

Table 18: Answer to Survey Question: Was the operation of the mechanical ventilation system explained to you when you bought or moved into the home?

Survey Response	Number of Homes
Yes	29
No	30
Don’t know	9
No response	2
Total	70

Study participants also answered questions about thermal comfort in winter and summer, air distribution, and moisture level.

- In winter / summer, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?
- How often do the following conditions affect comfort of occupants in your home?
  - Too much air movement
  - Not enough air movement
  - Indoor air is too dry
  - Indoor air is too damp
  - Indoor air as musty odor

The most commonly reported issues affecting occupant comfort a few times per week or more frequently are too cold in winter (29%), too hot in summer (31%), and not enough air movement (21%). Comparing responses from the 70 sampled homes with the larger sample of homes that completed the web-based survey (Table 19), fewer field study homes complained of being too hot in summer (31% versus 41%), but more of them complained of being too cold in winter (29% versus 20%). These differences may be partly explained by the web-based survey respondents being predominantly from SoCalGas territory, where the winter is milder. Forty-three percent of web-based survey respondents reported never opening windows in summer (Table 20), presumably relying on air conditioning for cooling. In contrast, only 23% of field study homes reported never opening windows in summer; presumably this indicates that the field study homes are more likely to open their window in summer to cool the house. This may explain why fewer field study homes reported being too hot in summer, compared to web-based survey respondents. Interestingly, the percent reporting too cold in summer was roughly twice as high in the HENGH homes. Reported rates of other types of discomfort were similar between the two samples.

Table 19: Comparison of survey responses from field study with results from HENGH survey

Issues Affecting Occupant Comfort a Few Times per Week or More Frequently	Field Study (N=70)	HENGH Survey (N=2271)
Too hot in summer	31%	41%
Too cold in winter	29%	20%
Not enough air movement	21%	18%
Too hot in winter	14%	10%
Indoor air too dry	9%	11%
Too cold in summer	4%	9%
Too much air movement	1%	5%
Musty odor	1%	3%
Indoor air too damp	1%	2%

See Appendix A for details about HENGH web-based survey.

3.1.4 Self-Reported Window Use Under Typical Conditions

As part of the activity survey, participants estimated their typical window use by season. The results are generally consistent with the findings of the prior mailed survey (Price et al., 2007). In summer, fall, and spring, approximately half of the homes (47% on average) reported substantial window use (>2 hours per day on average); but during winter more than half (57%) reported not opening their windows at all. For context, it is important to note the finding of Offermann (2009) that actual window use exceeded seasonal projected use in the sample of homes for which both types of data were available.

Two study participants gave written feedback that keeping windows closed during the one-week monitoring period was a significant deviation from their normal use.

- "Closed windows was the most difficult given the good weather."
- "We really missed having our windows open, but other than that it was not bad."

Table 20: Self-Reported Window Use in Sampled Homes

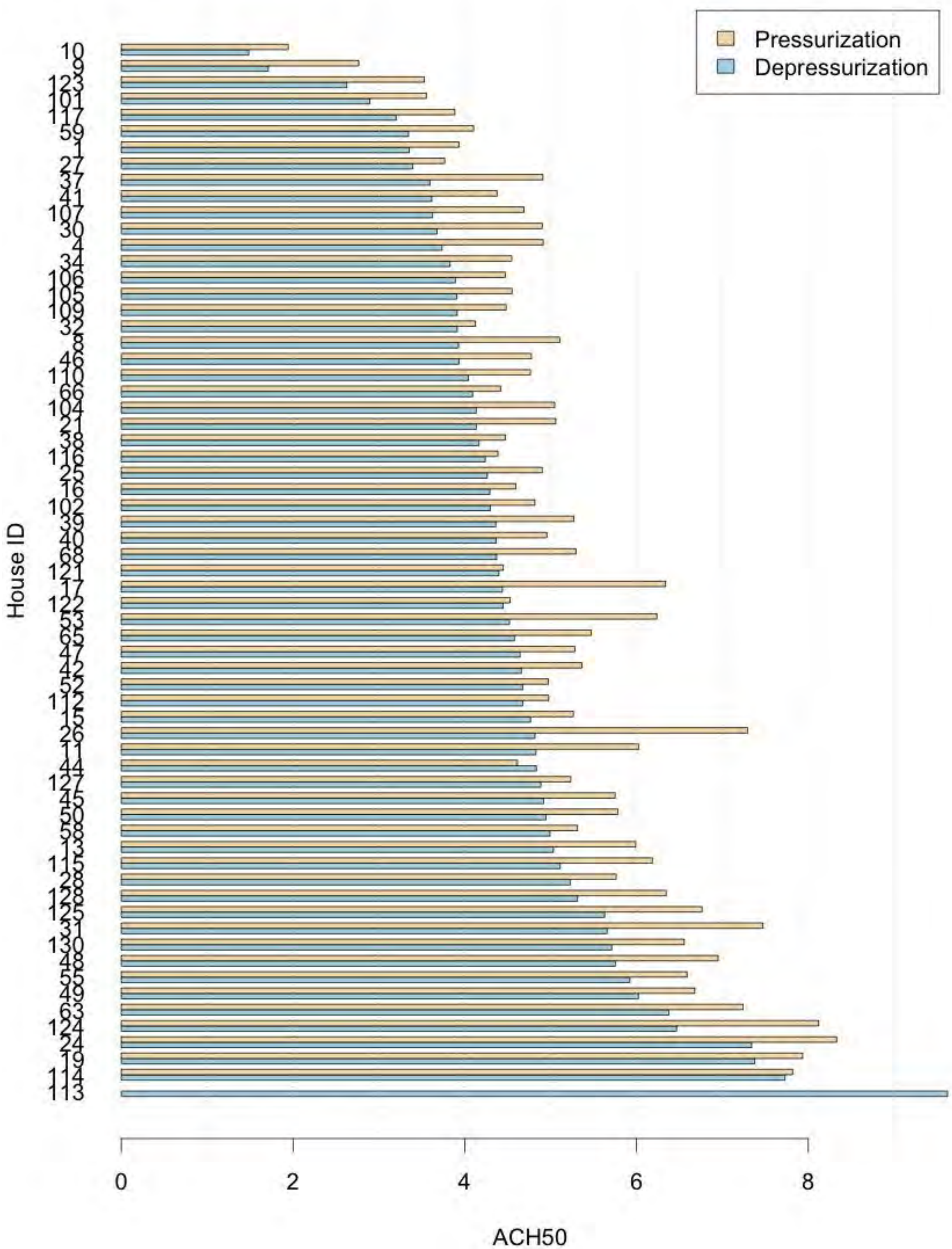
Hours per Day	Percent of respondents saying that windows in their home were opened for the number of hours in the first column							
	Summer		Fall		Winter		Spring	
	Field Study	Survey	Field Study	Survey	Field Study	Survey	Field Study	Survey
8+	17%	28%	24%	38%	3%	20%	27%	40%
2–8	29%	14%	26%	25%	10%	18%	19%	25%
1–2	29%	11%	27%	14%	26%	20%	30%	14%
0	23%	43%	19%	18%	57%	38%	20%	16%
No response	3%	4%	4%	4%	4%	5%	4%	5%

See Appendix A for details about HENGH web-based survey.

3.2 Envelope and Duct Leakage

Envelope leakage was measured using the DeltaQ test by first blowing air into a home (pressurization) then repeating the testing by sucking air out of the home (depressurization). The results were converted to ACH50 using the volume of the home and a calculated flow at 50 Pa. The results are shown in order from most leaky to most tight in Figure 3. Measured air leakage under pressurization was higher than depressurization by 20% on average. This result is not unusual and is due to "valving" of some envelope leaks, e.g., from an exhaust fan damper being pushed open during pressurization. Most homes were between 3 and 6 ACH50 (Figure 4). Only four homes had envelope leakage less than 3 ACH50, the level required for compliance with the 2018 International Energy Conservation Code (ICC 2018).

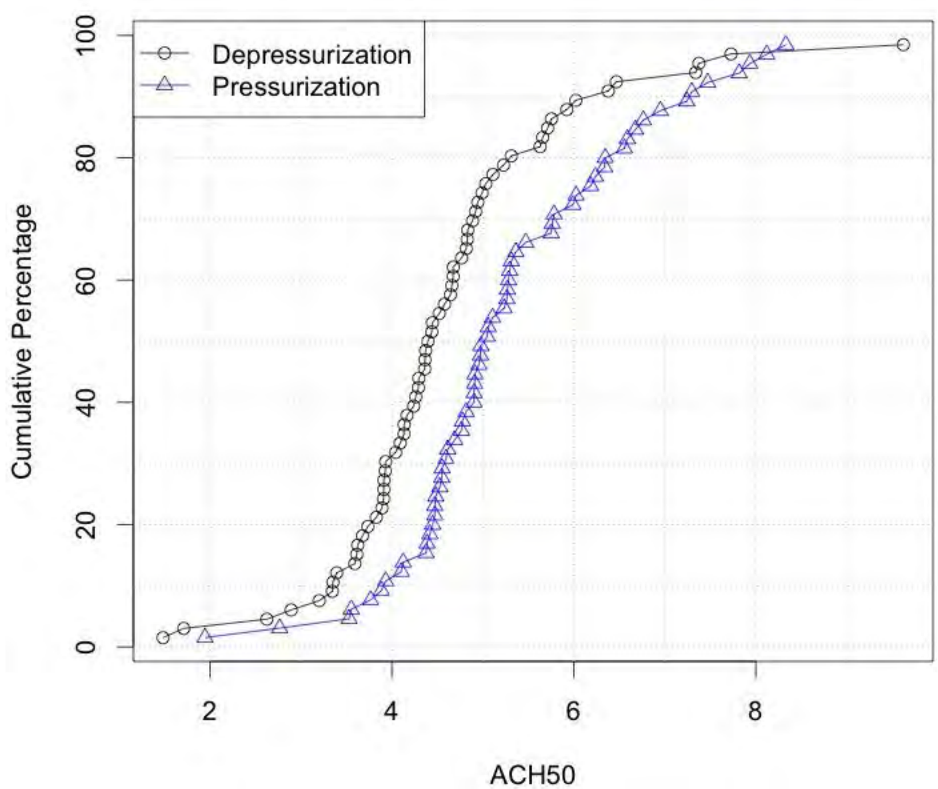
Figure 3: Envelope Leakage Measured by DeltaQ Test



House 113 is an outlier in terms of its small floor area (675 ft^2). Air leakage measured during pressurization was nearly twice the value as measured during depressurization. A damper being pushed open during pressurization test could explain the large difference in the air leakage measured under the two test conditions.

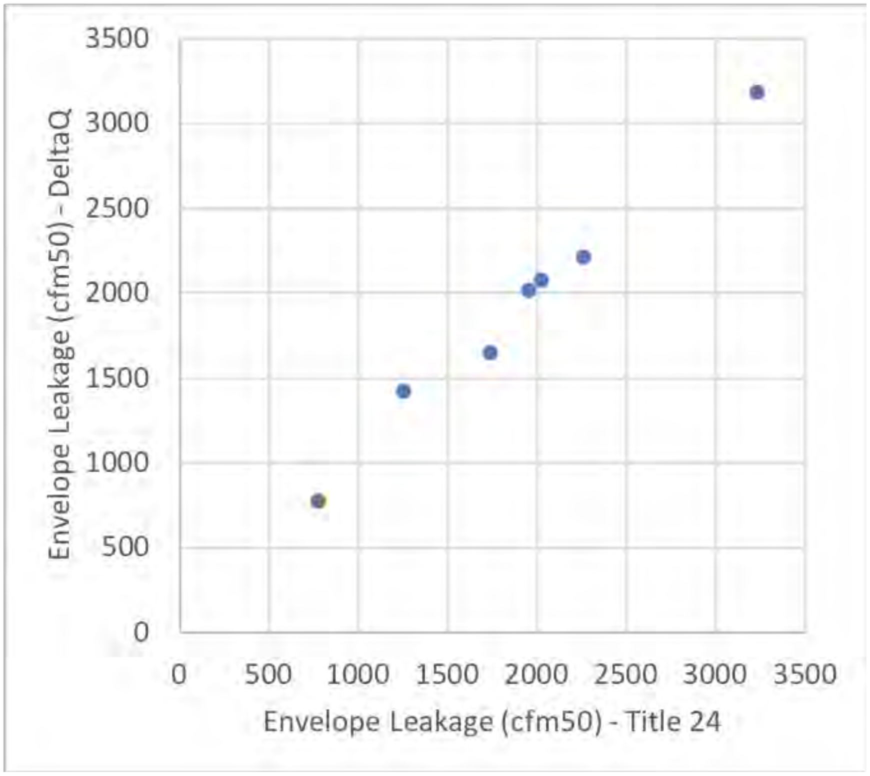
It is noteworthy that the measured envelope air leakage of study homes built mostly in 2012 to 2016 is in the same range as air leakage of California homes built in the early 2000s, as reported on the online residential diagnostics database (resdb.lbl.gov) and in Chan et al. (2013).

Figure 4: Distribution of ACH50 from Envelope Leakage Measurements



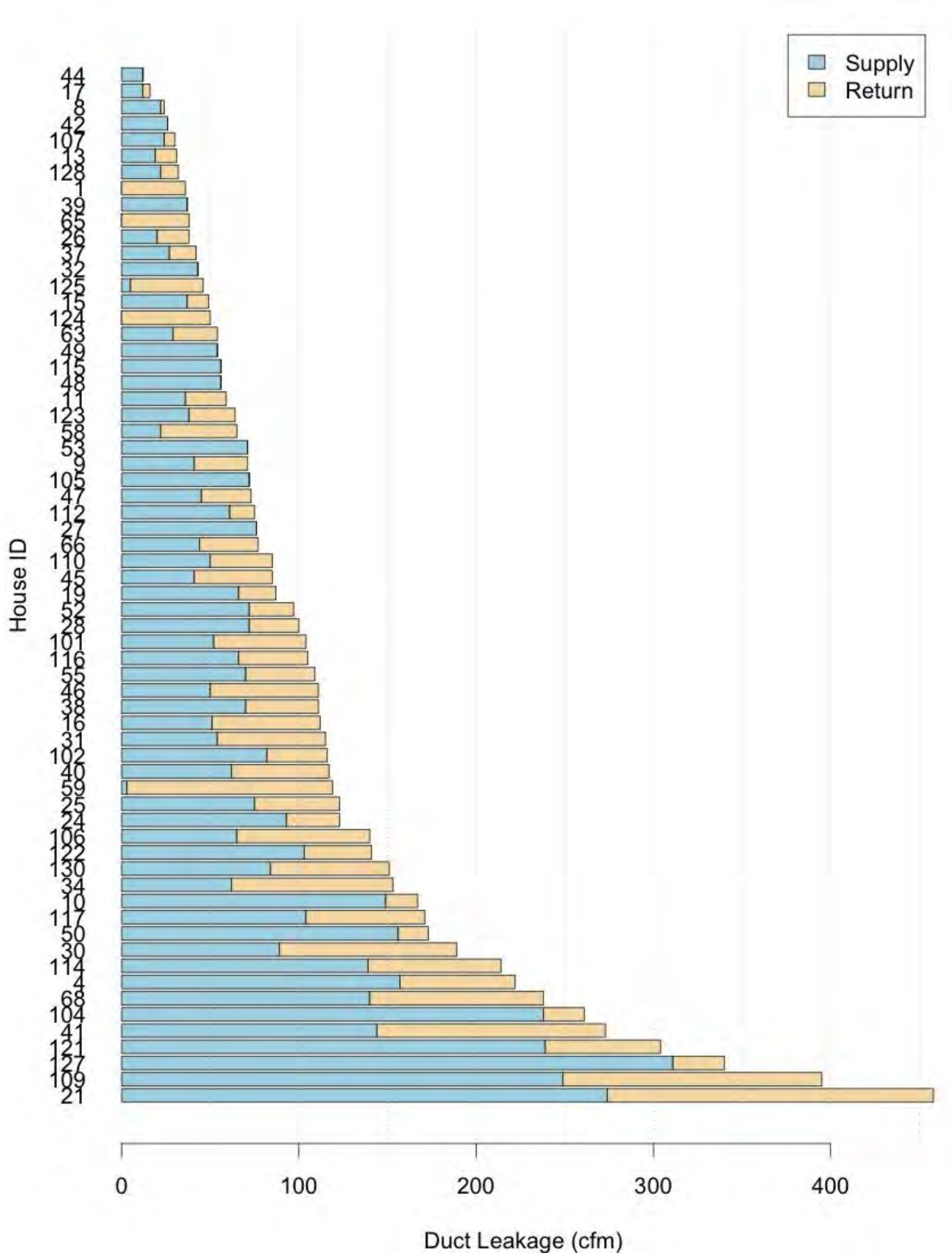
Title 24 compliance documents were obtained from CHEERS/CalCERTs for a subset of the homes (N=23). The measured envelope leakage was reported on the CF-1R form for only eight of these homes, as reporting is not mandatory. Figure 5 shows that envelope leakage measured in this study using the DeltaQ method corresponded closely to those reported in the Title 24 compliance records, which were likely measured by a standard blower door test. The two measurements of air leakage agreed with each other to within 5% in most of the 23 homes with data from both.

Figure 5: Comparison of Envelope Leakage Reported in Title 24 Compliance Records and Measured by DeltaQ Test



The DeltaQ test measures duct leakage at the operating pressure of the central fan system and measures supply and return leaks separately, as shown in Figure 6. Valid duct leakage measurements were obtained for 64 of 70 homes. Title 24 requires measurement of duct leakage at 25 Pa. Duct leakage measurements were available for all 23 homes from installation certificate (CF-6R) forms. Duct leakage measurements were also available from diagnostic testing results (CF-4R forms), but only for a subset of the homes (N=12). It is inappropriate to directly compare these two sets of measurements because they measure duct leakage under different equipment operating conditions.

Figure 6: Duct Leakage Measured by DeltaQ Test



3.3 Mechanical Ventilation System Characteristics and Flows

3.3.1 Dwelling unit Mechanical Ventilation

Sixty-four of the 70 homes had exhaust ventilation; the other six had supply ventilation. Table 21 shows the number of homes by ventilation system type, operation mode, and location(s) of exhaust or supply fan (if any).

Table 21: Dwelling unit Ventilation System Type

System Type	Operation Mode	Fan Location(s)	Number of Homes
Exhaust	Continuous	Laundry Room	43
		Bathroom	9
		Attic	3
	Intermittent	Laundry Room	5
		Bathrooms (multiple)	4
Supply	Continuous	Attic	4
	Intermittent	None*	2
Total			70

*These central fan integrated supply (CFIS) systems had a duct with motorized damper that connected the outdoors to the return side of the forced air system, but no supply fan.

3.3.1.1 Supply Ventilation

In four (001, 003, 009, 010) of the six supply ventilation homes, a continuous supply fan in the attic drew in outdoor air and ducted it to the supply side of the forced air HVAC system through a filter (see Figure 7). Three of the homes had an on/off switch that controlled operation of the inline supply fan. In one home, the on/off switch had a "Whole House Ventilation Control" label (Figure 8, left). The fourth home had a programmable controller (Figure 8, left) that is not labeled.

Two homes (031, 055) had central fan integrated (CFIS) systems. These systems had a motorized damper open to draw outdoor air into the return plenum where airflow was induced by the operation of the forced air system blower rather than a separate fan. Outdoor air was not filtered for these systems because the filters were located at the return grilles and the outdoor air was introduced downstream of the grille. These systems were wired for control by a programmable thermostat; but the ventilation function was not programmed at either home and the intended (design) control algorithm was not apparent. (See Figure 9 for examples of CFIS control systems). As a result, these two homes were tested with the exhaust fan in the laundry room operating continuously during the one-week monitoring period to provide code-mechanical ventilation at a rate that exceeded the code requirement.

Figure 7: Supply Ventilation Filters

Photos of the supply air filter used in three homes.

Figure 8: Continuous Supply Fan Control

(left) Label reads: “Whole House Ventilation Control. Leave on except for severe outdoor air quality”.
(right) Programmable controller used to control inline fan for supply ventilation.

Figure 9: Central Fan Integrated System

(top left) CFIS motorized damper and (top right) control module. (bottom) Thermostat showing ventilation control option was turned off.

3.3.1.2 Exhaust Ventilation

Of the 64 homes that met the Title 24 dwelling unit ventilation requirement with an exhaust system, 55 had continuous fan(s) and 9 had fans connected to controllers for intermittent operation. The continuous exhaust fan was located in the laundry room in 43 homes and in the bathroom in 9 homes. Three homes had a single continuous exhaust fan located remotely in the attic and connected to all bathrooms, as further described below. Five of the 9 intermittent exhaust fans were located in the laundry room and the other 4 were in bathrooms.

A simple on/off switch was used in the majority of homes that had continuous exhaust fans. In one home with a laundry exhaust fan, the only control was at the breaker panel (Figure 10).

Figure 10: Continuous exhaust ventilation controlled at breaker panel in one home

Three homes had a single exhaust fan located remotely in the attic and connected to all bathrooms; this configuration satisfied both local exhaust and dwelling unit mechanical ventilation airflow requirements. However, these homes had no switch inside the house that occupants could use to turn the fan on or off. The three homes with this type of exhaust ventilation system were located in the same housing development. The inline fan used in these homes had a rated airflow of 240 cfm. In all three cases, the field team observed installation problems. In one of the homes, the exhaust vent was detached from the roof (Figure 11, left). In the other two homes, the exhaust fan was not plugged in (Figure 11, right). In one of these two homes, the exhaust fan did not work and had to be replaced. Study participants contacted the builder and the repair occurred prior to the one-week monitoring in all three cases. A general challenge of this type of system is the following: without balancing dampers and commissioning to set these dampers the airflows from each bathroom can be quite different from one another. Table 22 shows the measured airflow rates in various bathrooms connected to the single exhaust fan.

Figure 11: Continuous exhaust ventilation provided by a fan in attic

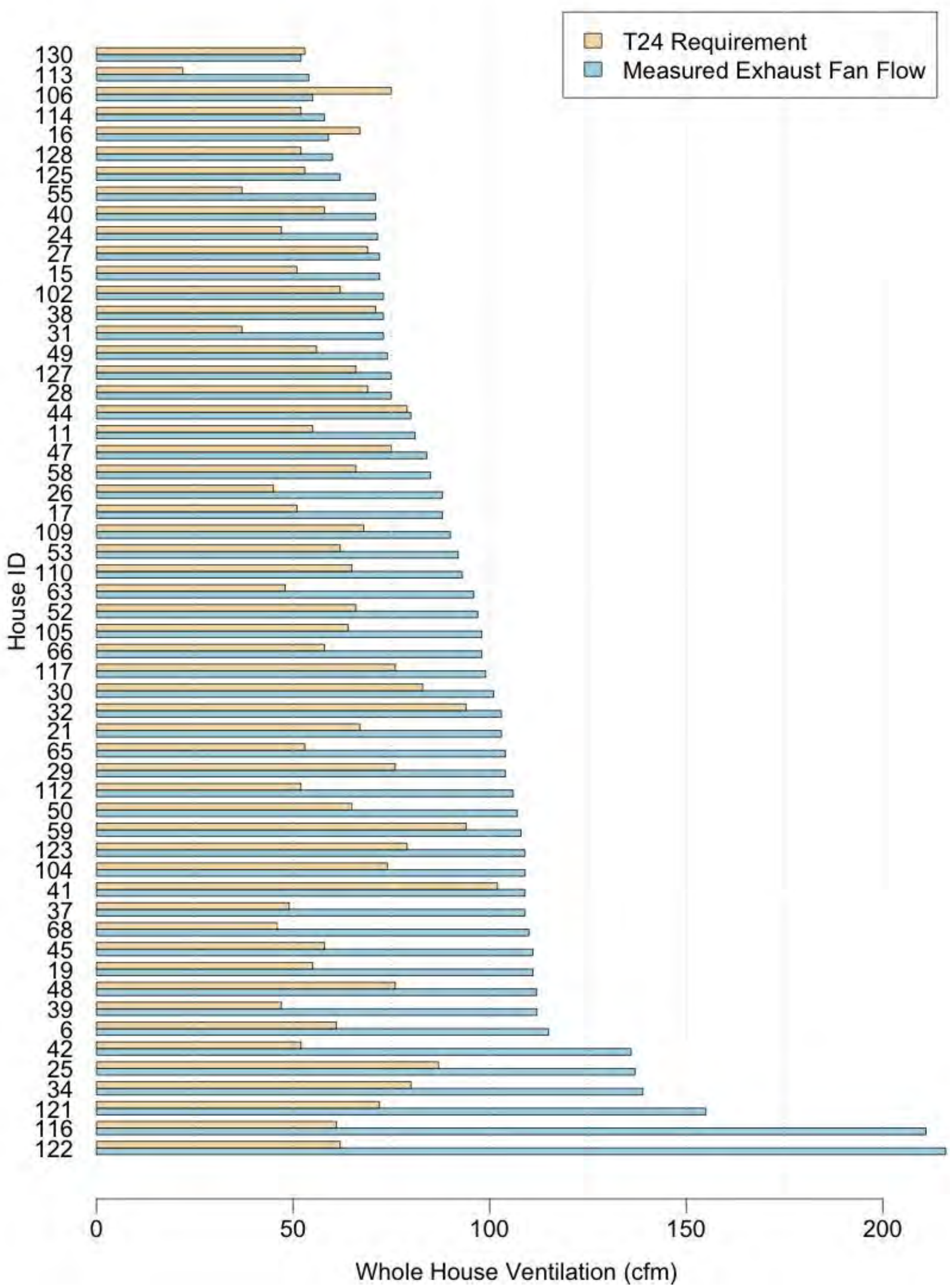
Observed installation problem: (left) exhaust fan detached from roof, (right) exhaust fan not plugged in.

Table 22: Measured Airflow in Bathrooms Connected to a Single Continuous Exhaust Fan in Attic

	Measured Airflow (cfm)		
	House 116	House 121	House 122
Master Bathroom	49	25	39
Master Bathroom – Toilet	32	12	35
Full Bathroom 2	49	66	51
Full Bathroom 3	81	52	91
Total	211	155	216

Figure 12 shows the measured airflow of the dwelling unit continuous exhaust ventilation system rank ordered by measured airflow. In all but two cases (016, 106), the measured flows exceeded the Title 24 minimum requirement. The highest measured airflow rates were from the three homes (116, 121, 122) that used a single 240-cfm rated exhaust fan in the attic. The average minimum requirement was 63 cfm and the average installed flow was 96 cfm, or about 50% more than the minimum requirement. This is similar to the results in Stratton et al. (2012) for previous tests of new (built in 2010/2011) California homes.

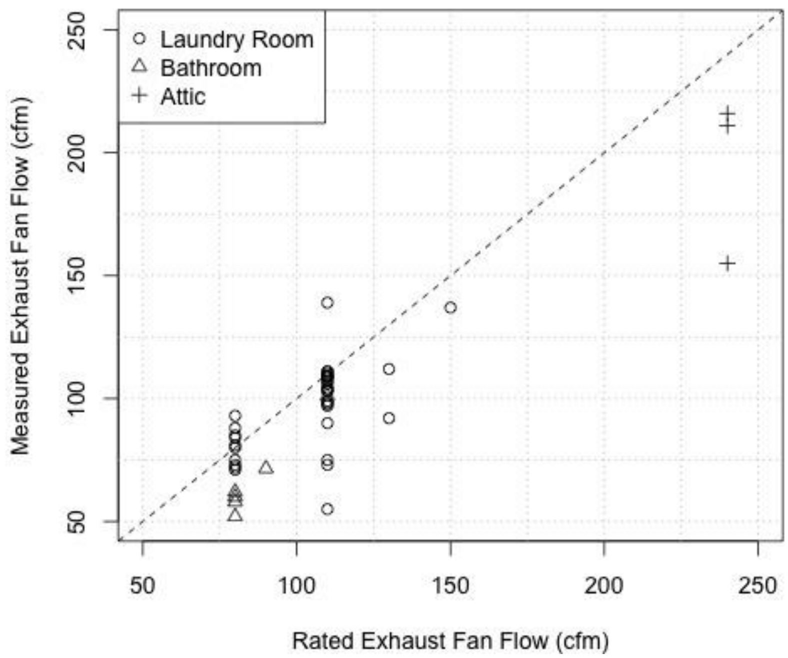
Figure 12: Dwelling unit Ventilation Fan Flow Rate



N=56, includes only continuously operating exhaust system with valid measured fan flow rate. Plot includes two homes with CFIS (031, 055) that were operated with laundry exhaust fan during the one-week monitoring period.

Figure 13 shows that the majority of the exhaust fans used to provide dwelling unit ventilation were rated at either 80 or 110 cfm. These were commonly available fan capacities provided by fan manufacturers. Note that the 110 cfm rated fans did not always achieve their rated flow, but still provided more flow than the minimum required by Title 24.

Figure 13: Rated and Measured Fan Flow Rate of Dwelling unit Exhaust Ventilation



3.3.1.3 Labeling and Operating Condition of Dwelling unit Ventilation in Homes As-Found

On the initial visit, the mechanical ventilation system was running in 18 homes (26%). The system was turned off in 52 homes. A key predictor of whether the system was operating appears to be whether the system control switch was labeled, and how clear the label was. Table 23 presents a summary of the system status when the research team first arrived to the home, by control type and presence or absence of any identifying label.

Table 23: Dwelling unit Ventilation System Control

System Control	Label	System Status (as-found) - ON	System Status (as-found) – OFF
On/Off Switch	Yes	7	5
	No	2	40
Programmable Controller	No	5	5
Thermostat	No	0	2
Breaker Panel	No	1	0
No Controller	No	3	0
Total		18	52

Both Title 24 and ASHRAE Standard 62.2 require that the controller of a dwelling unit ventilation system have an identifying and informative label. ASHRAE Guideline 24 provides the following example language for labeling:

> *Manual switches associated with a whole-building ventilation system should have a clear label such as, "This controls the ventilation system of the home. Leave on except for severe outdoor contamination." In addition, guidance on operations and maintenance procedures should be provided to occupants.*

The Title 24 Residential Compliance Manual also provides suggested labeling language, such as "Ventilation Control", "Operate whenever the house is in use", or "Keep on except when gone over 7 days". The Compliance Manual recommends using more detailed labeling for intermittent systems to provide occupants with basic information on how to operate the timer. However, no specific wording is mandated in Title 24.

Only 11 homes had any label on the exhaust fan switch that identified it as controlling the dwelling unit ventilation system and all were on laundry room exhaust fans. In addition, only 1 in 6 homes that used supply ventilation had a labeled controller to identify its purpose.

The absence of labels is likely a contributing factor leading to systems being turned off. Furthermore, several of these labels were poorly worded, unclear and possibly confusing to occupants. A wide variety of labels were found (a couple of examples are illustrated in Figure 14). The following is a summary of the labeling "language":

- "Whole House Ventilation Control. Leave on except for severe outdoor air quality." (010, 026, 039, 049, 065; houses located in Davis, El Dorado Hills, Elk Grove, Manteca)
- "**Keep fan "ON" at all times** except in case of outdoor air contamination or if home is vacant for more than 7 days." (029, 048, 050; houses located in Brentwood, Elk Grove)

- "To maintain minimum levels of outside air ventilation required by the State of California, this fan should be on at all times when the building is occupied, unless there is outdoor air contamination." (053; house located in Hayward)
- "Continuous Duty" (105, 106, 109; houses located in Chino, Lake Forest)

Figure 14: Dwelling unit Ventilation System Label

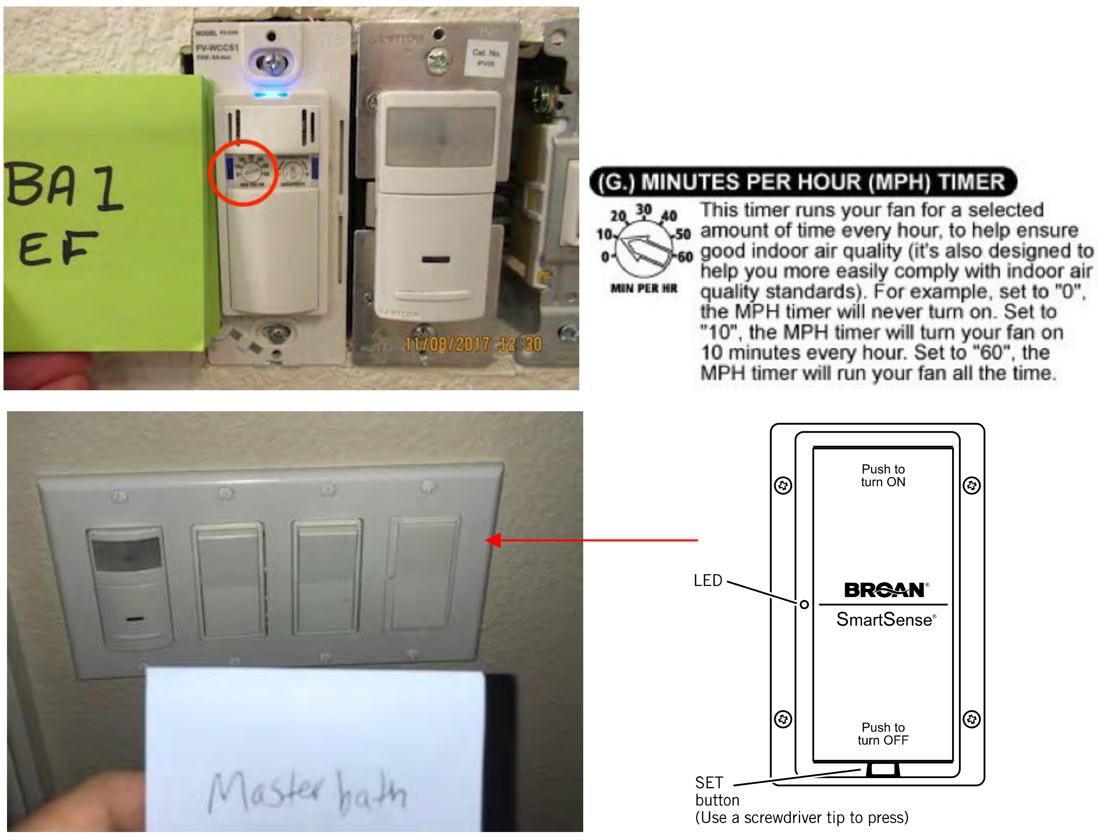
The wording of the dwelling unit ventilation system label, like the choice of the system installer, has a direct impact on the understanding of the study participants. In the three homes that had the message "Continuous Duty", all three systems were turned off.

In 7 out of 9 cases where a more descriptive message was used to explain the purpose of the dwelling unit ventilation system, the system (laundry exhaust fan) was running when the research team arrived to the house. There was only one case (065) where the study participant did not understand that the intent was for the fan to be on continuously. A study participant in House 053 understood the meaning of the label, but explained that s/he did not feel dwelling unit ventilation system was always necessary. Occupants in House 053 made it a habit to turn the laundry exhaust fan off. They reported that the exhaust fan makes the laundry room colder in winter as another reason to turn it off.

Programmable controllers of dwelling unit ventilation systems also appeared to be confusing to study participants, leading to these systems not being operated. The field team observed two types of programmable controllers used in bathrooms (Figure 15). These programmable controllers also have humidity control. In addition, five homes from the same community development (004, 005, 007, 008, 013) used a different type of programmable controller in the laundry room (Figure 16) that does not have humidity control. The field team did <u>not</u> adjust the fan runtime setting on the programmable controller for the one-week monitoring.

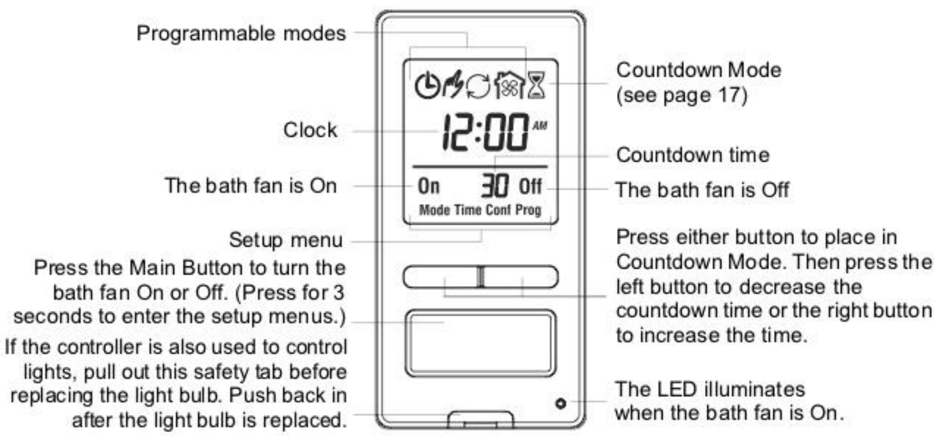
Among the nine homes that used exhaust ventilation controlled by a programmable controller, only four (007, 101, 107, 115) had fans that were programmed to operate intermittently. Fans were set to run between 10 and 30 minutes every hour. Exhaust fans in the remaining five homes either did not operate at all during the one-week monitoring (005 and 046), operated constantly rather than intermittently for one week (013), operated constantly for a few days then turned off (008) or vice versa (004, i.e., off for a few days, then turned on). These results show that the runtime of intermittent exhaust fans was not properly set in many cases. The programmed setting can be easily overridden, leading to possible unintentional disabling of the ventilation system.

Figure 15: Programmable Controller Used to Control Exhaust Ventilation in Bathrooms



Schematics of programmable controller from online user manual: (top) Panasonic WhisperControls Adjustable Condensation Sensor used in home 046; (bottom) Broan SmartSense Intelligent Ventilation System used in home 101, 107 and 115.

Figure 16: Programmable Controller Used to Control Exhaust Ventilation in Laundry Room



Schematics of programmable controller from online user manual Honeywell Programmable Bath Fan Control.

3.3.2 Kitchen Range Hood

In more than half of the kitchens (N=38) exhaust ventilation was provided by an over the range (OTR) microwave with exhaust fan. Our measurements found that OTRs appeared to have much lower exhaust airflows then the 32 range hoods, as shown in Table 24; but as noted below, these data could be substantially biased by the method we used to measure airflow for OTRs.

The field method for measuring OTR exhaust flow in this study involved taping over the air inlet at the top front of the OTR and measuring the inlet airflow at the bottom. Since airflow through the microwave unit is generally restricted, it is very possible that the total exhaust ventilation is reduced when the higher inlet is obstructed. The trend of OTRs having lower airflows than range hoods has been reported in previous laboratory and field studies (e.g., Kim et al., 2018).

Table 24: Measured Kitchen Range Hood Fan Flow (cfm)

Fan Speed Setting	Mean (cfm) Median (5^{th}–95^{th} %tile) (cfm)	
	Range Hood	Microwave
Low	142 137 (59–292)	80 76 (33–141)
Medium	265 224 (81–625)	124 121 (78–184)
High	341 257 (138–806)	128 124 (37–216)

Most, but not all of the homes had kitchen exhaust devices that met the Title 24 minimum airflow requirement of 100 cfm as measured (Table 25); but many did so only at medium and high speed settings that may not comply with the 3 sone sound requirement. In general, the OTRs needed to operate at higher fan speeds to meet the 100 cfm requirement and only 24% of the OTRs met the airflow requirement at low speed. Nine (24%) of the OTRs did not move 100 cfm at any speed setting. In light of the potential bias noted above, we can only say that the actual airflows of OTR units as installed deserves further attention.

Table 25: Fan Speed Settings at Which Range Hoods and Over-the-Range Microwave Exhaust Fans Moved at Least 100 cfm, as Required by Title 24.

Lowest Fan Speed Setting Moving at Least 100 cfm	Range Hood	Over-the-Range Microwave
Low	22	9
Medium	7	14
High	3	6
No setting that moved at least 100 cfm	0	9
Total	32	38

Make and model information were obtained for 66 of the 70 range hood or OTRs. Only 11 of the 66 were listed in the Home Ventilating Institute (HVI) online catalog as having certified airflows and sound ratings; these include three distinct range hood models in four homes and two distinct OTR models across seven homes. Table 26 shows the HVI-certified airflow and sound levels at high speed and low or "working" speed as well as the measured fan flows at all settings. All four of the range hoods moved 100 cfm at the low fan setting, which also met the sound requirement of <3 sones. None of the OTRs met the airflow requirement at the working speed, which was the only setting rated at <3 sones. All but one of the OTRs moved at least 100 cfm on high speed. The one that did not move 100 cfm had such low airflows that we suspect it may not have been installed properly for venting.

Table 26: Rated and Measured Performance of HVI-Rated Range Hoods and Over-the-Range Microwave Exhaust Fans.

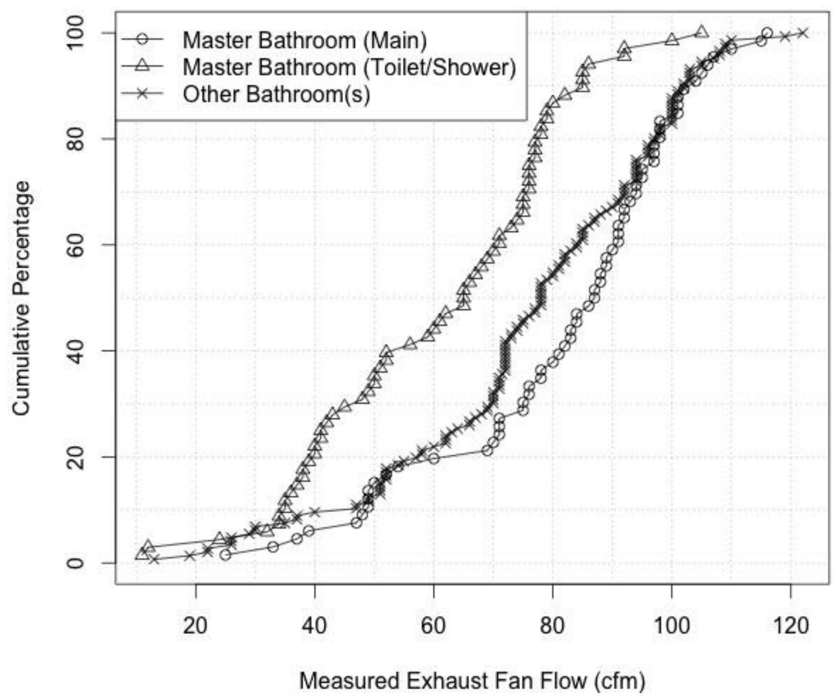
HVI Rated Kitchen Ventilation	HVI Rated CFM	HVI Rated Sones	House ID	Measured Fan Flow (cfm)
Broan QP136SS	LS = 120, HS = 290	0.8, 5	027	132, 293
GE JV966DSS	WS = 160, HS = 590	0.4, 7.5	112	130, 224, 348, 434
			115	161, 266, 591, 780
KitchenAid KVWB606DSS	WS = 170, HS = 380	1.1, 5.5	010	138, 194, 227, 240
Whirlpool WMH31017	WS = 140, HS = 210	2, 5	001	77, 116
			019	68, 102
			028*	36, 42*
			046	84, 111
Whirlpool WMH53520	WS = 110, HS = 290	1.5, 7	015	58, 91, 97, 107
			040	82, 138, 130, 145
			101	79, 104, 102, 109

LS = low speed, WS = working speed, HS = high speed. Each row of measured fan flows represents one exhaust fan / home. *Suspect installation problem with venting.

3.3.3 Bathroom Exhaust Fan

Most general bathroom exhaust fans met the requirement of 50 cfm minimum airflow for an intermittently operated fan. Figure 17 shows a cumulative distribution of the bathroom fan flow rates broken down into three categories: the main fan in the master bathroom; auxiliary fans in the master bath suite (e.g. in toilet room or shower; these are not required to meet the minimum airflow specifications if there is another fan in the bathroom), and exhaust fans in other bathrooms. Exhaust fans in the toilet room or shower tended to have lower measured airflows.

Figure 17: Bathroom Exhaust Fan Measured Flow Rates



The field team observed that in approximately two-thirds of homes (N=44) the main exhaust fan in the master bathroom had a humidistat control. The most common setting was 80% relative humidity for 20-minute runtime. However, lower relative humidity settings were also used: 30% (N=1), 50-60% (N=5), and 70-79% (N=6). Runtime was more consistently set between 15 and 20 minutes (N=18), with a few outliers: 5 minutes (N=2) and 40 minutes (N=1).

3.3.4 Mechanical and Total Ventilation Rate

Figure 18 summarizes the total mechanical ventilation airflow rate provided by all exhaust fans in homes and the estimated total outdoor airflow including air infiltration, during the week of monitoring. The mechanical fan flows were calculated by summing exhaust fan flows (dwelling unit exhaust fan, and other fans in bathroom, range hood, clothes dryer) weighted by their average usage time. Since it was not practical to directly measure the airflow of the clothes dryers in most homes, we assumed dryer airflow of 125 cfm based on a recent ENERGY STAR report[5]. The mechanical systems provided a large portion of total outdoor air in almost all homes and 78% on average.

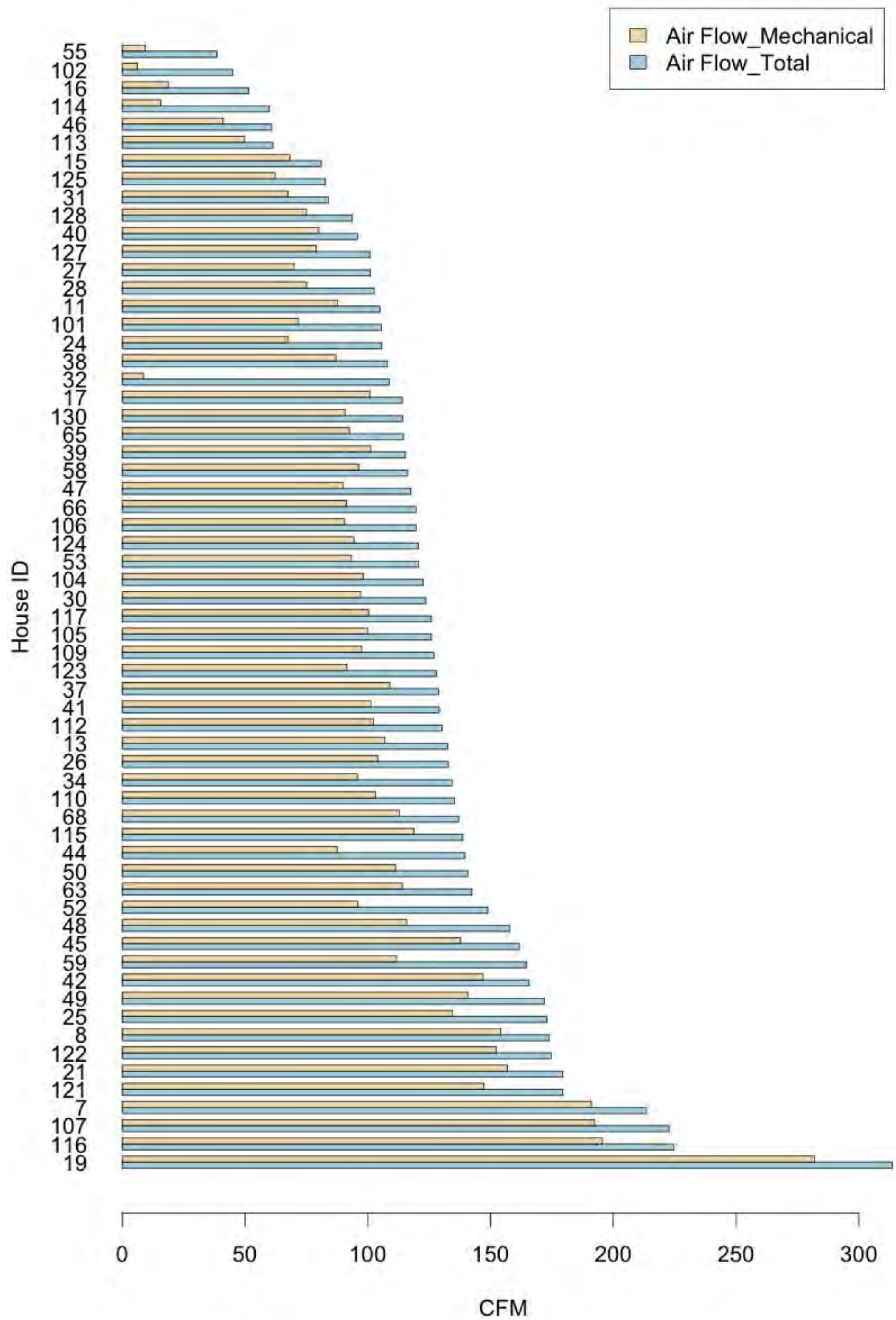
---

[5] ENERGY STAR reports rated fan flow of clothes dryer typically range between 100 and 150 cfm. https://www.energystar.gov/sites/default/files/asset/document/ENERGY_STAR_Scoping_Report_Residential_Clothes_Dryers.pdf

The total mechanical airflow was very low in five homes (016, 032, 055, 102, 114) in which the continuous exhaust fan that was supposed to provide dwelling unit mechanical ventilation was turned off by occupants during the monitoring week. Another home (046) had an intermittent exhaust fan that was not correctly programmed to provide sufficient ventilation.

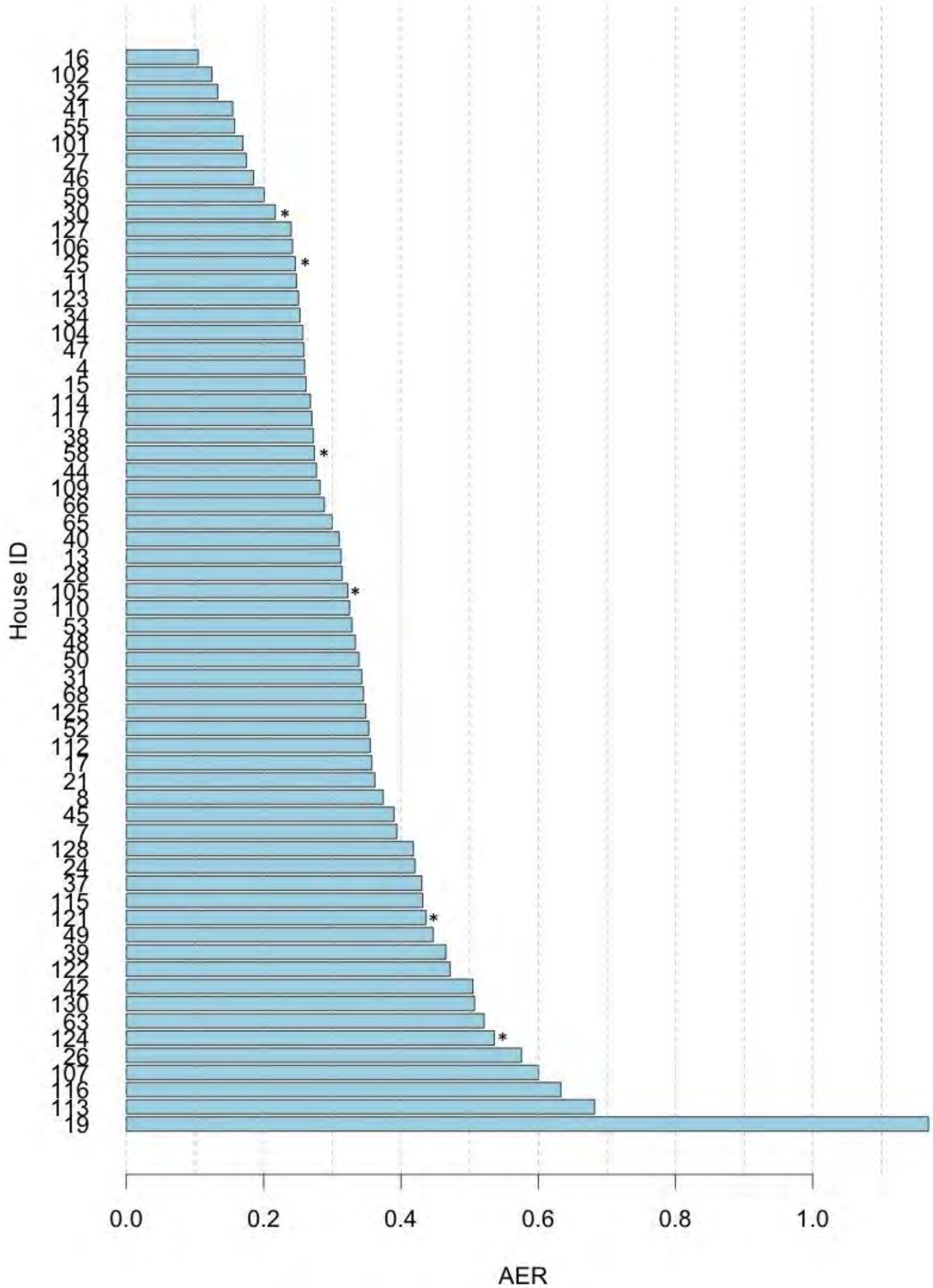
Figure 19 presents the total estimated air exchange rate (AER) provided by all mechanical fan flows and air infiltration. There are six homes identified in Figure 19 where occupants reported to have opened their house-to-patio and/or garage door(s) for more than 3 hours per day on average during the one-week monitoring; in these homes natural ventilation may have increased the overall AER substantially beyond what is estimated based on mechanical fan flow and air infiltration alone. Figure 19 also identified six homes in which the dwelling unit mechanical ventilation did not operate as designed to meet the Title 24 standard. Excluding results from these six homes suggest an AER estimate of about 0.35/h (mean = 0.37/h, median = 0.33/h), with most values between 0.20/h and 0.61/h, for homes complying with the standard. The air exchange rates estimated for homes operating with Title 24 compliant systems were higher than those measured by Offermann (2009) before the Title 24 standard was set in 2008. Offermann reported median AERs of 0.26/h for 107 homes measured during a single monitoring day and 0.24/h for 21 homes measured over a 2-week period.

Figure 18 Mechanical and Total Ventilation Airflow Rate



N=63. This plot excludes four homes that used supply ventilation because the mechanical airflow could not readily be measured. The plot also excludes three homes with missing DeltaQ test result because building envelope airtightness is required to calculate air infiltration (part of total ventilation).

Figure 19 Total Estimated Air Exchange Rate



N=63. This plot excludes four homes that used supply ventilation because the mechanical airflow could not readily be measured. The plot also excludes three homes with missing DeltaQ test result because building envelope airtightness is required to calculate air infiltration (part of total ventilation). There are six homes (*) where opening of the house-to-patio and/or garage door(s) for more than 3 hours per day on average may have increased the overall AER substantially (see later section for more details on window and door usage).

3.3.5 Air Filters in Central Forced Air Systems

The characteristics and conditions of air filters installed in the forced air systems when the field teams arrived to the house are summarized in Table 27 to Table 30. Many homes (68%) had more than one air filter (Table 27). Almost all filters (96%) were rated MERV 8 or higher, and 30% were rated MERV 11 or higher (Table 28). The field team recorded any information they could obtain about the length of time since the filters were last changed and visually assessed filter loading. If the last change date was not marked on the air filter, study participants were asked to recall when the filter was last changed. Nineteen of the 85 filters (22%) for which data were obtained had not been changed within the past 12 months (Table 29). Eighteen of the 67 homes (27%) had at least one filter that appeared overdue for replacement (assessed onsite by the field team as "very dirty") and roughly one fifth of all the air filters were assessed to be "very dirty" (Table 30).

Table 27: Number of Air Filters Characterized Per Home

Number of Air Filters	Number of Homes
1 Filter	22
2 Filters	34
3 Filters	10
4+ Filters	3
Total	69*

* Statistics presented for homes with central forced air system only (one home, 113, has minisplit and no central forced air).

Table 28: Air Filter MERV Ratings

MERV	Number of Air Filters
6	2
7	2
8	57
10	17
11	22
12	1
13	9
14	1
Total	111

Table 29: Time Since Last Air Filter Change

Marked or Estimated Time	Number of Air Filters
0 to 2 Months	33
3 to 5 Months	16
6 to 8 Months	17
12 to 15 Months	8
Never Changed	11
Total	85

Table 30: Condition of Air Filters Observed by Field Team

Air Filter Condition	Number of Homes	Number of Air Filters
Clean or Like New	20	39
Used or Dirty	29	65
Very Dirty	18	24
Total	67*	128

* Total excludes one home (113) without a central forced air system (this home had a minisplit heat pump with no filter for air quality), one home (127) without any air filters installed in the return air registers, and one home (117) for which field observations were missing.

3.3.6 Standalone Air Cleaners

The participant survey asked if a standalone (portable) air filter, air purifier, or air cleaner is used in the home. Fourteen replied yes. The percentage of homes that used air cleaners was higher in homes that also answered yes to whether anyone in the household has been diagnosed with asthma (33% versus 17%). Respondents reporting someone in the household with allergies were no more likely to have a standalone air cleaner compared to households without someone with allergies.

Table 31: Use of Standalone Air Cleaners in Homes With/out Occupants Diagnosed with Asthma or Allergies

Standalone Air Cleaners	Asthma		Allergies	
	Yes (N=18)	No (N=46)	Yes (N=37)	No (N=28)
Yes	6	8	8	6
No	12	38	29	22
Percentage of Homes with Standalone Air Cleaners	33%	17%	22%	21%

Among the homes that use standalone air cleaners, most study participants reported placing them in bedrooms.

Table 32: Placement of Standalone Air Cleaners

Standalone Air Cleaners	Number of Homes (N=14*)
Master Bedroom	6
Other Bedroom(s)	4
Living Room	3
Home Office	1
Laundry Room	2

* Study participants have the option of selecting more than one location in survey.

3.4 Occupancy and Activity

Results of self-reported occupancy from the daily activity log filled out by participants during the study period are summarized in Table 33 and Table 34. Most of the homes had one to three occupants at home at any given time when occupied. Most homes (88% of those responding) were occupied 16 or more hours per day on average.

Table 33: Self-Reported Average Occupancy (Number of People) When Home Was Occupied

Average Occupancy	Number of Homes
1 to <2 People	23
2 to <3 People	20
3 to <4 People	14
4 to <5 People	4
5 to <6 People	4
6 to <7 People	3
No Response	2
Total	70

Table 34: Self-Reported Average Number of Occupied Hours per Day During One-Week Monitoring

Number of Occupied Hours	Number of Homes
> 23 Hours	16
20 to <23 Hours	27
16 to <20 Hours	17
12 to <16 Hours	3
6 to <12 Hours	3
< 6 Hours	2
No Response	2
Total	70

3.4.1 Self-Reported Window Use During Monitoring

The results in Table 35 and Table 36 show that the occupants reported that they mostly complied with the request to keep windows closed during the test period. The majority of homes (N=47) reported no window use. Only 21 homes reported some window used. Three homes (006, 110, 116) that opened a window regularly did so only for short periods (5 to 25 minutes) each time. Of the 68 participants who answered the question about window use only 6 opened windows for more than 3 hours per week and only one household reported opening windows for more than 7 hours during the week. It is important to note that the question asked only about window opening and did include opening a patio door, which can provide substantially more natural ventilation than an open window.

Table 35: Self-Reported Window Use (Number of Times) During One-Week Monitoring Period

Number of Times	Number of Homes
0	47
1–2	12
3–5	4
6–10	2
10–20	2
25	1
No Response	2
Total	70

Table 36: Self-Reported Window Use (Total Length of Time) During One-Week Monitoring Period

Total Length of Time	Number of Homes
0	47
<1 Hour	10
1 to 3 Hours	5
3 to 7 Hours	5
21 Hours	1
No Response	2
Total	70

3.4.2 Monitored Exterior Door Opening

Monitoring data from state open/close sensors show that in the majority of the 63 homes with valid data exterior doors were closed most of the time: in 90% of homes the garage-to-house door was open for less than 30 minutes per day on average and in 70% of homes the house-to-patio door was open for less than 30 minutes per day on average. There were six homes where the house-to-patio door(s) was open for more than 3 hours per days and may have added to the overall AER substantially (025, 030, 058, 105, 121, and 124). Another 4 homes had the patio door open for 1 to 3 hours. Since the amount of patio door opening was not recorded (door could have been open any amount between a crack and fully open), the impact of the open patio door on air exchange is not known. In House 025 the garage-to-house door was also open for more than 3 hours per day on average.

Table 37: Average Duration of Door Opening Per Day During Monitoring Week

Average Duration of Door Opening Per Day	Door to Attached Garage	Patio Door
	Number of Homes	
<30 Minutes	56	45
30 Minutes to 1 Hour	3	9
1 to 3 Hours	3	4
>3 Hours	1	6
Total	63	64

3.4.3 Self-Reported Cooking and Other Activities

Summary results for self-reported cooking activities are presented in Table 38 to Table 40. Of the 68 participants who provided information about cooking frequency, 50% said they used their cooktop 7 or more times per week, i.e. at least once per day on average; but only eight (12%) reported using the cooktop 15 or more times, i.e., more than twice per day on average. Ovens were used much less frequently and outdoor grills even less frequently. In 59% of the homes the average cooktop use lasted for 10–30 minutes and in another 29% the average cooktop use was between 30 and 60 minutes. Oven use was split more evenly between these times and outdoor grill use skewed even more to longer durations.

Table 38: Self-Reported Cooktop Use (Number of Times) During Monitoring Week

Number of Cooktop Use	Number of Homes
None	2
1–3 Times	16
4–6 Times	16
7–14 Times	26
15–21 Times	6
More than 21 Times	2
No Response	2
Total	70

Table 39: Self-Reported Oven and Outdoor Grill Use During Monitoring Week

Number of Uses	Number of Homes	
	Oven	Outdoor Grill
None	16	52
1 Time	14	9
2–3 Times	21	7
4–5 Times	11	0
6–8 Times	6	0
No Response	2	2
Total	70	70

Table 40: Self-Reported Average Duration of Cooking Activities During One-Week Monitoring

Number of Uses	Number of Homes		
	Cooktop	Oven	Outdoor Grill
Less than 10 Minutes	3	3	0
10–30 Minutes	40	20	5
30–60 Minutes	20	24	8
>60 Minutes	3	5	3
No Usage Reported	2	16	52
No Response	2	2	2
Total	70	70	70

3.5 Air Quality Measurements

The following discussion summarizes the field test results and compares indoor air quality measurements from HENGH to the results reported in Offermann (2009), herein described as the CNHS (for California New Home Study).

3.5.1 Formaldehyde

Table 41 shows that in both HENGH and CNHS homes the vast majority of formaldehyde was from indoor sources, and that HENGH homes had lower indoor formaldehyde compared to CNHS homes, despite being newer when tested[6]. The mean indoor formaldehyde concentration was lower in HENGH by about 45% and the median was lower by about 38% compared to CNHS.

[6] There is some evidence (e.g., in Park and Ikeda, 2006) that formaldehyde emission rates are higher when homes are new.

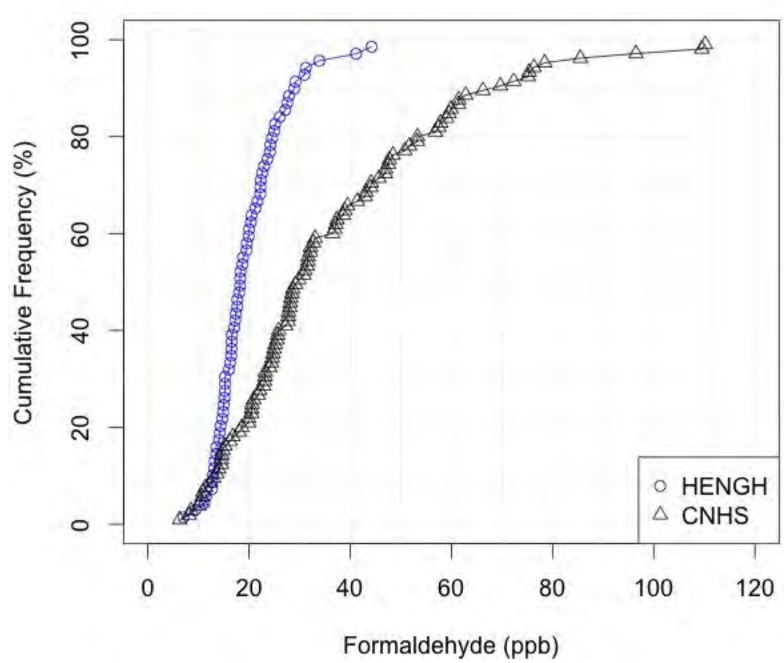
Table 41: Comparison of HENGH and CNHS Passive Formaldehyde Measurements

Formaldehyde	HENGH	CNHS
Indoor	N=68	N=104
Mean (ppb)	19.8	36.3
Median (ppb)	18.2	29.5
Outdoor	N=68	N=43
Mean (ppb)	2.7	2.8
Median (ppb)	2.8	1.8

The six homes that had a patio or a house-to-garage door open for more than 3 hours per day on average did not have substantially lower formaldehyde and excluding those homes does not change the average indoor formaldehyde (mean = 19.9 ppb).

The distributions presented in Figure 20 show that 25% percent of the CNHS homes had formaldehyde concentrations higher than the highest formaldehyde level measured in any HENGH home.

Figure 20: Comparison of HENGH and CNHS Passive Formaldehyde Measurements



The substantial reduction in formaldehyde compared to the CNHS a decade earlier appears to result from both a lower emission rate and a reduction in homes that are severely under-ventilated. The mean indoor formaldehyde indoor emission rate calculated for homes in this study was 6.8 μg/m^3-h (based on 61 homes with all of the required component data) compared to a mean 13 μg/m^3-h calculated from 99 homes with the required component data in CNHS. The data required to calculate air exchange rate are indoor and outdoor formaldehyde concentrations and an estimate of the overall average air exchange rate over the week. For HENGH, only 61 homes had measured mechanical airflow and envelope air leakage (needed for calculating air infiltration rate) and valid indoor and outdoor formaldehyde concentrations. The CNHS estimated a wider range in formaldehyde indoor emission rates (10th to 90th percentile = 4.0 to 23 μg/m^3-h). The HENGH study found a narrower range (10th to 90th percentile = 3.2 to 11.4 μg/m^3-h). The reduction in indoor emission rate is likely a result from California's regulation to limit formaldehyde emissions from composite wood products that came into effect between the two studies. But it is important to note that our method of estimating AER based on mechanical airflow and air infiltration but excluding natural ventilation may have underestimated AER, and subsequently the formaldehyde indoor emission rate, by a small amount.

A potential indicator of the benefit of lower material emission rates is also apparent from the six HENGH homes that did not operate with code-compliant mechanical ventilation during the monitoring week, as discussed above in the section on air exchange rates. These included five homes in which occupants turned off the dwelling unit exhaust fan and a sixth in which the intermittent exhaust fan was not programmed correctly. Excluding these homes does not change the central estimate of indoor formaldehyde for HENGH: mean = 19.7 ppb, median = 18.2 ppb.

The lower formaldehyde concentrations measured by HENGH in comparison to CNHS are also partly the result of a higher baseline outdoor air exchange with mechanical ventilation. Many of the highest formaldehyde levels reported by Offermann were in CNHS homes that had air exchange rates below the minimum AER provided by mechanical ventilation systems in HENGH homes.

HENGH measured formaldehyde concentrations in the indoor main living space (e.g., living room) and also in master bedroom. Generally differences were small between locations; but in some homes a higher concentration of formaldehyde was measured in the master bedroom compared to the central monitoring location.

Figure 21: One-Week Integrated Formaldehyde Measured with Passive Samples: Comparison of Concentrations at Bedroom and Central (Main) Indoor Locations

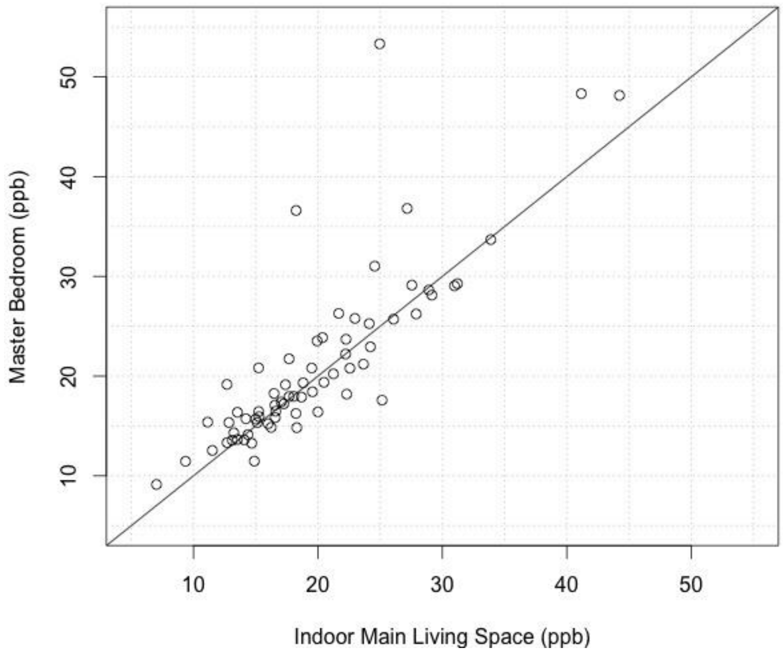
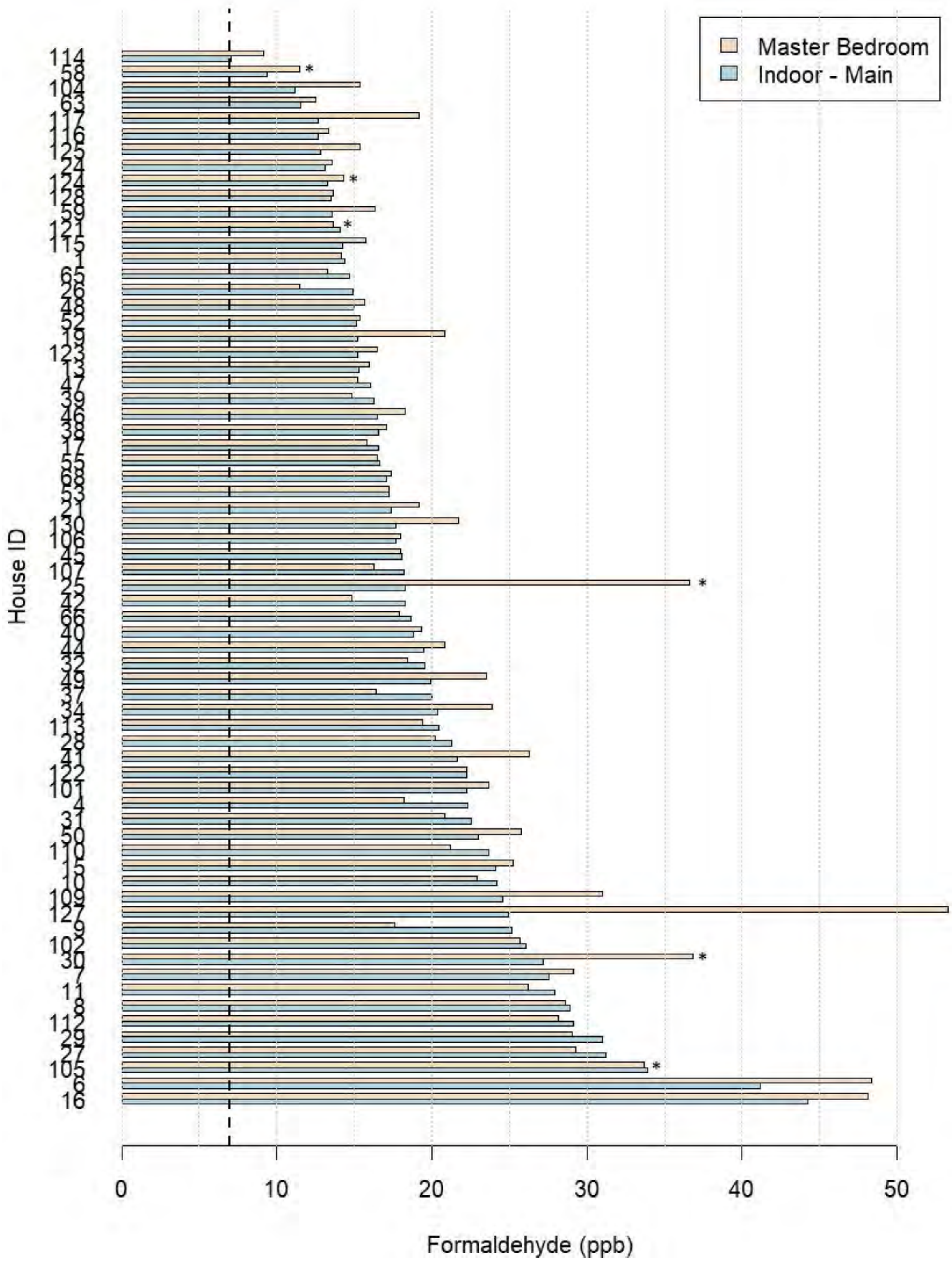


Figure 22: One-Week Integrated Formaldehyde Measured With Passive Samplers at Two Indoor Locations, Ordered by Concentration at Central (Main) Site



OEHHA REL (7 ppb) shown as dotted line. There are six homes (*) where opening of the house-to-patio and/or garage door(s) for more than 3 hours per day on average may have increased the overall AER substantially (see earlier section for more details on window and door usage).

Indoor formaldehyde concentrations were also measured using time-resolved monitors that were co-located with the passive samples both at the indoor main living space and in the master bedroom. Figure 23 compares the one-week integrated formaldehyde concentrations measured by the time-resolved monitor at the two locations. Similar to results from passive samplers, higher formaldehyde concentrations were measured in the master bedroom of some homes, compared to the main living area.

Figure 23: One-Week Integrated Indoor Formaldehyde Concentrations from Time-Resolved Monitor

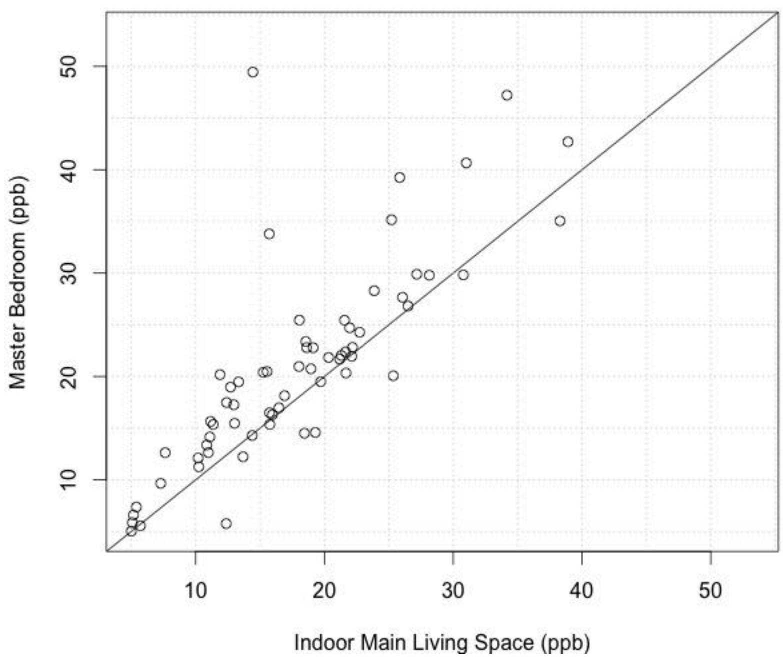
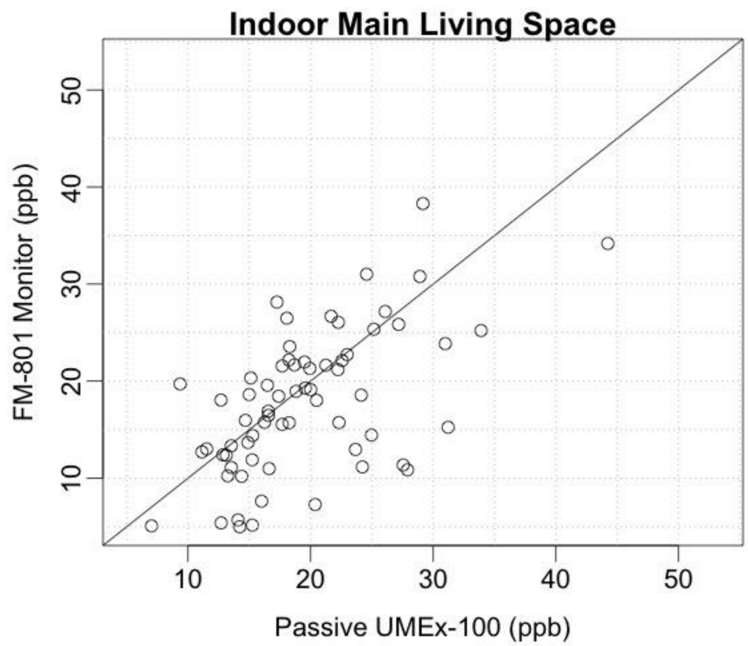


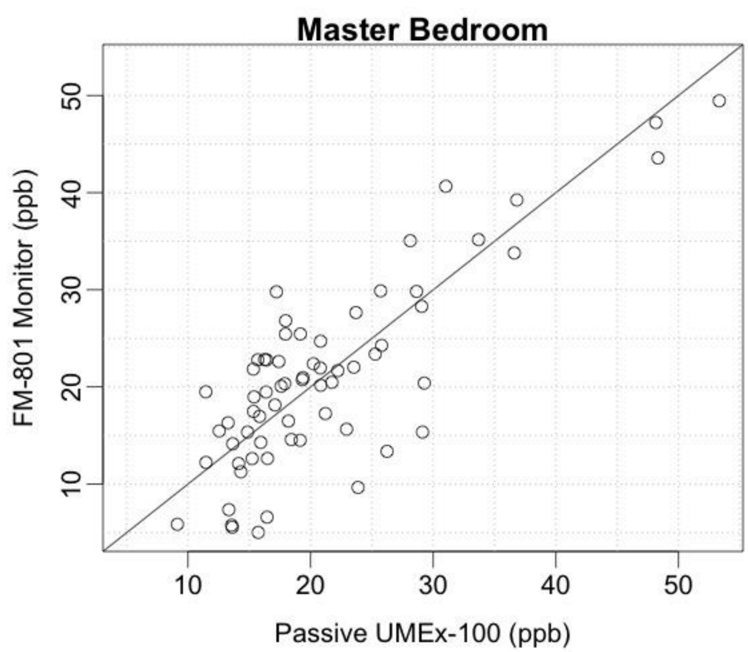
Table 42: Comparison of Time-Integrated Formaldehyde Measurements Using UMEx-100 Samplers and Gray-Wolf FM-801 Monitors

Formaldehyde	UMEx-100 Samplers	Gray-Wolf FM-801 Monitors
Indoor Main	N=68	N=67
Mean (ppb)	19.8	18.1
Median (ppb)	18.2	18.0
5^{th} to 95^{th} %tile (ppb)	11.9 – 31.1	5.5 – 30.9
Master Bedroom	N=68	N=66
Mean (ppb)	21.1	21.3
Median (ppb)	18.2	20.4
5^{th} to 95^{th} %tile (ppb)	12.8 – 36.7	6.0 – 42.2

Average formaldehyde concentrations measured by the real-time monitors provided similar aggregate results as the time-integrated passive samples (Table 42). However, considerable scattering was observed when comparing the time-average of the time-resolved to the time-integrated passive samples for each home (Figure 24). A better fit, in terms of R^2 from linear regression, was obtained for paired measurements from the master bedroom.

Figure 24: Comparison of Passive and Time-Resolved Formaldehyde Measurements





Comparison of passive and real-time formaldehyde measurements averaged over a one-week period. Linear regression gives R^2 = 0.33 for indoor main living space, and R^2=0.66 for master bedroom.

Future analysis of the real-time monitored formaldehyde and estimates of air change rates will evaluate effects of temperature and relative humidity on indoor formaldehyde emission rates, as suggested in previous research (Parthasarathy et al., 2011).

3.5.2 Fine Particulate Matter ($PM_{2.5}$)

$PM_{2.5}$ concentrations measured using real-time instruments (MetOne and pDR) were adjusted using gravimetric filter measurements to account for differences in particle size distribution between the field tests and instrument calibration. An adjustment factor (multiplier) was defined as follows:

$PM_{2.5}$ (real-time, adjusted) = $PM_{2.5}$ (real-time, unadjusted) x Adjustment Factor

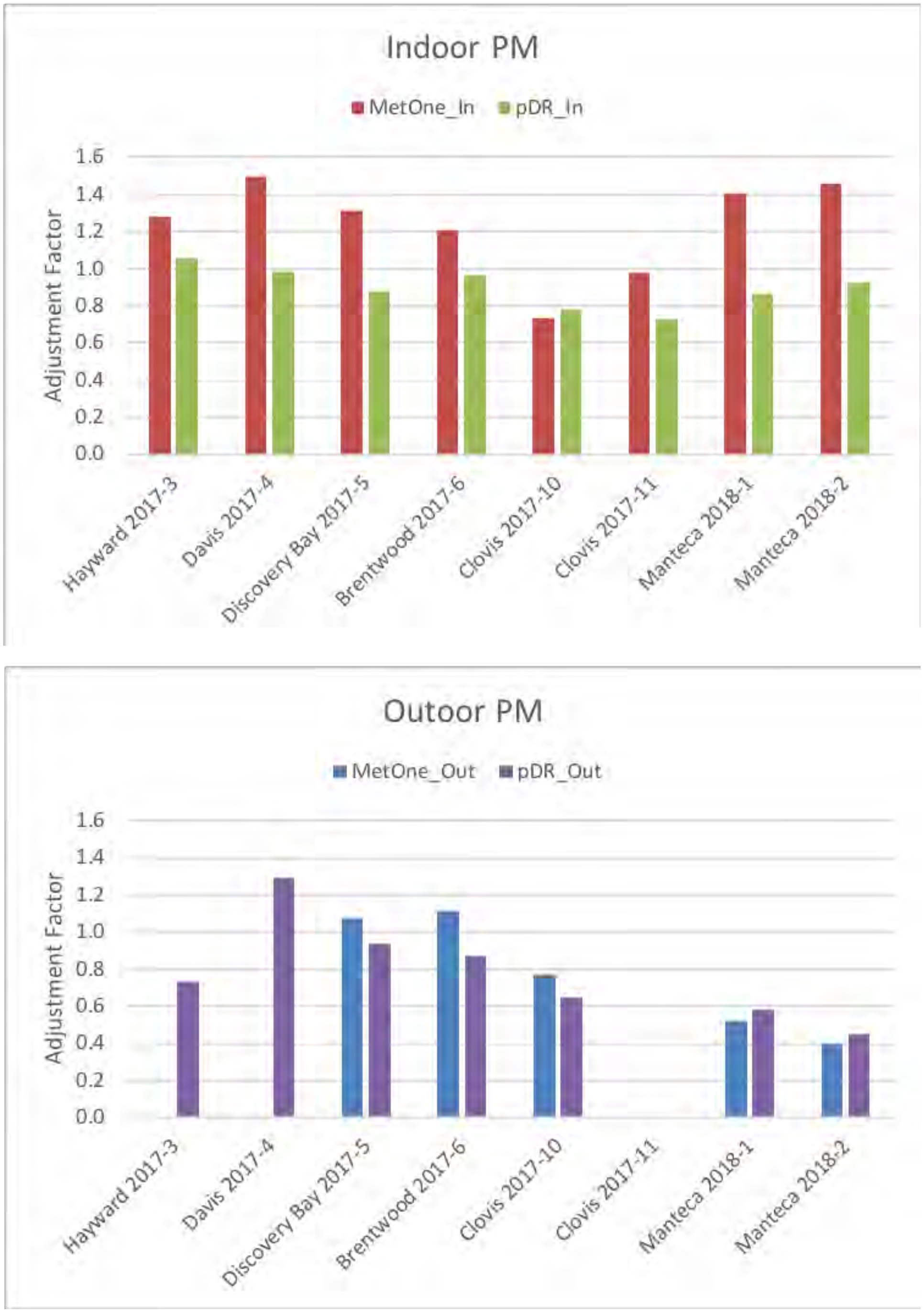
Figure 25 shows indoor and outdoor adjustment factors calculated from filter measurements indoors at 8 homes and outdoors at 7 homes for the pDR and 5 homes for the MetOne photometers. The adjustment factors for indoor measurements were not insignificant: they accounted for ~20% underestimate from MetOne, and ~10% overestimate from pDR, on average. The calculated adjustment factors were applied to all indoor measurements.

Table 43: $PM_{2.5}$ Adjustment Factor Using Filter Measurements

$PM_{2.5}$ Instrument	Indoor	Outdoor
MetOne	1.23	0.78
pDR	0.90	0.79

No adjustments were made for the outdoor measurements, even though Table 43 suggests that both MetOne and pDR may have overestimated the outdoor $PM_{2.5}$ concentrations. This is because unlike the adjustment factors estimated for indoor measurements (Figure 25), where MetOne consistently underestimated indoor $PM_{2.5}$ concentrations, and pDR consistently overestimated indoor $PM_{2.5}$ concentrations, the outdoor adjustment factors were more variable from home to home. The larger variability is thought to result from variations in particle size, mass distribution and compositions of outdoor $PM_{2.5}$, as well as environmental conditions when the data were collected. Consequently, applying a single adjustment factor to outdoor $PM_{2.5}$ measurements would not have improved accuracy of the results. Future analysis could compare outdoor MetOne data with the $PM_{2.5}$ concentrations reported at nearby ambient air quality monitoring stations.

Figure 25: PM$_{2.5}$ Adjustment Factors Calculated from Filter Measurements



Column labels show city and year-month where real-time and filter measurements of PM$_{2.5}$ were collected.

Table 44 shows that the mean and median indoor PM$_{2.5}$ concentrations were much lower in HENGH than in CNHS. The median concentration outside of HENGH homes was also lower than the median outside of CNHS homes. The lower indoor PM$_{2.5}$ in HENGH compared to CNHS homes can only partly be attributed to the lower outdoor concentrations since the ratio of median HENGH/CNHS indoor concentrations is 0.48 and the ratio of median outdoor concentrations is 0.78. The ratio of median indoor to median outdoor concentration was approximately 0.5 for HENGH homes and approximately 0.8 in the CNHS. Other possible explanations include the benefits of higher performance air filters in HENGH homes and a potential benefit of filtration by the building shell associated with the exhaust ventilation systems, as reported by Singer et al. (2017). The higher quality air filters in HENGH homes compared to CNHS would only be a factor in homes that in which the forced air systems operated for a substantial fraction of time during the week of monitoring. An analysis of the potential factors that could have resulted in the lower indoor concentrations and indoor/outdoor ratios is planned and will be reported separately when it is available.

While 20 of the 67 HENGH homes with outdoor data had outdoor $PM_{2.5}$ exceed the CalEPA annual ambient air quality standard of 12 $\mu g/m^3$, only 12 of the 67 homes with indoor data had indoor concentrations exceed that benchmark (Figure 26).

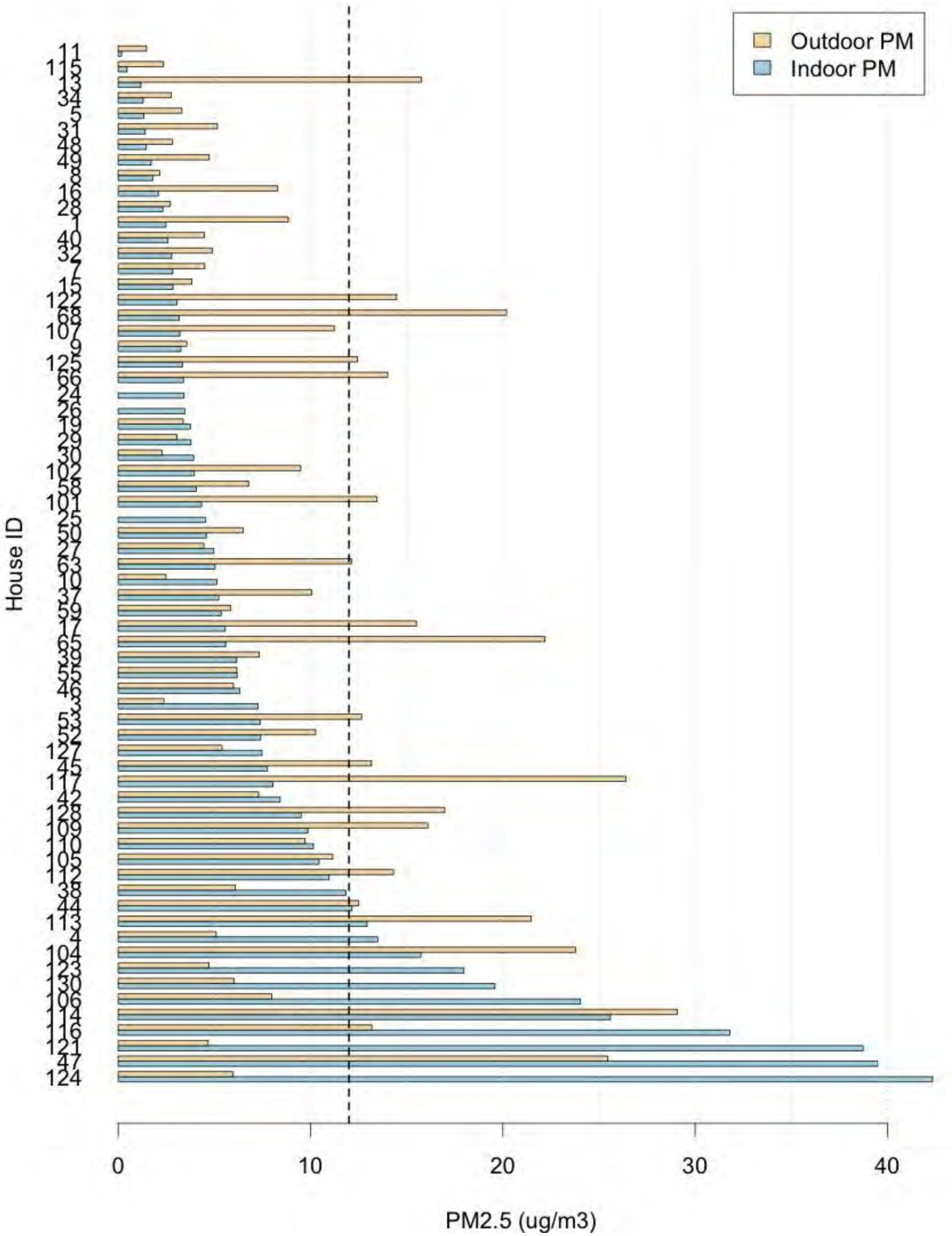
Table 44: Comparison of HENGH and CNHS $PM_{2.5}$ Measurements

$PM_{2.5}$	HENGH	CNHS
Indoor	N=67	N=28
Mean ($\mu g/m^3$)	8.3	13.3
Median ($\mu g/m^3$)	5.0	10.4
Outdoor	N=67	N=11
Mean ($\mu g/m^3$)	9.3	7.9
Median ($\mu g/m^3$)	6.8	8.7

To examine the dependence of indoor $PM_{2.5}$ concentrations on outdoor concentrations, Figure 27 shows the ratio of indoor to outdoor $PM_{2.5}$ in relation to outdoor $PM_{2.5}$. Most homes (68%) showed an indoor/outdoor ratio less than unity. As expected, data suggested large variability in indoor/outdoor $PM_{2.5}$ ratios, with values ranging between 0.2 and 3.2 (5^{th} to 95^{th} percentile). The central estimates of indoor/outdoor $PM_{2.5}$ ratio are mean = 1.1 and median = 0.68.

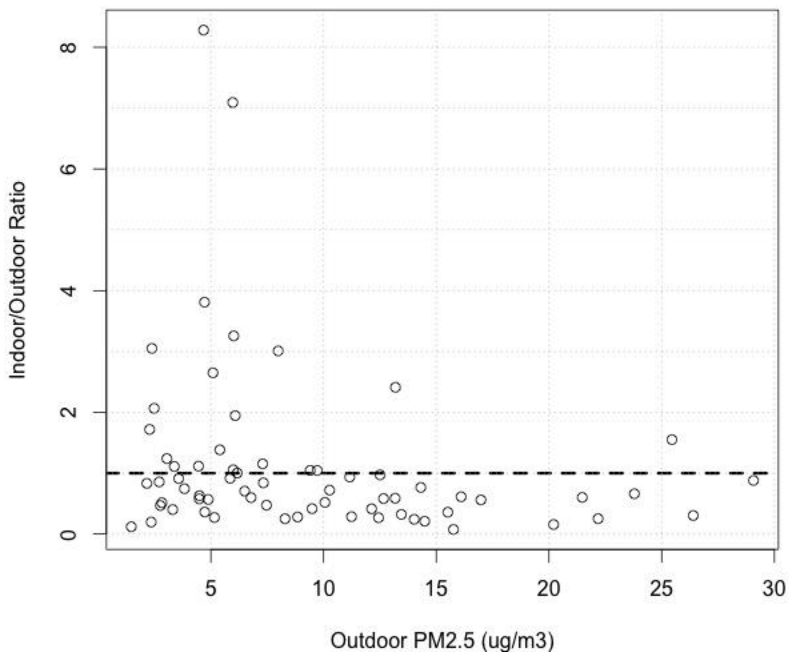
In homes that were monitored when outdoor $PM_{2.5}$ concentrations were relatively high (>15 $\mu g/m^3$), the indoor/outdoor ratio (N=11) has a central tendency of about 0.55 (mean = 0.55, median = 0.56). Future analysis of $PM_{2.5}$ will seek to isolate contributions from indoor sources and calculate infiltration factors.

Figure 26: One-Week Average $PM_{2.5}$ Concentrations



CalEPA ambient air quality annual standard of 12 ug/m^3 showed as dotted line.

Figure 27: Indoor/Outdoor $PM_{2.5}$ Ratio



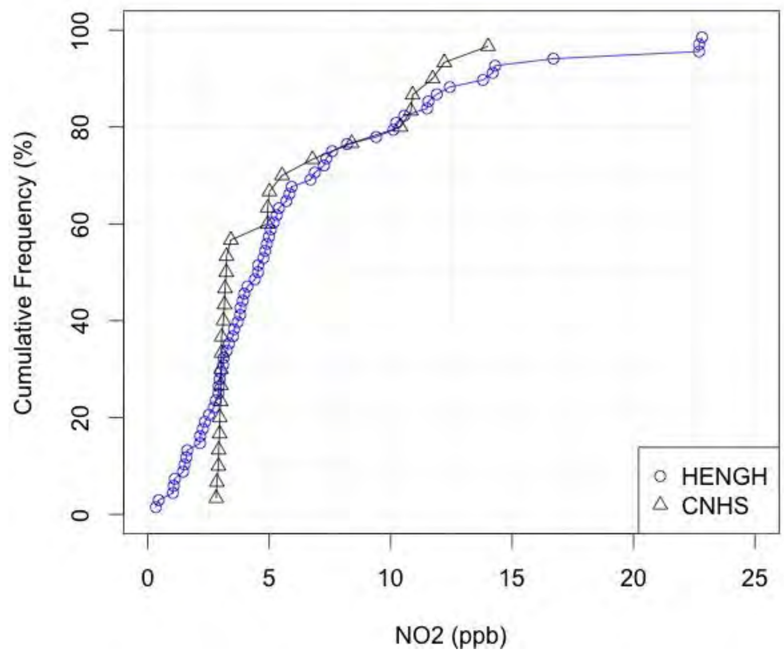
3.5.3 Nitrogen Oxides (NO_X) and Nitrogen Dioxide (NO_2)

The indoor NO_2 concentrations measured in HENGH were slightly higher than those reported in CNHS homes as shown in Table 45 and Figure 28 while median outdoor levels were similar in the two studies (Table 45). There were seven HENGH homes with indoor concentrations NO_2 concentrations that were similar or higher than the highest measured in any CNHS home. All of the measured NO_2 concentrations were well below the US EPA 53 ppb annual ambient air quality standard for NO_2.

Table 45: Comparison of HENGH and CNHS One-Week Integrated NO_2 Measurements

NO_2	HENGH	CNHS
Indoor	N=67	N=29
Mean (ppb)	6.2	5.4
Median (ppb)	4.5	3.2
Outdoor	N=66	N=11
Mean (ppb)	5.6	3.5
Median (ppb)	3.7	3.1

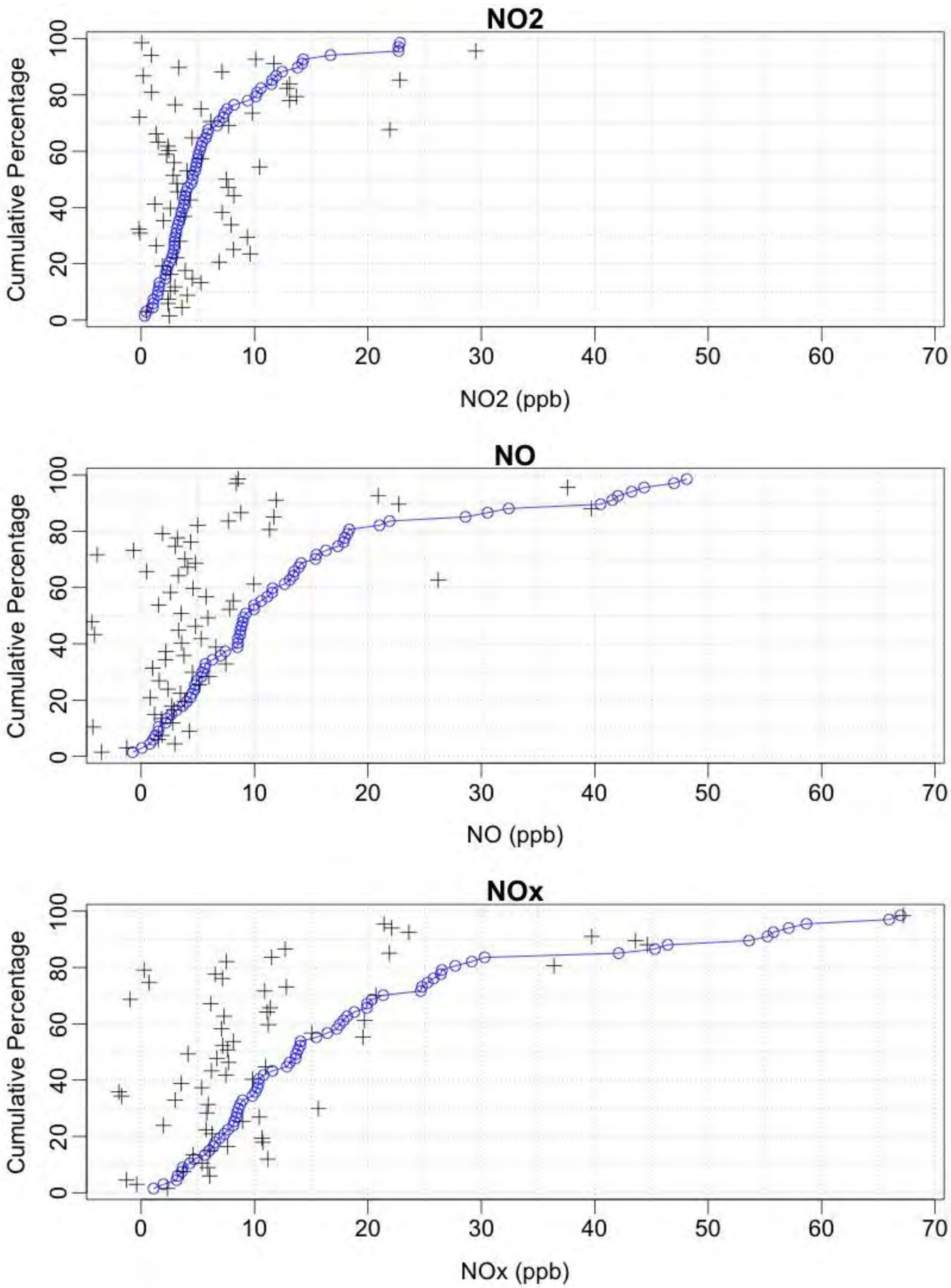
Figure 28: Comparison of HENGH and CNHS One-Week Integrated NO_2 Measurements



These results imply that the gas cooking appliances in the HENGH homes did not lead to widespread problems with indoor NO_2; this is in contrast to a recent study that found gas cooking is a significant source leading to elevated NO_2 in California homes that cook frequently with gas burners (Mullen et al., 2016).

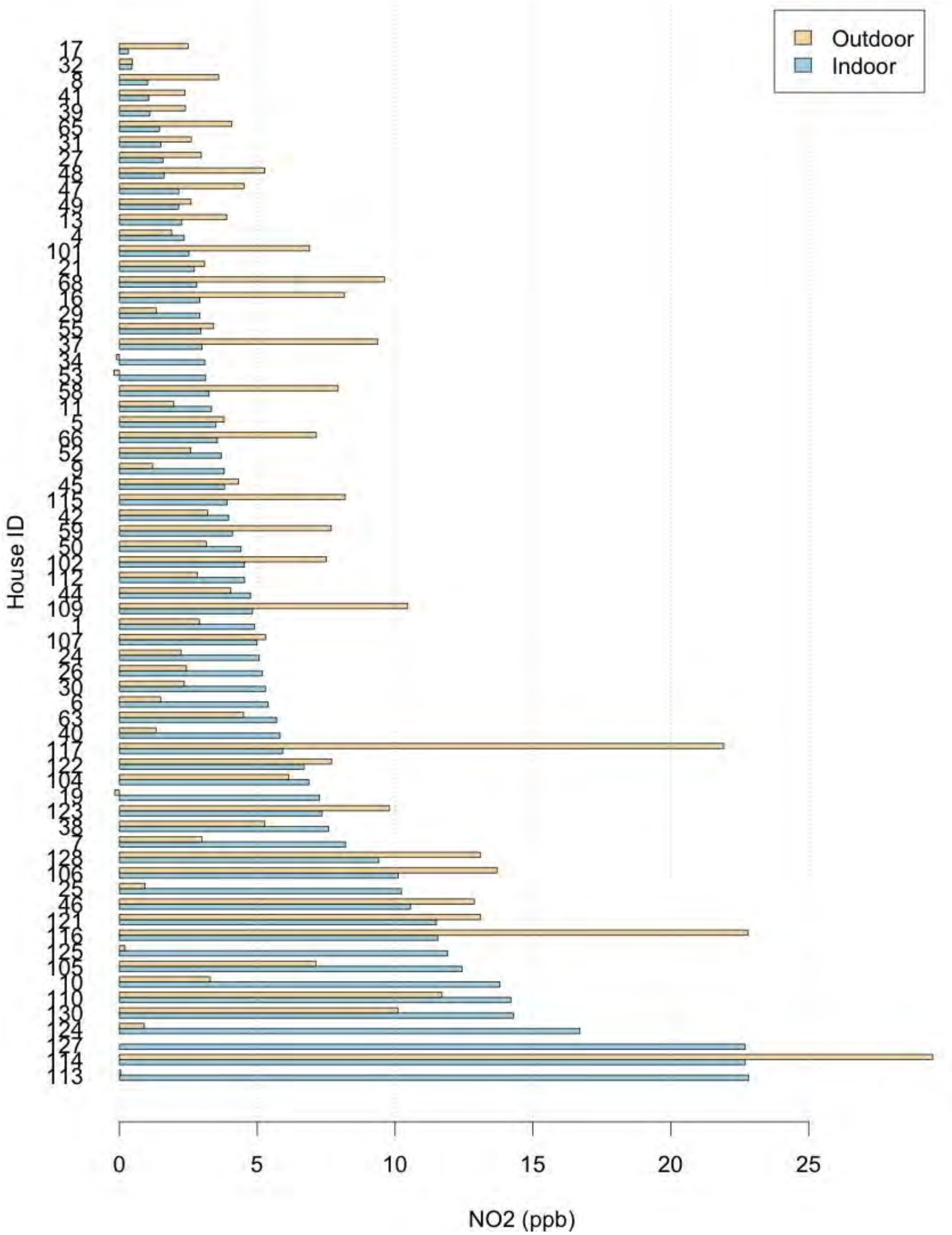
Even though NO_2 concentrations measured by HENGH are similar to levels found in CNHS, the two studies differed in that HENGH homes all used gas for cooking, whereas almost all homes (98%) from the prior study used electric ranges. For NO and NO_X, Figure 29 shows that indoor concentrations were almost always higher than outdoors and that increased outdoor concentrations lead to increased indoor concentrations. For NO_2 deposition indoors results in indoor concentrations being substantially lower than outdoors when indoor sources represent a small contribution to total NO_2.

Figure 29: One-Week Integrated NO_2, NO, and NO_X Concentrations



Ranked ordered indoor NO_2, NO, and NO_X concentrations plotted as blue circles. Corresponding outdoor concentrations plotted as black crosses.

Figure 30: One-Week Integrated NO_2 Indoor Concentrations from Passive Samples



All NO_2 concentrations below USEPA annual standard of 53 ppb.

3.5.4 Carbon Dioxide (CO_2)

Figure 31 shows the distributions of average CO_2 concentrations over the monitoring period for various locations within the study homes. The highest time-averaged concentrations were in the master bedroom and the top 60% of the other bedroom locations were slightly higher than the main indoor living space.

Figure 31: CO_2 Measurements in indoor main living space and bedrooms

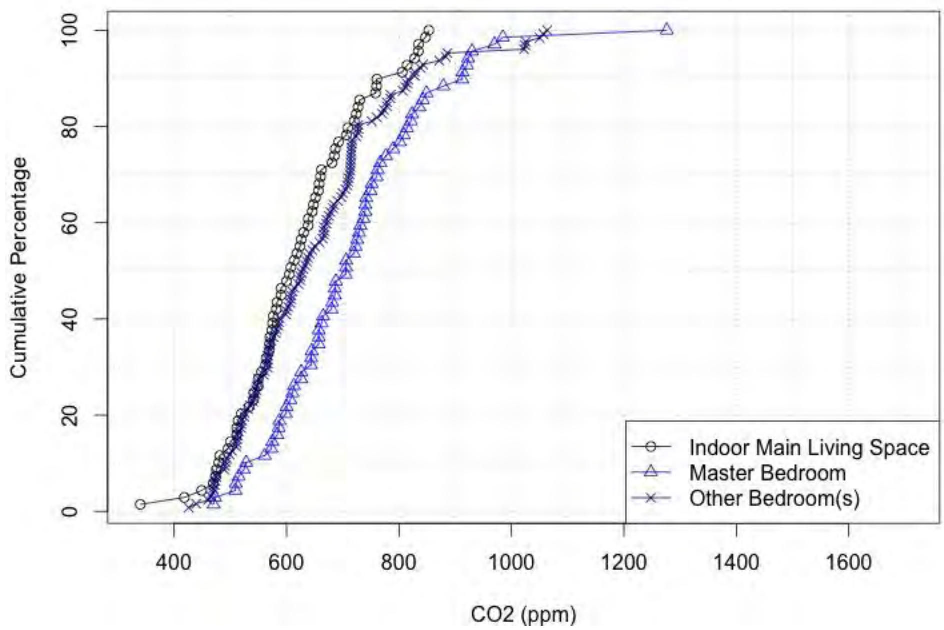


Table 46 shows that the median of time-averaged CO_2 concentrations across HENGH homes was substantially higher than the median for the CNHS sample, but the means for the two studies were very similar.

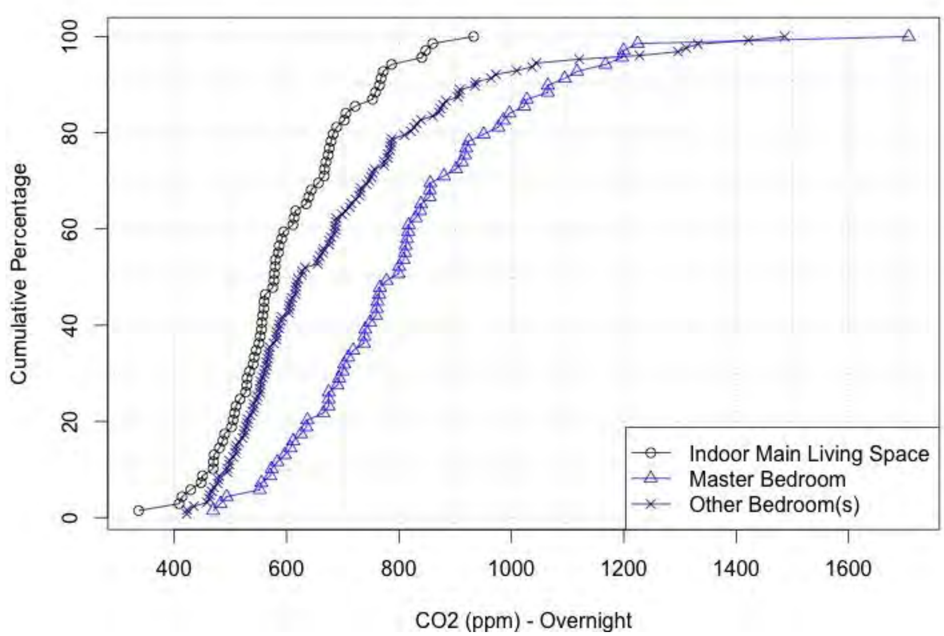
Table 46: Comparison of HENGH and CNHS CO_2 Measurements

CO_2	HENGH	CNHS
Indoor	N=69	N=107
Mean (ppm)	620	610
Median (ppm)	608	564
10^{th} to 90^{th} %-tile (ppm)	481–770	405–890

In the absence of a consensus limit for CO_2 in residences, we use the ASHRAE 62.1 guideline level of 1100 ppm (700 ppm above the outdoor background of roughly 400 ppm) as a benchmark[7] for CO_2. And considering that the ASHRAE guideline applies during occupied periods only, the average concentrations over an interval that include unoccupied periods should be solidly below this level. While only one home had time-averaged CO_2 above 1100 (in the master bedroom), several others had CO_2 above 1000 in other bedrooms. This suggests the possibility of concentrations exceeding 1100 during at least some occupied periods.

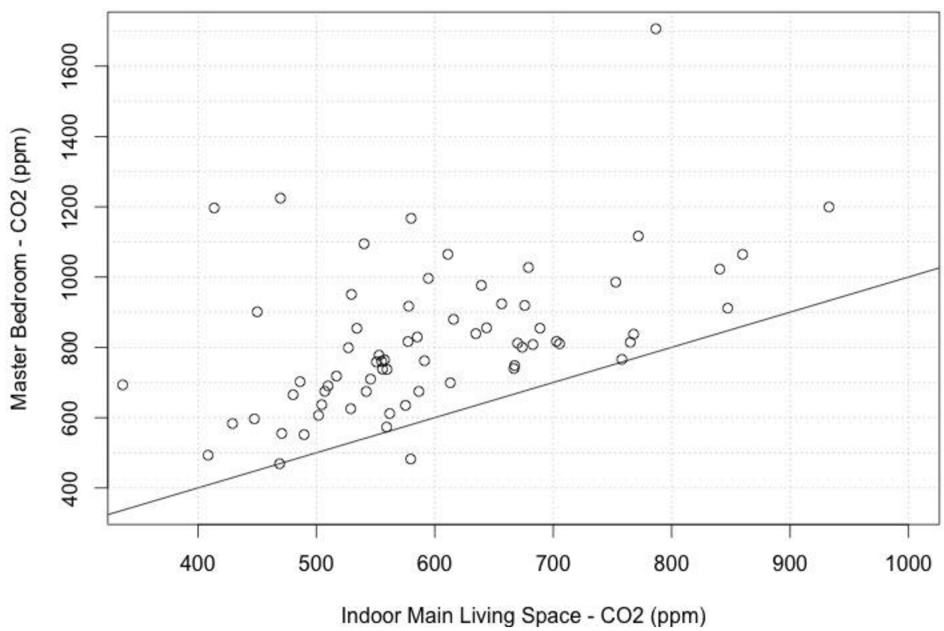
The difference in time-averaged CO_2 by indoor location results, unsurprisingly, from the bedrooms having much higher CO_2 overnight. Figure 32 shows the distributions of average CO_2 concentrations in each room, looking only at data from midnight to 5am (across all days with data during this time period). Six of the master bedrooms and 10% of the other bedrooms had mean CO_2 concentrations overnight in excess of 1100 ppm. Figure 33 compares the overnight CO_2 concentrations measured in the indoor main living space and master bedroom of the same homes.

Figure 32: Overnight (midnight-5am) CO_2 Measurements in Indoor Main Living Space and Bedrooms



7 ASHRAE 62.1 guideline level of +700 ppm above outdoor background (currently about 400 ppm) is largely based on odor concern in commercial buildings, which is not intended for residences.

Figure 33: Overnight (midnight-5am) CO_2 Measurements in Indoor Main Living Space and Master Bedroom



3.5.5 Temperature and Relative Humidity

Time-averaged indoor temperature and relative humidity measured in this study were similar to CNHS. The (24h) time-averaged indoor air temperature results reported for the CNHS study had the same median and mean of 22.4 °C, and a range of 17.1 to 28.2 °C across homes. The mean indoor air temperatures measured over the roughly weeklong monitoring periods in HENGH homes had the same median and mean of 22.9 °C, and a range of 17.8 to 27.1 °C across homes. CNHS reported 24-hour average indoor relative humidity with a median of 43%, a mean of 45%, and a range of 20% to 64% across homes. The mean relative humidity measured over the roughly weeklong monitoring periods in HENGH homes had the same median and mean of 45%, and a range of 28% to 60% across homes.

3.6 Fan Sizing and Air Tightness Requirements from the Simulation Study

The dwelling unit ventilation fan sizing methods with the poorest weighted average IAQ (highest relative exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method and the Total Ventilation Rate Method. These had weighted average relative exposures of 1.3 and 1.4, respectively. Of all sizing methods, the proposed ***Title 24 2019*** sizing method maintained relative exposure closest to 1.0. The ASHRAE 62.2-2016 method and the ***Qtotal*** method were the next best approaches. The ASHRAE 62.2-2016 fan/infiltration superposition method consistently under-ventilated and had average relative exposure of about 1.09, while the ***Qtotal*** method consistently over-ventilated, with relative exposures averaging about 0.93. ***Qtotal*** was the only sizing method that maintained exposure below 1.0 in all simulated cases. The best approaches from an IAQ standpoint were the ***T24 2019*** and ***Qtotal*** methods. They increased the weighted average energy use by 3 and 5% relative to the ASHRAE 62.2-2016 method. The difference in weighted average total consumption between any of these three sizing methods was roughly 300 kWh/year.

Most of the sizing methods had widely spread relative exposure values, meaning that most homes were either under- or over-ventilated relative to target rates in 62.2 and Title 24. This inconsistency increases the risk of either higher exposures to indoor emitted pollutants or excess energy consumption for individual homes, even when the weighted average results are acceptable. The ASHRAE 62.2-2016 fan sizing method, which accounts fully for infiltration and fan type (i.e., the differences between balanced and unbalanced fans), had the most consistent pollutant exposure and ventilation rates across all cases, irrespective of climate zone, fan type, airtightness or house prototype. This sizing method had average exposure of 1.09, due to biases in the exhaust fan sub-additivity calculations in ASHRAE 62.2-2016. If desired, the CEC could adopt an alternative sub-additivity formulation that would eliminate most of this bias, and should reduce average exposure very close to 1.0. The adopted Title 24_2019 fan sizing method also had quite consistent exposure values, though it tended to over-ventilate leakier homes.

An airtightness requirement of 3 ACH50 in new California homes was found to have a predicted weighted average energy savings from 1 to 5% of total HVAC energy use, depending on what fan sizing method was used. Most of these savings were from reducing the ventilation rate and allowing higher concentrations of indoor emitted pollutants under the hypothetical airtightness requirement. The fixed airflow fan sizing methods saved more energy (roughly 3 to 5%) but worsened IAQ by increasing exposure by 5 to 24%. The energy savings are low because the majority of the projected new construction will be in mild climates, and because the interactions between unbalance mechanical ventilation and natural infiltration lead to small changes in total airflow when we tighten to this 3 ACH50 limit. Energy use decreased as weighted average exposure increased, essentially trading potentially higher pollutant exposure for improved energy performance. The sizing methods that accounted for infiltration and/or fan type had substantially reduced weighted average energy savings (1%), while they marginally improved IAQ (reduced exposure by roughly 3 to 4%) under an airtightness requirement. These fan sizing methods are designed to ensure a similar dwelling unit ventilation rate across levels of airtightness, which they did with moderate success. Savings from an air leakage requirement were roughly double in the 2-story vs. 1-story prototype homes, because of their increased natural infiltration rates. Savings were also higher in climates with the harshest weather (CZ16 and CZ1), but the lack of new construction in these zones nearly eliminated their effect on the weighted average results. When HVAC energy consumption was normalized by exposure to ensure equivalent IAQ in all simulated cases, the energy savings for airtightening from 5 to 3 ACH50 were well below 1% for all fan sizing methods.

The adopted fan sizing method in the 2019 Title 24 energy code produces results that are relatively independent of regarding air leakage limits, because it provided weighted average exposure nearly equal to 1 under both airtightness scenarios (existing and airtightened). Weighted average exposure would increase 5% with an air leakage limit in the energy code, though it would still be less than exposure achieved using the ASH622_2016 sizing method.

Relative to the ASHRAE 62.2-2016 method, the adopted T24 2019 fan sizing method over-ventilates leaky homes (3 and 5 ACH50), with increased site energy consumption ranging from 70 to, 1,400 kWh/year, when averaged across climate zones. Our results suggest that unless occupant exposure to indoor generated contaminants is allowed to increase by 5-10%, then an airtightness limit will have very marginal savings of roughly 1% of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5% are possible through airtightening.

CHAPTER 4: Conclusions and Recommendations

Conclusions

The following conclusions may be drawn from the field study of homes constructed since the 2008 version of the Title 24 Building Energy Efficiency Standards first required mechanical ventilation.

1. The vast majority of homes appear to have ventilation equipment that exceeds the minimum airflow requirements for dwelling unit and bathroom ventilation, and dwelling unit ventilation systems appear to be substantially oversized (by roughly 50% on average in the study sample). The oversizing appears to result from use of standard sizes of exhaust fans, as most homes with exhaust ventilation had either an 80 cfm or a 110 cfm fan. This suggests that increasing ventilation requirements in future versions of Title 24 may have only a small impact on the ventilation equipment installed in homes.
2. The most common equipment used to meet the dwelling unit ventilation requirement appears to be a single exhaust fan (used in 60 of 70 study homes). The most common control for these exhaust systems appears to be continuous operation (55 homes) and the most common location for the exhaust fan was the laundry room (48 homes).
3. Having a clear label on the controller – as required by the Standard – appears to greatly increase the chance that the dwelling unit ventilation system will be operated. It was common for the dwelling unit ventilation system to be turned off as the systems were operating in only 18 of 70 study homes when the field team arrived. It was uncommon for ventilation control switches to have informative labels as required by the Standards, as control switches were labeled in only 12 of 70 study homes. Homes with clearly labeled control switches were much more likely to have ventilation operating.
4. Understanding about ventilation systems appears to be mixed: just over half of the participants in this study said they understood how to operate the ventilation system in their home and about half of those who could recall said that the ventilation system was explained to them when they bought the house.
5. The kitchen ventilation equipment in many homes appears to meet most but not all of the requirements, specifically not meeting the requirement of moving ≥100 cfm at a setting with a certified sound rating of ≤3 sones. While most homes had a range hood or over-the-range microwave exhaust fan (OTR) that met the 100 cfm minimum airflow requirement, many of the range hoods and most of the OTRs did so only at medium or high speed, and some OTRs did not meet the airflow requirement even at the highest speed setting. An important caveat to this finding is that the OTR airflows could be biased low based on the measurement method, which required taping over the air inlets provided at the front top of some OTRs. Not all kitchen ventilation equipment was HVI certified. There is a need for the CEC to HERS verify compliance with the 62.2 requirement for the range hood fans to be HVI certified (as has been adopted in the 2019 Title 24 Part 6 standards).

6. Many homes had air filters in their forced air heating and cooling systems that should be at moderately to substantially effective at reducing $PM_{2.5}$ when operated. Of the 132 filters identified in study homes, MERV performance values were discerned for 111. Of these all but four were MERV8 or better and 33 were MERV11 or better. Eighteen of the 67 homes had at least one filter that appeared overdue for replacement (assessed onsite by the field team as "very dirty") and roughly one fifth of all the air filters were assessed to be "very dirty". Nineteen of the 85 filters for which data were obtained had not been changed within the past 12 months.
7. A substantial minority of field study participants reported discomfort or dissatisfaction with some environmental condition on a weekly basis during at least some season(s): roughly 30% reported too hot in summer, roughly 30% reported too cold in winter, roughly 20% reported not enough air movement, roughly 15% reported too hot in winter and roughly 10% too dry.
8. Similar to the results of prior surveys, a majority of participants reported no daily window opening in winter and roughly 20-25% reported no window opening during other seasons. This indicates an ongoing need for mechanical ventilation, as a substantial fraction of the population will not open windows to provide natural ventilation on a regular basis.
9. The envelope air tightness of California homes built 2012-2017 appears roughly similar to airtightness of homes built in the early 2000s, with over 80% of the homes falling in the range of 3–6 ACH50 under depressurization conditions. Only four of the study homes had envelopes tight enough to meet the 3 ACH50 requirement of the 2018 International Energy Conservation Code.
10. When operated with compliant dwelling unit mechanical ventilation and with windows closed, recently constructed homes appear as a group to have much lower formaldehyde than homes constructed a decade earlier and ventilated according to the owner's preference (CNHS). HENGH homes had a mean of 20 ppb and median of 18 ppb whereas CNHS homes had a mean of 36 ppb and median of 29 ppb of formaldehyde. The lower formaldehyde appears to result from both lower emissions and greatly reducing the number of homes that are severely under-ventilated. The mean emission rate calculated from 61 HENGH homes with required data was 6.8 $\mu g/m^3$-h. The mean of 99 CNHS homes with required data was 13 $\mu g/m^3$-h.
11. The time-averaged concentrations of fine particulate matter ($PM_{2.5}$) in the HENGH study homes (median of 5.0 $\mu g/m^3$) were generally lower than those reported in a subset of the California new homes studied a decade earlier (CNHS, median of 10.4 $\mu g/m^3$). And the ratio of indoor median to outdoor median decreased from roughly 0.8 for the CNHS homes to roughly 0.5 in the HENGH homes. If indoor emissions of $PM_{2.5}$ were not greatly different, this result suggests that more recently constructed homes may be providing a higher level of protection from outdoor particles. Further analysis is needed to resolve the factors that could be leading to these results.
12. Despite having and using gas cooking appliances – cooktops were used 7 or more times in 38 homes and 15 or more times in 8 homes – the time-averaged nitrogen dioxide (NO_2) concentrations in study homes were not much higher than in the CNHS study, in

which 98% had electric cooking appliances. It is still possible that some HENGH homes may have had high concentrations of NO_2 over short periods when cooking occurred. Time resolved NO_2 data collected with a sensor-based IAQ monitor will be analyzed in the future to evaluate this question.

13. Our simulation results suggest that the adopted changes to fan sizing in the 2019 Title 24 results in relative exposures close to one (i.e., meeting the IAQ requirements set forth in ASHRAE 62.2 -2016) across a wide range of homes and climates. Relative to the ASHRAE 62.2-2016 method, the adopted T24 2019 fan sizing method over-ventilates leaky homes (3 and 5 ACH50), with increased site energy consumption ranging from 70 to, 1,400 kWh/year, when averaged across climate zones. Unless occupant pollutant exposure is allowed to increase by 5-10% relative to target rates, then an airtightness limit (suggested to be 3 ACH50) will have very marginal statewide weighted average savings of roughly 1% of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5% are possible through airtightening. If pollutant exposure is held constant in new California homes, then energy savings from airtightening will be well below 1%.

Recommendations

In light of the findings that acceptable indoor air quality was achieved in almost all homes built to meet the 2008 or more recent Title 24 Building Energy Efficiency Standards, and that IAQ was generally improved relative to homes constructed before mechanical ventilation was required, we strongly recommend that the core ventilation requirements of dwelling unit and local exhaust ventilation should remain in the Title 24 Building Energy Efficiency Standards for the foreseeable future.

In light of the finding that many of the range hoods and most of the over the range microwave exhaust fans could achieve the required 100 cfm of airflow only at medium or higher speeds (which are likely louder than 3 sones), and that some OTRs could not achieve 100 cfm even at the highest setting, we recommend that builders pay more attention to selecting range hoods and OTRs that are certified by the Home Ventilating Institute as meeting the airflow and sound requirements and also take care to install low resistance ducting to maximize range hood and OTR airflow. We recommend that the Commission engage with HVI efforts to develop a certification for capture efficiency tests for range hoods and consider adding an explicit capture efficiency requirement for range hoods. An important caveat to this finding is that the OTR airflows could be biased low based on the measurement method, which required taping over the air inlets provided at the front top of some OTRs.

Recognizing that many homes were not using their dwelling unit mechanical ventilation systems when first visited by the research team, and the additional findings that the control switches in the majority of homes did not have clear labeling and those with clear labels were much more likely to be operating, we recommend that the Commission and the building industry work together to ensure that ventilation system controllers or switches in all new homes are equipped with *durable and understandable* labels describing their purpose and the importance of operating the dwelling unit mechanical ventilation system.

Confirming airflows in supply ventilation systems presents a general challenge for demonstrating compliance with ventilation standards. In this study, we encountered four homes with supply ventilation systems that could not be measured to verify airflows without substantial effort. There were accessibility challenges both with the exterior roof level inlets (which could only be reached with an extension ladder) and with ducts, which were encased in spray foam insulation. This indicates a need to find alternative measurement approaches to show compliance. One possibility is to add a requirement to the Title 24 Building Energy Efficiency Standards that ventilation equipment must incorporate an onboard diagnostic or technology to verify airflow as installed. We recommend that the Commission coordinate with entities that develop field methods to measure airflow for ventilation systems (e.g., RESNET Standard 380) to address this challenge.

Implementing the Title 24 2019 fan sizing approach had lower pollutant exposure and higher energy consumption than the ASHRAE 62.2-2016 method and gave consistent robust results with little variation in exposure across a wide range of homes and climates. If new home envelopes are tightened to below 3 ACH50 and ventilation fans are sized using the 2019 Title 24 requirements, exposure will increase by about 5% in new homes, while total HVAC energy use will be reduced by roughly 3%.

GLOSSARY

Term	Definition
ACH50	Air changes per hour at a pressure different of 50 Pascals between the living space and outdoors
AER	Air Exchange Rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CalCERTS	California's Home Energy Rating System (HERS) provider
CalEPA	California Environmental Protection Agency
CFM	Cubic feet per minute
CHEERS	California's Home Energy Rating System (HERS) Provider
CNHS	California New Home Study – the precursor to this study that investigated homes pre-mechanical ventilation requirements
CO_2	Carbon Dioxide
DeltaQ	DeltaQ Test – for measuring building envelope and duct leakage
EPIC	Electric Program Investment Charge
GTI	Gas Technology Institute
HENGH	Healthy Efficient New Gas Homes – the title of this study
IAQ	Indoor Air Quality
LBNL	Lawrence Berkeley National Laboratory
MERV	Minimum Efficiency Rating Value – a rating for air filters for removing particles. A higher value implies more removal of smaller particles.
NO	Nitrogen Monoxide – a byproduct of combustion
NO_2	Nitrogen Dioxide – a byproduct of combustion
NO_X	Various oxides of nitrogen – byproducts of combustion
Pa	Pascal
ppb	Parts per billion
PG&E	Pacific Gas and Electric Company
ppm	Parts per million

Term	Definition
$PM_{2.5}$	Particle mass less than 2.5 microns in diameter – usually expressed as a concentration in mass per unit volume
OEHHA	Office of Environmental Health Hazard Assessment
OTR	Over-the-range microwave
REL	Reference Exposure Level
RESNET	The National Home Energy Rating Network
SoCalGas	Southern California Gas Company
Title 24	California Building Energy Efficiency Standards
ug/m^3	Microgram per meter cube
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound

REFERENCES

ASHRAE. 2007. ASHRAE Standard 62.2-2007. Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. ASHRAE, Atlanta, GA.

ASTM E1554-2013, Standard Test Methods for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization. ASTM International, West Conshohocken, PA

Chan, WR, J Joh, and MH Sherman. (2013) Analysis of Air Leakage Measurements of US Houses, *Energy and Buildings,* **66**, 616-625.

Chan, WR, RL Maddalena, JC Stratton, T Hotchi, BC Singer, IS Walker, and MH Sherman. 2016. Healthy Efficient New Gas Homes (HENGH) Pilot Test Results. Lawrence Berkeley National Laboratory, Berkeley, California. LBNL-1005818

Chan, WR, YS Kim, BC Singer, IS Walker, and MH Sherman. 2016. Healthy Efficient New Gas Homes (HENGH) Field Study Protocol. Lawrence Berkeley National Laboratory, Berkeley, California. LBNL-1005819

Eklund, K., Kunkle, R., Banks, A. and Hales, D. (2015) Pacific Northwest Residential Effectiveness Study - FINAL REPORT Portland, OR, Northwest Energy Efficiency Alliance, Prepared by Washington State University Energy Program, NEEA Report #E15-015.

ICC. (2018). International Energy Conservation Code. International Code Council.

Kim, Y-S., Walker, I.S. and Delp, W.W. (2018). Development of a Standard Capture Efficiency Test Method for Residential Kitchen Ventilation. Science and Technology for the Built Environment. Vol. 24, No. 2. doi:10.1080/23744731.2017.1416171

Less, B, IS Walker, and MH Sherman. 2018. Fan Sizing and Airtightness Requirements for New California Homes. Lawrence Berkeley National Laboratory, Berkeley, California. LBNL Report Number Pending.

Mullen, N.A., Li, J., Russell, M.L., Spears, M., Less, B.D. and Singer, B.C. (2016) Results of the California Healthy Homes Indoor Air Quality Study of 2011-2013: impact of natural gas appliances on air pollutant concentrations, *Indoor Air*, **26**, 231-245.

Offermann, F. (2009). *Ventilation and Indoor Air Quality in New Homes* (No. CEC-500-2009-085). California Energy Commission.

Park, J. and Ikeda, K. (2006). Variations of formaldehyde and VOC levels during 3 years in new and older homes. Indoor Air; 16: 129-135. doi:10.1111/j.1600-0668.2005.00408.x

Parthasarathy, S., Maddalena, R.L., Russell, M.L., and Apte, M.G. (2011) Effect of Temperature and Humidity on Formaldehyde Emissions in Temporary Housing Units, Journal of the Air & Waste Management Association, 61:6, 689-695. DOI: 10.3155/1047-3289.61.6.689

Price, P. P., Sherman, M., Lee, R. H., and Piazza, T. (2007) *Ventilation Practices and Household Characteristics in New California Homes*. California Energy Commission Report number CEC-500-2007-033. Final Report, ARB Contract 03-326.

Price, P. and Sherman, M.H. (2006). Ventilation Behavior and Household Characteristics in New California Houses. Lawrence Berkeley National Laboratory Report number LBNL 59620.

Singer, B.C., Delp, W.W., Black, D.R., and Walker, I.S. (2017) Measured performance of filtration and ventilation systems for fine and ultrafine particles and ozone in an unoccupied modern California house. *Indoor Air* 27(4) 780-790. doi:10.1111/ina.12359

Sonne, J.K., Withers, C. and Vieira, R.K. (2015) Investigation of the effectiveness and failure rates of whole-house mechanical ventilation systems in Florida, Vol. Final Report, Cocoa, FL, Florida Solar Energy Center, FSEC-CR-2002-15.

Stratton, J.C., Walker, I.S. and Wray, C.P. (2012) Measuring Residential Ventilation System Airflows: Part 2 - Field Evaluation of Airflow Meter Devices and System Flow Verification, Berkeley, CA, Lab, L. B. N., Lawrence Berkeley National Lab, LBNL-5982E.

Walker, I.S., Wray, C.P., Dickerhoff, D.J. and Sherman, M.H. (2001) Evaluation of flow hood measurements for residential register flows, Berkeley CA, Lawrence Berkeley National Laboratory, LBNL-47382.

APPENDIX A:
IAQ Survey Results from the Healthy, Efficient, New Gas Homes Study

(Appendix A provided in a separate document.)

APPENDIX B:
Title 24 Fan Sizing and Airtightness Requirements for New California Homes

(Appendix B provided in a separate document.)

APPENDIX C:
Healthy Efficient New Gas Homes (HENGH) Pilot Test Results

(Appendix C provided in a separate document.)

APPENDIX D:
Daily Activity Log and Occupant Survey

(Appendix D provided in a separate document.)

APPENDIX A:
IAQ Survey Results from the Healthy, Efficient, New Gas Homes Study

Abstract

As a part of the Healthy Efficient New Gas Homes (HENGH) project, an occupant survey was conducted to obtain information about mechanical ventilation characteristics and occupant satisfaction of new homes. This survey was conducted by Lawrence Berkeley National Laboratory (LBNL) using the web-based LimeSurvey tool. The online survey contains 56 questions and takes approximately 20 minutes to complete. A total of 3,853 participants started the survey, of which 2,781 participants (72%) completed Part I of the survey, and 2,648 (69%) completed both parts of the survey. Basic statistics of the survey responses were summarized using all valid responses. In addition to summarizing survey data, statistical analyses were performed to characterize potential associations between IAQ satisfaction, comfort, and health indicators (i.e., any person in household with diagnosed allergy and/or asthma) with household parameters, such as floor area, number of occupants, kitchen and bathroom ventilation, window opening, and use of air cleaners. Logistic and ordinal logistic regression was used to characterize the relationship between a set of explanatory variables and the response parameter. Most surveyed homes are single-family detached homes, built between 2002 and 2006. Survey respondents were generally more satisfied with the indoor air quality in their home than the outdoor air quality near where they live. But because survey respondents tend to associate indoor air quality with other indoor environmental conditions, such as thermal comfort, air movement, and dryness, the term "indoor air quality" potentially has many meanings that could complicate interpretation of the survey data.

1 Background

The goals of the Healthy Efficient New Gas Homes (HENGH) project were to measure indoor air quality (IAQ) and document mechanical ventilation system characteristic in homes that were built to meet California's 2008 Title 24 Building Code (CEC, 2008). As a complement to the field study, a web-based survey was conducted to obtain information about mechanical ventilation characteristics and occupant satisfaction in homes built to the 2008 standards and also to homes built to directly preceding versions of the standards. Data were collected on the following parameters:

- Location and date of construction.
- House and household characteristics.
- Types of mechanical ventilation equipment and gas appliances installed, and how they are used.
- Occupant satisfaction with IAQ and other indoor environmental parameters.

- Occupant activities related to IAQ, such as window opening and use of an air cleaner.

Survey respondents were also asked if they would be interested in participating in the field study, in which indoor air quality and mechanical ventilation performance data were collected. This document describes the results of the occupant survey.

2 Method

2.1 Survey Description

This survey was conducted by Lawrence Berkeley National Laboratory (LBNL) using LimeSurvey, an open source online survey application. All survey data submitted by respondents is stored securely on a LBNL data server. The online survey contained 56 questions and was designed to enable most respondents to complete it in approximately 20 minutes. Invitations to participate in the self-administrated survey were sent to Southern California Gas Company (SoCalGas) customers by e-mail (see Appendix A-1). SoCalGas reached out to approximately 120,000 customers by email between June and September 2015. In addition, LBNL also advertised the survey through other professional contacts in the field of indoor air quality and energy efficiency.

The complete list of survey questions are given in Appendix A-2). The survey was reviewed and approved by LBNL's Institutional Review Board for Human Subjects Research. There were three mandatory eligibility questions: house type, year built, and zip code. Also, before start the survey, participants had to self-certify that they were 18 or order. Survey respondents had to live in a single-family detached house, townhouse, or duplex built in 2002 or later, with a California zip code. All subsequent questions were optional, meaning that survey respondents could skip any questions that they did not want to answer or for which they did not know the answer.

Table 1 summarizes the types of questions asked in the survey. The survey had two parts. The first part was a short survey on household indoor air quality (IAQ) satisfaction and characteristics. The second part asked follow-up questions with more details and it designed to take about 15 minutes to complete. A $100 sweepstake was available to all respondents regardless if they completed the survey or not, provided that they submit their contact information for notification purposes.

Table 1 Summary of survey questions.

	Survey Part I
Eligibility Questions	House type
	Year built
	Zip code
Home and Household Characteristics	Size of home
	Number of occupants
	Presence of natural gas appliance
	Mechanical ventilation equipment
Air Quality Satisfaction	Indoor air quality
	Outdoor air quality
Comfort Level	Too hot / too cold in some rooms
	Air movement
	Air dryness
	Musty odor
	Survey Part II
Detailed Home Characteristics	Number of stories
	Foundation type
	Number of bedrooms
	Number of bathrooms
	Garage type
	Year moved in
	Ownership
Natural Gas Appliances	Gas appliance locations
	Forced air system particle filtration

Kitchen Range Hood / Exhaust Fan	Kitchen ventilation type and usage
Bathroom Exhaust Fan	Bathroom exhaust fan control
Mechanical Ventilation System	Particle filtration type (outside air) User knowledge and satisfaction
Window Opening	Usage by season
Occupancy and Indoor Activities	Occupied hours Cooking activities Other activities: smoking, burning candles, vacuuming, cleaning agent use, spray use, pesticide spray use, solvent use, humidifier use, dehumidifier use
Other Indoor Sources	Air freshener use Wearing shoes Pets
Use of Air Cleaners and Health Indicators	Air cleaner use and location Asthma Allergy
Demographic Information	**Age** **Education** **Race** **Income**

The online survey contained several features to help respondents answer questions to the best of their knowledge. Example photos of mechanical ventilation systems and air filters were included in the survey (see Appendix A-2) to help respondents identify the type of equipment that they have in their home. Because it is difficult to identify particle filters by the physical appearance alone, common efficiency ratings used by leading filter manufacturers and retailers – e.g., 3M's MPR (microparticle performance rating), Home Depot's FPR (filter performance rating) – were also described in the survey to help respondents report the efficiency of their filter. The online version of the survey used logical and "piping" features to allow respondents skip or customerized a future question based on answer to a previous question.

2.2 Survey Responses

A total of 3,853 participants started the survey, of which 2,781 participants (72%) completed Part I of the survey, and 2,648 (69%) completed both parts of the survey. Most survey respondents provided their contact information and participated in the $100 sweepstake draw.

Table 2 shows the cities where survey respondents resided based on the zip codes they provided. The majority of them are from the Southern California area. Riverside and Palm Springs had the highest number of participants. Relatively few respondents resided in the Central Valley and coastal parts of Northern California. At the design phase of the survey, it was the intention that the survey would also be advertised to customers in Pacific Gas & Electric service territories, which would have increased the number of respondents in Northern California and some part of the Central Valley. However, due to some difficulties in getting the necessary permission to recruit utility customers, only agreement with SoCalGas was obtained within a time frame that that met the survey timeline.

Table 2 Geographical locations of survey participants (N=2,771).

City	Count (N)	City	N	City	N
Los Angeles	35	Industry	50	Bakersfield	155
Inglewood	60	San Diego	4	Mojave	212
Santa Monica	6	Palm Springs	621	Fresno	1
Torrance	9	San Bernardino	15	Palo Alto	1
Long Beach	21	Riverside	842	Oakland	7
Pasadena	21	Santa Ana	14	San Jose	4
Van Nuys	183	Anaheim	194	Stockton	3
Burbank	7	Oxnard	112	Sacramento	1
North Hollywood	4	Santa Barbara	188	Maryville	1

2.3 Survey Analysis

Univariate statistics of the survey responses were summarized using all valid responses. A few of the responses to open-ended questions were checked for validity, including year built, floor area, and number of occupants. Invalid answers (e.g., year built <1000, number of occupants >100) were discarded. In total, only a small number of responses (about 10) were discarded from this validation check.

In addition to summarizing survey data, statistical analyses were performed to characterize potential associations between IAQ satisfaction, comfort, and health indicators (i.e., any person in household with diagnosed allergy and/or asthma) with household parameters, such as floor area, number of occupants, kitchen and bathroom ventilation, window opening, and use of air cleaners. Logistic and ordinal logistic regression was used to evaluate relationships between potential explanatory variables and a response parameter.

Ordinal logistic regression was used to analyze data because the response variables are in ordered categories, such as those measuring opinion (e.g., very dissatisfied, somewhat dissatisfied, neutral, somewhat satisfied, very satisfied) and frequency (e.g., never, rarely, sometimes, most of the time, always). Also, these values are not continuous. Ordinal logistic regression is able to determine which of the independent variables have a statistically significant effect on the dependent variable. This regression method was used in similar survey studies that investigated the relationships between occupant IAQ satisfaction and IAQ parameters (Frontczak et al. 2012, Zalejska-Jonsson and Wilhelmsson 2013).

In performing the regression analysis, the correlations between survey responses to the different questions were tested to determine whether potential explanatory variables are independent of each other. After that, logistic regression is used for categorical parameters, and ordinal logistic regression for survey responses that have multiple ordered categories to characterize the relationship between explanatory variables and the response parameter.

The statistical software R was used for the statistical analysis. For ordinal logistic regression analysis, this study used the **polr** command from the **MASS** package to estimate an ordered logistic regression model. In performing the regression, survey responses with any missing data were excluded from the set of explanatory variables and the response parameter being analyzed. Results of regression analysis are reported in the form of odds ratios to describe the effect of explanatory variables on the response parameter.

For example, an ordinal logistic regression is performed to characterize the relationship between occupant indoor air quality satisfaction and explanatory variables. Equation (1) is the ordinal logistic regression model.

$$\log\left(\frac{P(Y\le k)}{P(Y>k)}\right) = a_k + b_1x_1 + b_2x_2 + b_3x_3 + \cdots \quad (1)$$

where P is the probability of indoor air quality satisfaction (Y) greater or less than a certain rating (k), $b_1 \ldots b_n$ are regression coefficients, and $x_1, x_2 \ldots x_n$ are explanatory variables. Odds ratios (OR) are used to describe the impact of explanatory variables on the response variable, which quantify the odds of increasing IAQ satisfaction by one rating unit (e.g., from 0 to 1, from 1 to 2, etc.) as a result of one unit increase in each of the explanatory variable.

$$Odds\ Ratios(OR) = \frac{P(Y\ge k\ |x_1=1)/P(Y<k|x_1=1)}{P(Y\ge k\ |x_1=0)/P(Y<k|x_1=0)} = \frac{\exp[a_k+b_1(1)]}{\exp[a_k+b_1(0)]} = e^{b_1} \quad (2)$$

When the OR is greater than 1, the impact of the explanatory variable(s) on the response variable is positive. When the OR is less than 1, the impact is negative.

3 Results and Discussion

3.1 Summary of House and Household Characteristics

Table 3 summarizes the characteristics of survey participants. Most respondents (97%) lived in single-family detached homes and most (91%) were homeowners. Most homes (63%) were between 140 and 279 m^2 (1,500–3,000 ft^2). There were similar numbers of single (49%) and two-story (48%) homes. Homes tended to have either 3 (30%) or 4 (37%) bedrooms. Most homes (72%) had 3 or more bathrooms. Almost half of the homes (46%) were occupied by two or fewer occupants.

Most homes (76%) were built between 2002 and 2006, before the 2007 housing market crash. There were very few responses about homes (N=28) built after 2011, which is the earliest year that the homes were very likely to have been built to the 2008 Title 24 code. Most homes built during the years of 2008-2010 were permitted prior to the 2008 Code taking effect. Still, almost three-quarters of the homes in the survey dataset were built post 2003, which was the build year of homes that were surveyed by a prior study (CEC, 2007) on occupant satisfaction with mechanical ventilation, indoor air quality, and comfort.

Survey respondents were asked to indicate all races/ethnicities of people living in their household. This means that there may have been more than one answer for each survey completed. White, Caucasian is the most common (53%), followed by Hispanic/Latino (17%) and Asian or Pacific Islander (14%). The majority (60%) of heads of household of the surveyed homes had a college or more advanced degree. Almost half of the households (46%) had a combined income of above $100,000.

Table 4 shows the characteristics of gas appliances and mechanical ventilation systems. Survey respondents were asked to select all gas appliances they had in their homes. Since the survey participants were SoCalGas customers, most of homes had natural gas appliances. Most homes had a central gas furnace (88%), gas water heater (89%), and used gas for cooking (92% had gas cooktop). In addition, 85% indicated that they had a gas clothes dryer, and 72% had a gas fireplace. Gas furnaces were most commonly installed in the attic (73%) and water heater were most commonly installed in the garage (87%). Six percent of respondents did not know where their furnace was located and 12% did not know where their water heater was located.

Most survey respondents indicated that they had a kitchen range hood (91%) and bathroom exhaust fans (91%) in their home. Whole-house fans (18%) were relatively common based on the survey responses. A small percentage of survey respondents (8%) indicated that they had a kitchen exhaust fan separate from the range hood. Few of the respondents (4%) reported having a continuously operating exhaust fan for ventilation.

Most survey respondents (76%) indicated that they were aware that they had a particle air filter in their central forced air system; 4% thought their system did not have a filter and 20% did not know or answered "NA". 2516 respondents answered that they have a particle filter in their center air forced system. About one-third (34%) of the respondents describe their air filter as "traditional, inexpensive" type. A larger fraction of homes (53%) indicated that they have either medium (MERV 8-11) or high (MERV ≥12) efficiency air filters.

Table 3 Summary of basic house and household characteristics in surveyed homes.

Parameter	Survey Response Counts (%)							
Floor Area m2 (ft2)	<140 (<1500)	140–186 (1500–2000)	186–232 (2000–2500)	232–279 (2500–3000)	279–325 (3000–3500)	325–372 (3500–4000)	>372 (>4000)	NA
	198 (7%)	584 (21%)	692 (25%)	568 (20.5%)	354 (13%)	196 (7%)	145 (5%)	34 (1%)
Stories	1	2	3	Other				
	1364 (49%)	1318 (48%)	52 (2%)	37 (1%)				
Year built	2002	2003–2004	2005–2006	2007–2008	2009–2010	>2011		
	346 (12%)	799 (29%)	982 (35%)	473 (17%)	143 (5%)	28 (1%)		
Ownership	Own	Rent	Other	NA				
	2510 (91%)	223 (8%)	9 (0.3%)	29 (1%)				
House Types	Single Family	Town House	Duplex	Other				
	2687 (97%)	69 (2.5%)	15 (0.5%)	0				

Parameter	Survey Response Counts (%)								
Foundation Types	Concrete Slab	Crawlspace	Basement	Don't Know	NA				
	2604 (94%)	63 (2%)	24 (1%)	73 (2.6%)	7 (0.3%)				
Number of occupants	≤2	3	4	5	≥6	NA			
	1228 (46%)	423 (15%)	513 (19%)	291 (11%)	237 (9%)	19 (1%)			
Number of Bedrooms	≤2	3	4	5	≥6	NA			
	269 (10%)	845 (30%)	1026 (37%)	506 (18%)	84 (3%)	38 (1%)			
Number of bathrooms	≤2	3	4	5	≥6	NA			
	749 (27%)	1412 (51%)	388 (14%)	155 (6%)	33 (1%)	34 (1%)			
Education Level	No Schooling	1 to 8th Grade	9th to 12th Grade	Completed High School	Some College	Associate's Degree	College Degree	Graduate Degree	NA
	4 (0.1%)	2 (0.1%)	22 (1%)	140 (5%)	551 (18%)	295 (11%)	845 (30%)	819 (30%)	133 (5%)

Parameter	Survey Response Counts (%)							
Races	American Indian, Alaska Native	Asian or Pacific Islander	Black, African American	Hispanic/ Latino	White, Caucasian	Mixed Race	Other	NA
	62 (2%)	383 (14%)	152 (5%)	469 (17%)	1469 (53%)	31 (1%)	0	205 (7%)
Income	Less than $35,000	$35,000 to $49,999	$50,000 to $74,999	$75,000 to $99,999	$100,000 to $150,000	Greater than $150,000	NA	
	134 **(5%)**	**210** **(8%)**	**399** **(14%)**	**443** **(16%)**	**697** **(25%)**	**595** **(21%)**	**293** **(11%)**	

Table 4 Summary of gas appliances and mechanical ventilation systems in surveyed homes.

Parameter	Survey Response Counts (%)									
Gas Appliance	Central Gas Furnace	Gas Wall Furnace	Free Standing Gas Heater	Gas Water Heater	Gas Cooktop	Gas Oven	Gas Clothes Dryer	Gas Fireplace	None	Don't Know
	2433 (88%)	61 (2%)	112 (4%)	2470 (89%)	2543 (92%)	1695 (61%)	2344 (85%)	2002 (72%)	21 (0.7%)	37 (1%)
Location of Gas Furnace	Attic	Basement or Crawl-space	Attached Garage	Interior Closet	Other Space (Inside Home)	Other Space (Outside Home)	Don't Know	NA		
	1765 (73%)	12 (0.5%)	278 (11%)	57 (2%)	29 (1%)	62 (2.5%)	145 (6%)	85 (3%)		
Location of Water Heater	Attic	Basement or Crawl-space	Attached Garage	Interior Closet	Other Space (Inside Home)	Other Space (Outside Home)	Don't Know	NA		
	23 (1%)	12 (0.5%)	2159 (87%)	42 (2%)	20 (1%)	119 (5%)	12 (0.5%)	83 (3%)		
Location of Clothes Dryer	Laundry Room	Basement or Crawl-space	Attached Garage	Interior Closet	Other Space (Inside Home)	Other Space (Outside Home)	Don't Know	NA		
	2100 (90%)	1 (<0.01%)	77 (3%)	59 (2.5%)	31 (1.3%)	0	1 (<0.01%)	75 (3%)		

Parameter	Survey Response Counts (%)									
Mechanical Ventilation System	Kitchen Range Hood	Kitchen Exhaust Fan	Bathroom Exhaust Fan	Continuous Exhaust Fan	Fresh Air Vent	Heat/ Energy Recovery Ventilator	Whole House Fan	Radon Control System	None	Don't Know
	2516 (91%)	232 (8%)	2521 (91%)	113 (4%)	640 (23%)	38 (1%)	504 (18%)	32 (1%)	20 (1%)	113 (4%)
Particle Air Filter in Central Forced Air System	Yes	No, system does not have a particle air filter	No, does not have a central forced air heating system	Don't Know	NA					
	2103 (76%)	108 (4%)	10 (0.3%)	321 (12%)	229 (8%)					
Particle Air Filter Type	Tradition-al, Inexpensive Filter	Medium Efficiency Filter	High Efficiency Filter	Electro-static Filter	Other	Don't Know	NA			
	725 **(34%)**	**635** **(30%)**	**482** **(23%)**	**99** **(5%)**	**10** **(0.5%)**	**150** **(7%)**	**2** **(<0.01%)**			

Figure 1 to Figure 6 compare some of the basic house characteristics by year built. Homes are grouped into three year-built categories: 2002-2005, 2006-2010, and 2011-2015. Note that only 1 % (28) of homes were built after 2011. Figure 1 shows an increase in mean floor area between 2002 and 2008, and again from 2009 onwards, with a drop between 2008 and 2009 (likely related to 2007 housing market crash). The mean floor area for the three year built-categories show an increasing trend: 2,530 ft² for 2002-2005, 2,630 ft² for 2006-2010, and 2,760 ft² for 2011-2015. Figure 2 shows that there are slightly more multi-story homes built after 2011 in our survey compare to older homes, partly because there are proportionally more multi-story townhomes represented in the 2011–2015 year built group. Most homes have between 2 and 4 occupants (Figure 3) regardless of year built.

Figure 1 Mean floor area of homes built in different years. The red and blue dotted lines show mean floor area of homes built 2002-2005 and 2006-2010, respectively.

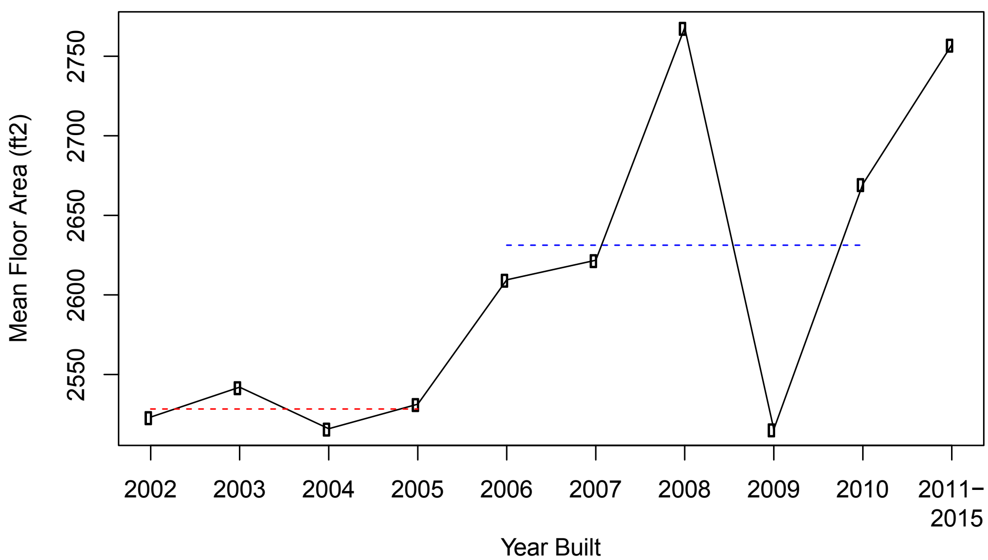


Figure 2 Number of stories of homes built in different years.

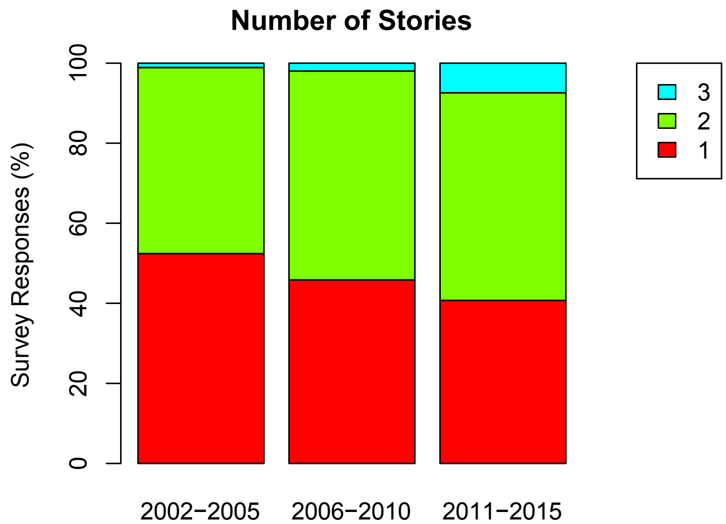
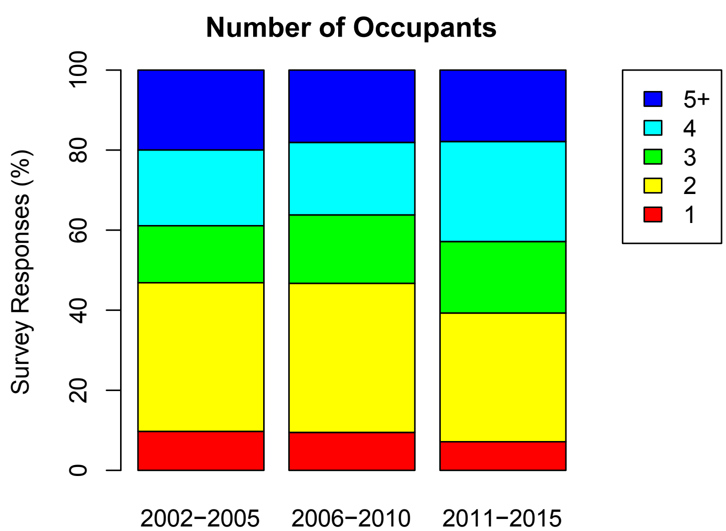


Figure 3 Number of occupants currently living in surveyed homes built in different years.



The prevalence of using natural gas for space heating, water heating, cooking (cooktop), and clothes drying are about the same regardless of year built (Figure 4). "NA" in Figure 4 represents all responses that did not reply "Yes" to the question whether a home has a particular natural gas appliance. "NA" can mean that a home does not have that particular appliance, or the appliance use alternate fuel other than natural gas. Responses that selected "None" or "Don't' know" as the answer when asked to list gas appliances present in their homes are excluded from this comparison.

Kitchen range hood and bathroom exhaust fans are commonly found in the surveyed homes regardless of year built; the other mechanical ventilation equipment is less common ("NA" can mean that a home does not have that mechanical ventilation equipment, or home owners answered they do not know whether they have it or not). Figure 5 did not include a comparison for heat or energy recovery systems (H/ERV) or radon control systems because very few surveyed homes were reported to have them. Continuous exhaust fans, fresh air vents, and whole house fans are slightly more common among homes built after 2011 compared to other homes. Figure 6 shows that similar types of particle filters are reported being used in the central forced air system in surveyed homes regardless of year built. About 20% of survey respondents selected fresh air vent as part of their mechanical ventilation system. In the survey, a photo (see Appendix A-2) that shows a fresh air vent connected to heating and cooling system was provided to help illustrate what it may look like.

Figure 4 Presence of gas appliances in surveyed homes built in different years.

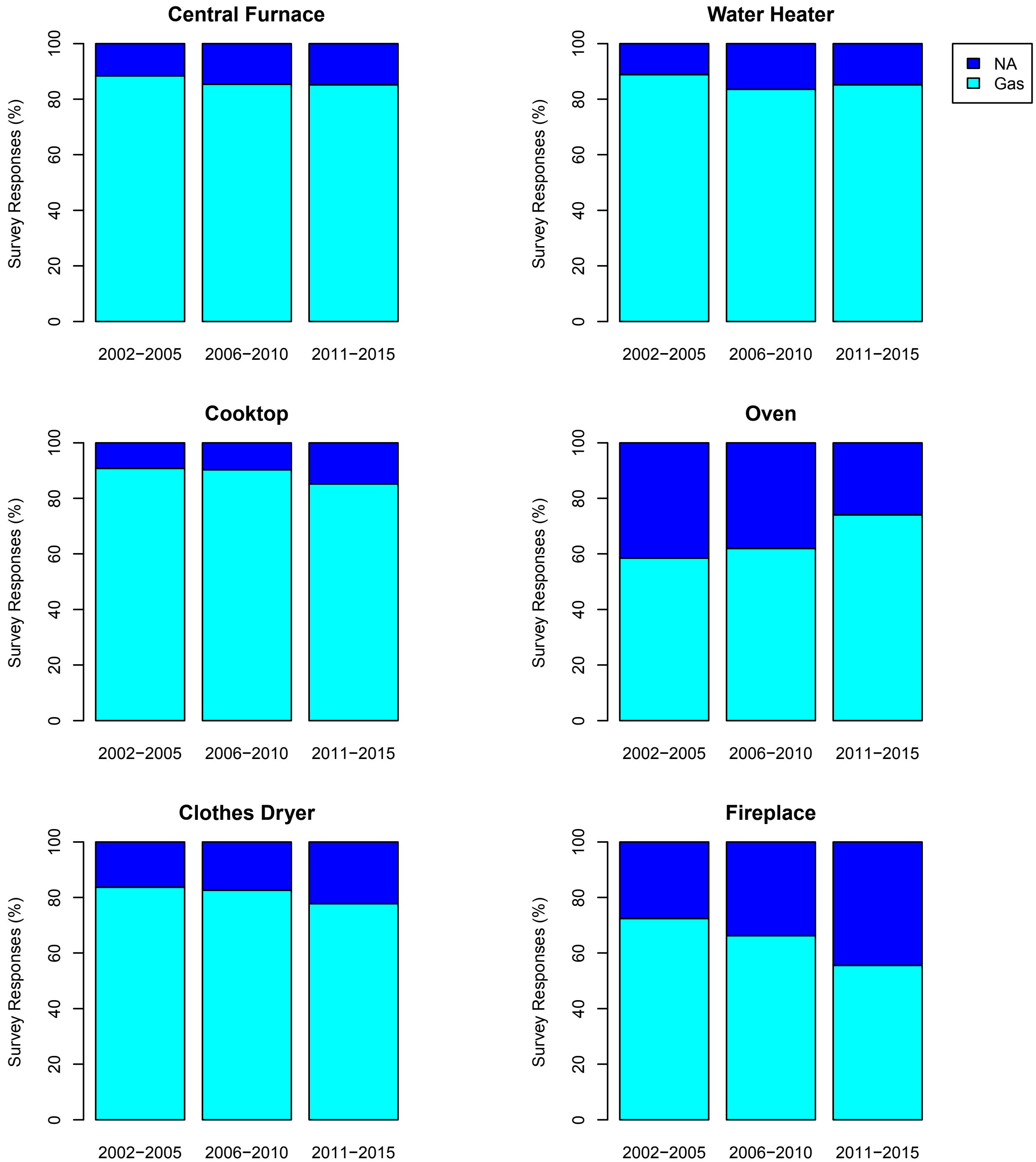


Figure 5 Presence of mechanical ventilation equipment in surveyed homes built in different years.

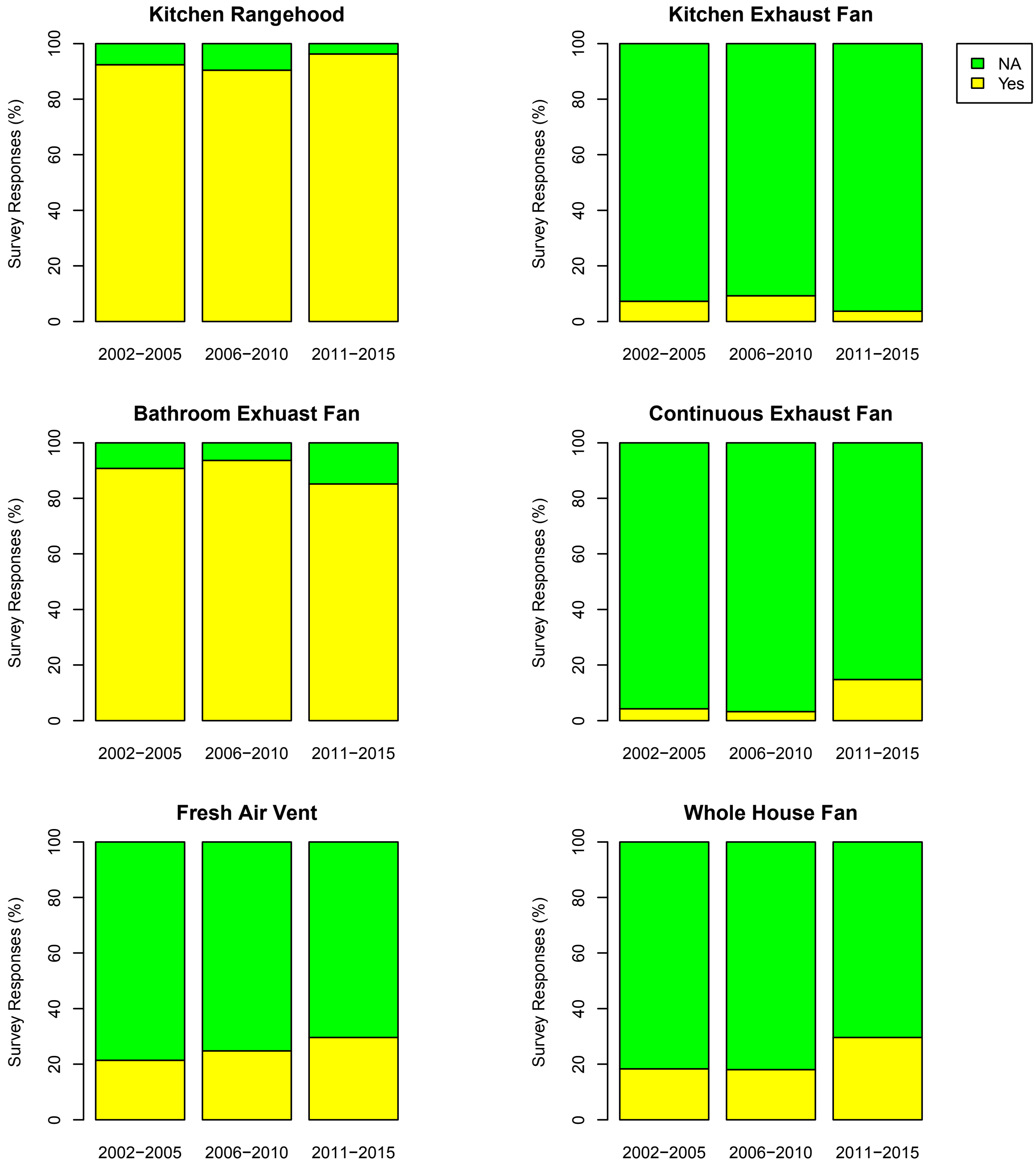
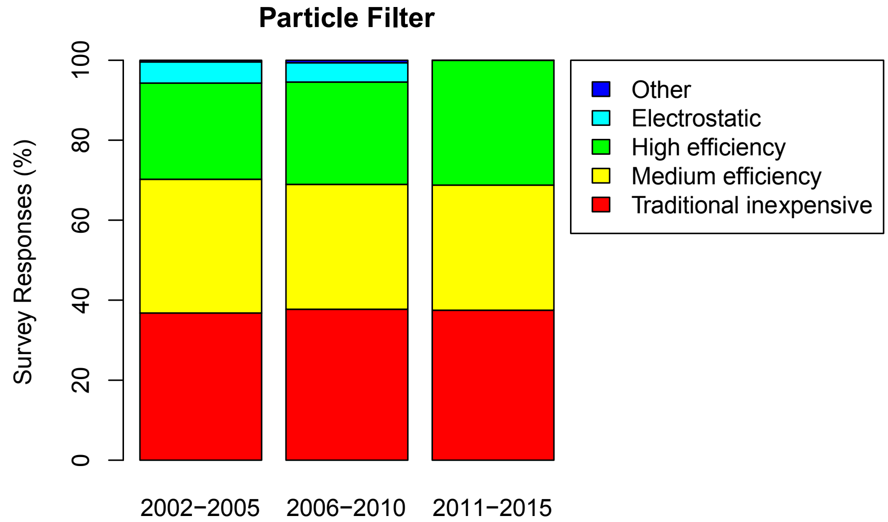


Figure 6 Particle filter types used in central forced air system in surveyed homes built in different years.

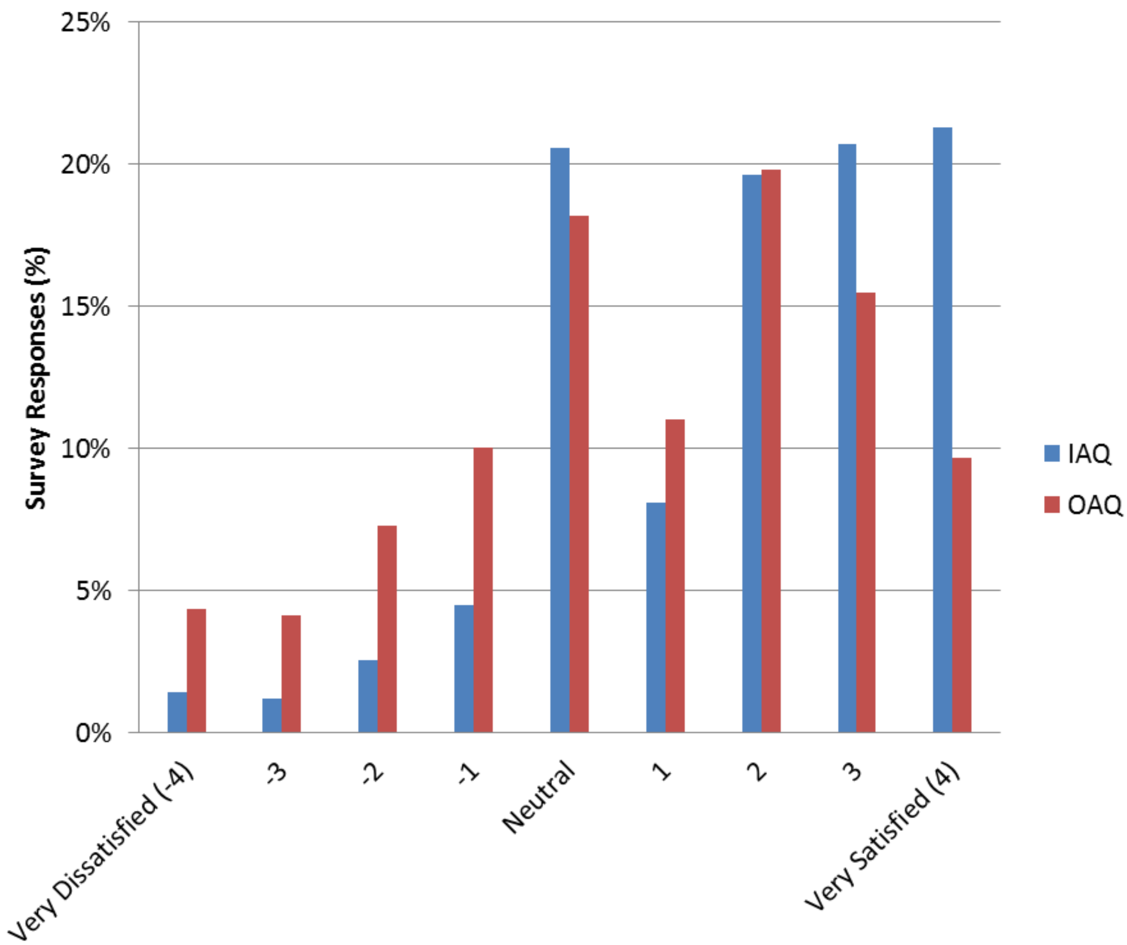


3.2 Occupant Satisfaction with Air Quality and Comfort

3.2.1 Occupant Satisfaction with Outdoor and Indoor Air Quality

Survey respondents were asked to rate their satisfaction with indoor and outdoor air quality. Results are summarized in Figure 7 (see Appendix A-3 for detailed statistics). Survey respondents were generally more satisfied with the indoor air quality in their home than the outdoor air quality near where they live. Twice as many survey respondents were very satisfied (rating = 4) with their indoor air quality (21%), compared to only 10% who were very satisfied with the outdoor air quality. Dissatisfaction (rating <0) with outdoor air quality (26%) is more common than dissatisfaction with indoor air quality (10%).

Figure 7 Occupant satisfaction on indoor air quality (IAQ, N=2,765) and outdoor air quality (OAQ, N=2,766).



3.2.2 Occupant Satisfaction with Comfort

In addition to satisfaction with indoor and outdoor air quality, the survey also gathered data on occupant satisfaction on comfort related to thermal conditioning, air movement, and moisture in their home. Survey respondents were asked the frequency that any occupants felt uncomfortable with air temperature in winter and summer, too much or not enough air movement, air too dry or too damp, or air has musty odor. Appendix A-3 has more detailed statistics of the results.

Figure 8 shows that the most common complaint with regard to thermal comfort is some room(s) being too hot in the summer: 41% of study participants complained that some room(s) are too hot in the summer a few times a week or more often, compared to 20% of study participants who complained of some room(s) being too cold in the winter. Survey respondents were also asked if some room(s) were too warm in the winter or too cool in the summer, which may suggest poor control or distribution of thermal conditioning to different rooms in the house. Only 10% of survey respondents indicated this to be an issue a few times a week or more frequently in either the heating or cooling season ("NA" can mean that the participant did not answer for this question: 3-10% of participants did not answer for this question).

Figure 8 Occupant satisfaction with thermal comfort in their homes.

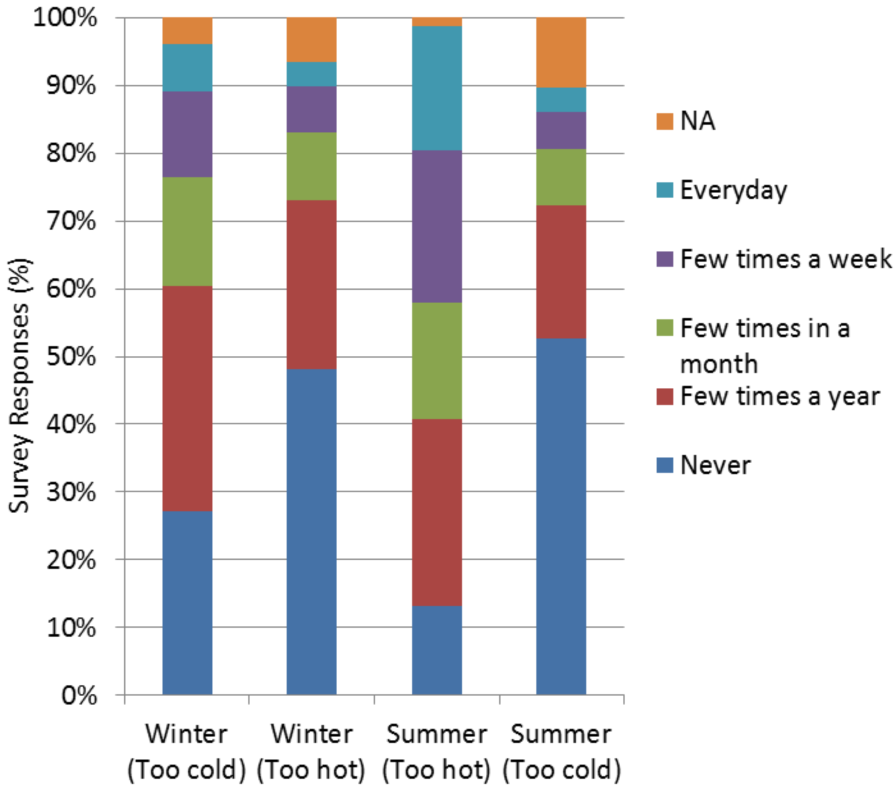
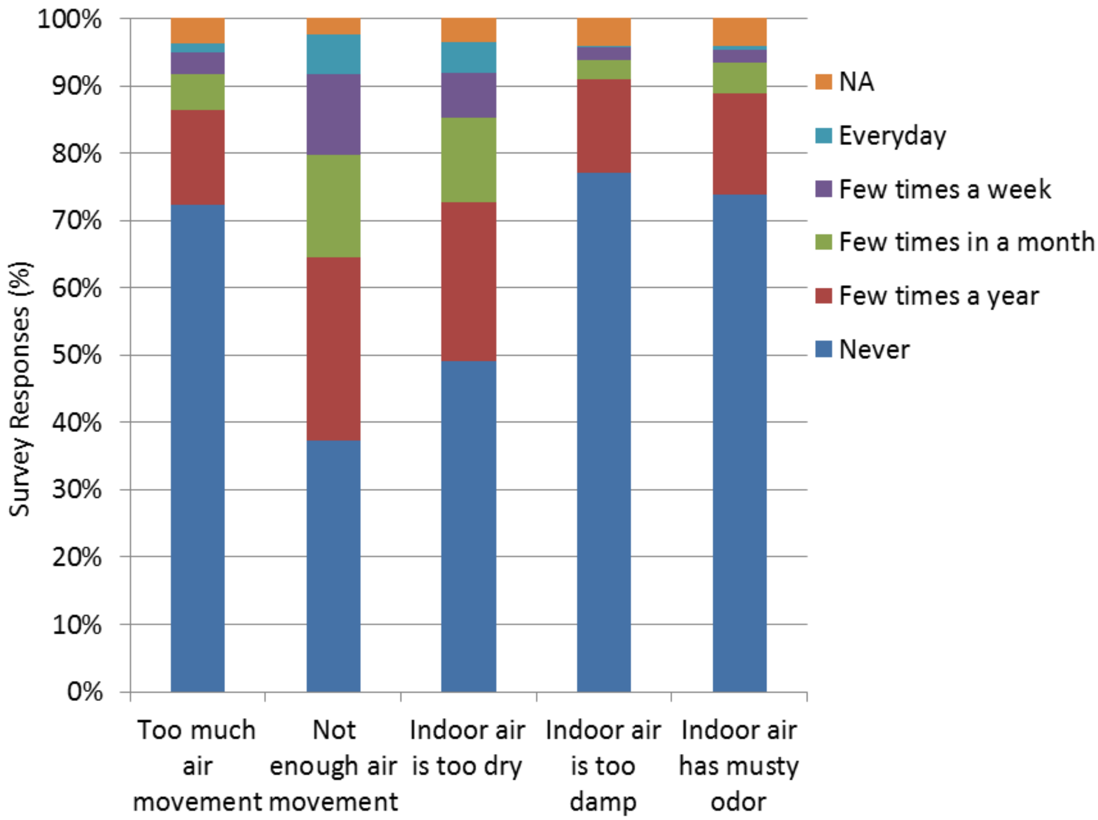


Figure 9 shows that more survey respondents complained about stagnant air (not enough air movement) than draftiness (too much air movement) in their homes. 18% of the responses indicated that stagnant air affects comfort in their home a few times a week or more frequently. Occupants are generally satisfied with the moisture level in their homes. About 12% of survey respondents complained that indoor air is too dry a few times a week or more frequently. Few homes (2%) had excess moisture that adversely impacted the comfort of the survey respondents ("NA" can mean that the participant did not answer for this question: 2 -4% of participants did not answer for this question).

Figure 9 Occupant satisfaction with indoor air movement and moisture level in their homes.



3.2.3 Factors Associated with IAQ Satisfaction

Table 5 to Table 7 summarize results from ordinal logistic regression performed to characterize the relationship between occupant indoor air quality satisfaction and three sets of explanatory variables: (i) house and household characteristics, (ii) thermal comfort, and (iii) indoor environmental conditions associated with air movement and moisture level.

In the survey, self-reported IAQ satisfaction questions used a 9-point scale with endpoints ranging between "very dissatisfied" and "very satisfied." The actual question from the survey is shown below.

IAQ satisfaction: To what extent are you satisfied or dissatisfied with the indoor air quality in your home?

Very Dissatisfied				**Neutral**				**Very Satisfied**
☐	☐	☐	☐	☐	☐	☐	☐	☐

For comfort satisfaction, the survey asked how often does anyone in the home feel uncomfortable in because of temperature, air movement and dryness. A 5-point scale with endpoints ranging between "Never" and "Every day" is used, as shown below.

Thermal comfort: In winter, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times in a month	Few times a week	Every day
Too hot in some room(s).	☐	☐	☐	☐	☐
Too cold in some room(s).	☐	☐	☐	☐	☐

In summer, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too hot in some room(s).	☐	☐	☐	☐	☐
Too cold in some room(s).	☐	☐	☐	☐	☐

Indoor environmental conditions: How often do the following conditions affect the comfort of occupants in your home?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too much air movement.	☐	☐	☐	☐	☐
Not enough air movement.	☐	☐	☐	☐	☐
Indoor air is too dry.	☐	☐	☐	☐	☐
Indoor air is too damp.	☐	☐	☐	☐	☐
Indoor air has musty odor.	☐	☐	☐	☐	☐

For house characteristics, the survey asked respondents to provide the house size and number of occupants. Also, the survey asked the respondent to indicate which ventilation equipment was present from a list that included fresh air vent, continuous operating ventilation exhaust fan, kitchen exhaust fan, bathroom exhaust fan, HRV (Heat Recovery Ventilator) or ERV (Energy Recovery Ventilator), Whole house fan, Radon control system and others.

Regression results are presented in terms of proportional odds ratios (OR), which quantify the odds of increasing IAQ satisfaction by one rating unit (e.g., from 0 to 1, from 1 to 2, etc.) as a result of one unit increase in each of the explanatory variables (e.g., for this analysis, never = 0, few times a year = 0.1, few times a month = 1, few times a week = 3, every day = 7). The results, provided in Table 5, shows that the number of occupants and the presence of fresh air vent are the parameters that have a p-value <0.05 (highlighted in bold font) associated with IAQ satisfaction. p-value <0.05 is used to test the null hypothesis that OR = 1 (i.e. no effect). OR = 0.87 means that each additional occupant would change the odds of increasing IAQ satisfaction by one rating unit by 0.87, i.e. increasing number of occupants in household would likely decreases the overall IAQ satisfaction. The 95% confidence interval for this OR is between 0.83 and 0.90. Neither floor area nor number of stories is statistically associated with IAQ satisfaction. Survey respondents, who answered that they have a fresh air vent reported higher ratings with indoor air quality satisfaction (OR = 1.46). But the survey respondents who answered that they have a continuous exhaust fan did not show statistically significant associations with IAQ satisfaction. This is interesting since the purpose of the fresh air vent and the continuous exhaust fan is basically the same: they are used to provide air exchange with the outdoors. However, it is possible that survey respondents can associate the words "fresh air vent" with IAQ more than a "continuous exhaust fan". This can be an endemic issue with surveys that rely on occupants to report on equipment. The potential that a respondent will subconsciously link the terms may be reduced by having these questions separated in the survey. Also, the order of the questions could be reversed, such that IAQ satisfaction is determined prior to priming respondents with the term 'fresh air'. Alternatively, a neutral term could be used to describe the central fan integrated system (e.g., outside air intake on central HVAC).

Table 6 and Table 7 show that thermal comfort and indoor environmental conditions likely have an effect on occupant ratings of IAQ satisfaction.

Table 6 shows that the frequency of discomfort because of some room(s) being too hot in summer (OR=0.85), and some room(s) being too cold in winter (OR=0.94), are both negatively associated with IAQ satisfaction. Table 7 shows that discomfort because of musty odor lowers the odds of IAQ satisfaction (OR=0.70). Other factors that are also negatively associated with IAQ satisfaction include not enough air movement (OR = 0.80) and indoor air being too dry (OR = 0.86). Factors that suggest more potential sources of indoor pollutants (e.g., number of occupants) and increasing the discomfort of odor issues (e.g., musty odor) are negatively associated with IAQ satisfaction ratings. Musty odor is likely a result of persistent dampness in the home. However, a higher reported frequency of from indoor air being too damp does not have a statistically significant association with occupant rating of IAQ satisfaction (Table 7). This may be because occupants do not perceive excess moisture or dampness as a reason for causing discomfort, unlike musty odor. The previous California new home study also found similar results: i.e., that people expect and are willing to accept a certain amount of moisture and discomfort and do not consider these to be unacceptable for overall IAQ satisfaction (CEC, 2007).

Table 5 Odds ratios of IAQ satisfaction improving with specific house or household characteristic.

House or Household Characteristics	Indoor Air Quality Satisfaction (N=2,686)			
	Odds Ratio	95% Confidence Interval		p-value
		2.5%	97.5%	
Floor area*	1.11	0.64	2.17	0.64
Number of stories	0.96	0.85	1.09	0.57
Number of occupants	**0.87**	**0.83**	**0.90**	**3e-10**
Presence of fresh air vent	**1.46**	**1.24**	**1.72**	**4.3e-06**
Presence of continuous exhaust fan	1.13	0.79	1.62	0.50

*Floor area was divided by 929 m2 (10,000 ft2) to transform to a dimensionless parameter in this analysis.

Table 6 Odds ratios of thermal comfort on indoor air quality satisfaction.

Thermal Comfort	Indoor air Quality Satisfaction (N=2,718)			
	Odds Ratio	95% Confidence Interval		p-value
		2.5%	97.5%	
Winter (Too cold in some rooms)	0.94	0.89	0.99	1.2e-02
Winter (Too hot in some rooms)	0.95	0.89	1.01	0.11
Summer (Too cold in some rooms)	0.96	0.90	1.02	0.24
Summer (Too hot in some rooms)	0.85	0.82	0.88	1.7e-22

Table 7 Odds ratios of indoor environmental conditions on indoor air quality satisfaction.

Indoor Environmental Conditions	Indoor air Quality Satisfaction (N=2,578)			
	Odds Ratio	95% Confidence Interval		p-value
		2.5%	97.5%	
Too much air movement	1.01	0.93	1.09	0.85
Not enough air movement	0.80	0.76	0.83	1.3e-24
Indoor air is too dry	0.86	0.82	0.90	1.34e-09
Indoor air is too damp	0.94	0.80	1.11	0.50
Indoor air has musty odor	0.70	0.62	0.79	3.49e-09

3.3 Kitchen Ventilation

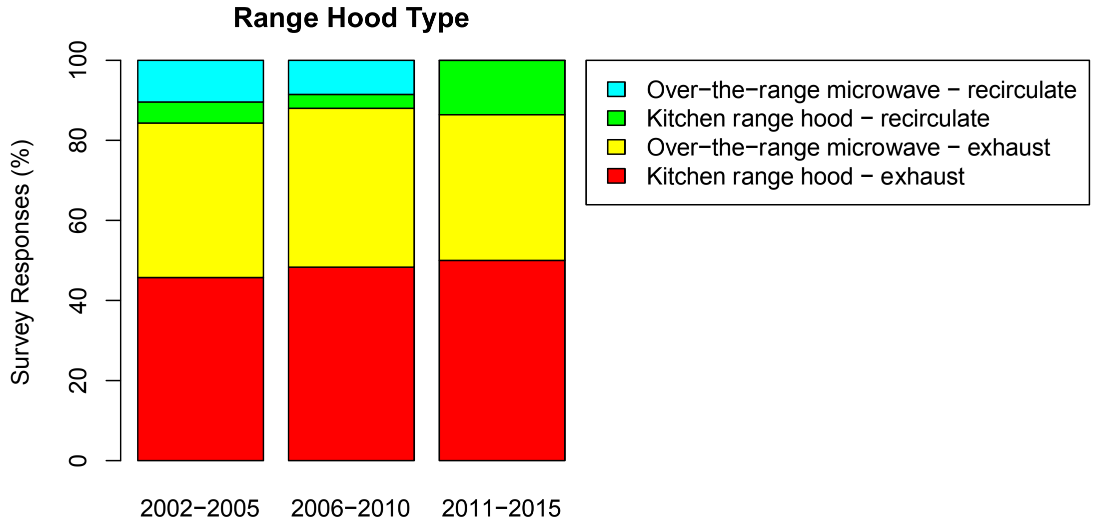
3.3.1 Kitchen range hood types and usage

Survey respondents were asked to identify the type of range hood they have and the frequency of usage. Table 8 shows that a kitchen range hood that exhausts air to the outside is the most common type (43%), followed by an over-the-range microwave that exhausts air to outside (33%). Less common are kitchen range hoods and over-the-range microwaves that recirculate air back into the kitchen (4% and 8%, respectively). Figure 10 shows a slight increase in kitchen range hood that exhausts air to outside comparing homes built 2006-2010 to homes built 2002-2005. Results of the newest year built group (2011-2015) are more uncertain because of the small sample size (N=28) and based on Title 24 (2008), all of these homes should have a kitchen range hood that exhausts air to the outside.

Table 8 Types of range hood present in surveyed homes (N = 2,516).

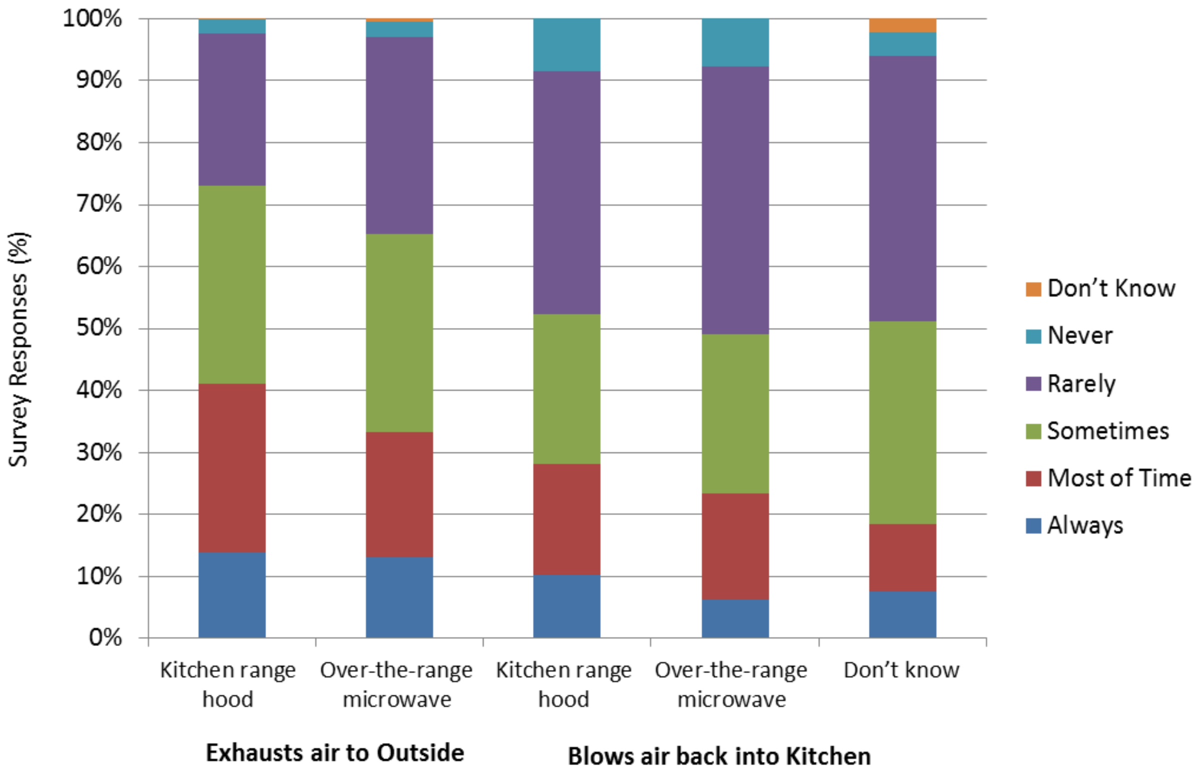
Parameter	Survey Response Counts (%)					
Range Hood Type	Kitchen range hood exhausts air to outside	Kitchen range hood blows air back into kitchen	Over-the-range microwave exhausts air to outside	Over-the-range microwave blows air back into kitchen	Don’t know	NA
	1081 (43%)	107 (4%)	901 (33%)	222 (8%)	131 (5%)	74 (3%)

Figure 10 Kitchen range hood type in homes built in different years (these are percentages of participants who answered other than "don't know")



Survey respondents were asked how often the kitchen range hood is used when cooking with a cooktop. Figure 4 shows that survey respondents who had a range hood that vents to the outside reported using their range hood more frequently than those who had a recirculating range hood. This could reflect occupants observing that the venting range hood is more effective in dealing with pollutants, heat and moisture emitted during cooking. See Appendix A-3 for more detailed statistics on range hood usage frequency.

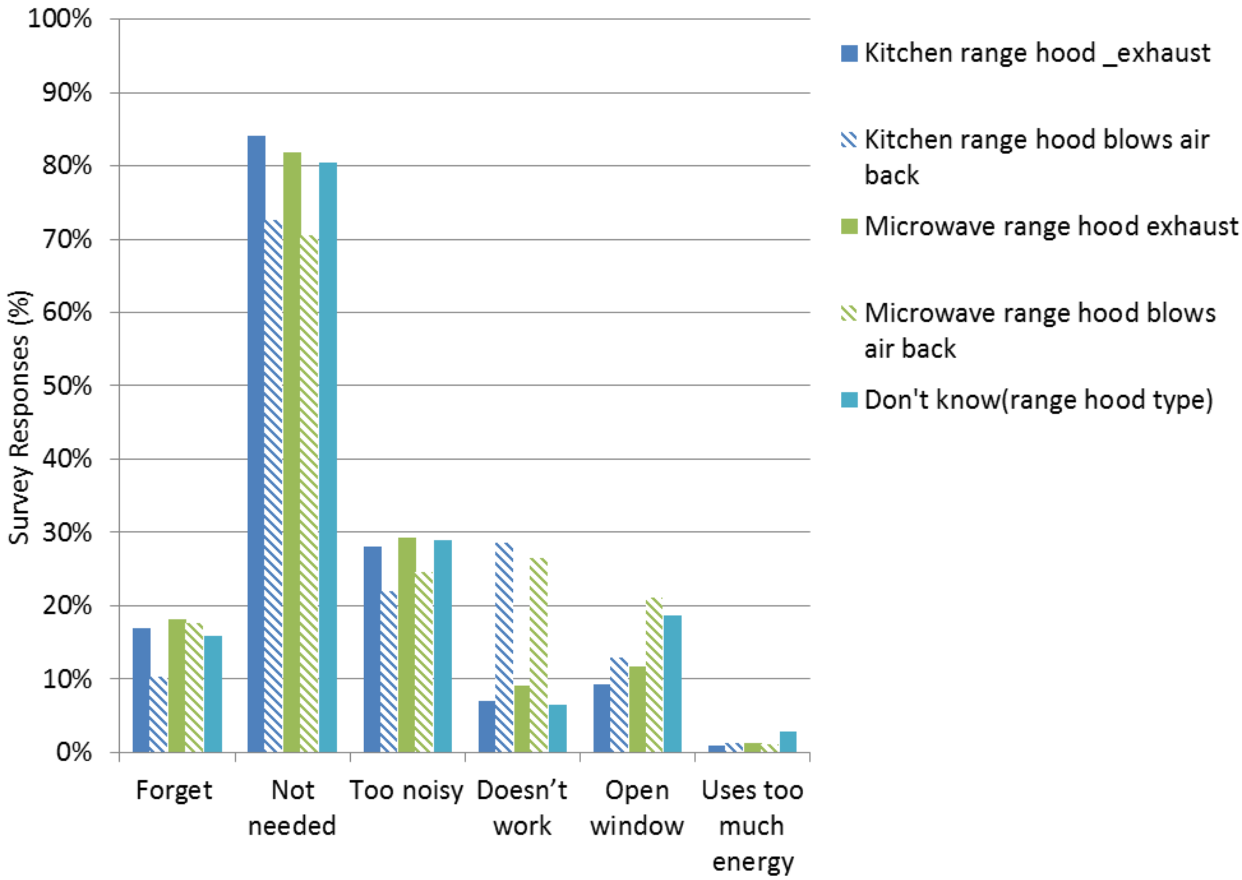
Figure 11 Frequency of the kitchen range hood usage.



Survey respondents who indicated that they use the range hood sometimes or less frequently were asked the reasons for not using the range hood. The respondents could choose more than one answer if applicable. Figure 12 shows that the most common reason for not using the range hood is "not needed for what is being cooked". This suggests that users are making an assessment of the need, presumably based on some observable indicator such as odor, excess moisture, heat or smoke. Range hood being too noisy and forgetting to turn on range hood were other explanations indicated by respondents for not using the range hood; but there were relatively minor compared to the perception that the range hood is not always needed when cooking. Energy use by the range hood was not a common concern among users.

Almost 25% of survey respondents with a recirculating range hood indicated that they do not use their range hood because it is ineffective at removing cooking fumes or odors. In comparison, less than 10% of survey respondents who with a venting range hood indicated that as a reason for not using it. This difference by range hood type suggests that users are aware that range hoods that vent to outside are more effective at removing cooking fumes or odors than ones that blow air back into the kitchen. This may also explain why a relatively higher percentage of survey respondents who have a range hood that blows air back into the kitchen open their windows instead when they cook.

Figure 12 Reasons not for using range hood when cooking with cooktop.



3.3.2 Factors Associated with Range Hood Use

An ordinal logistic regression was performed to characterize whether kitchen range hood types and frequency of cooktop use have statistical significance on range hood use frequency. Survey respondents were asked the frequency of cooktop use for preparing breakfast, lunch, dinner and other meals. The total number of cooktop uses per week was estimated by summing all meals prepared. For self-reported frequency of cooktop usage, a 5-point scale with endpoints ranging between "0 time per week" and "7 times per week" is used, as shown below.

On average, how many times per week is your cooktop and/or oven used for cooking, including boiling water?

	0 time per week	1 to 2 times per week	3 to 4 times per week	5 to 6 times per week	7 times per week
Breakfast	☐	☐	☐	☐	☐
Lunch	☐	☐	☐	☐	☐
Dinner	☐	☐	☐	☐	☐
Other cooking	☐	☐	☐	☐	☐

The regression result is shown in Table 9. Range hood use is positively correlated with the cooking frequency (OR=1.05, P<0.05). As suggested by the comparison shown in Figure 11, range hood types also had statistically significant effects on the frequency of the range hood usage. The frequency of range hood use is reduced when survey respondents indicated that they have a range hood that blows air back to the kitchen (OR = 0.37), or they have an over-the-range microwave range hood that blows air back to the kitchen (OR = 0.46). Survey respondents who do not know the type of range hood they have may be less familiar with their appliance because of infrequent use, so it makes sense that range hood use frequency tends to be lower if the range hood type is unknown.

Table 9 Odds ratios of cooking activity and range hood type on range hood use frequency.

Cooking Activity and Range Hood Type	Range Hood Use Frequency (N=2,561)			
		95% Confidence Interval		
	OR	2.5%	97.5%	p-value
Cooking Frequency (Total Number of Meals per Week)	1.05	1.04	1.07	6.8e-16
Range Hood (Exhaust)	1.09	0.75	1.6	0.64
Range hood (Recirculate)	0.37	0.21	0.65	5.6e-04
Microwave Range Hood (Exhaust)	0.78	0.53	1.16	0.22
Microwave Range Hood (Recirculate)	0.46	0.29	0.73	9.6e-04
Don’t Know (Type Unknown)	0.44	0.26	0.75	0.003

3.4 Bathroom Ventilation

Survey respondents were asked about the type(s) of bathroom exhaust fan control they have in their homes. Table 10 shows that the most common control was a manual on/off switch. Automatic controls, such as a timer, humidity sensor, and/or occupancy sensor were less common overall. The 2008 Title 24 requirements for intermittent local exhaust ventilation do not specify what type of control is used, only that there is a control. Specific controls are specified by some programs, such as the 2013 CalGreen building code which required that bathroom fans must be controlled by a humidistat.

Table 10 Bathroom exhaust fan control type.

Bathroom Exhaust Fan Control Type	Full Bathroom (N = 2,736)	Half Bathroom (N = 1,112)
Auto-on timer control	84 (3%)	28 (3%)
Auto-on humidity sensor	30 (1%)	1 (0.1%)
Auto-on occupancy sensor	23 (1%)	11 (1%)
Comes on when light is turned on	267 (10%)	82 (7%)
Manual on/off switch	2168 (79%)	831 (75%)
On all the time	9 (0.3%)	8 (0.7%)
No exhaust fan	182 (7%)	44 (4%)
NA	316 (12%)	119 (11%)

Figure 13 shows the percentage of homes with automatic bathroom exhaust fan control (left), and homes with manual control (right) in at least one of the full bathroom. Automatic control includes bathroom exhaust fans that are controlled by a timer, humidity sensor, and/or occupancy sensor. Manual control includes bathroom exhaust fans that are controlled by a manual on/off switch, and also those that come on when light is switched on. Survey respondents were asked to enter the number of full bathrooms having each of the control types, meaning that it is possible for homes to have some full bathrooms with automatic control, other full bathrooms with manual control, and/or full bathrooms with both types of control (i.e. the sum of automatic and manual control may not equal 100%). Only homes that the survey respondents indicated presence of an exhaust fan in at least one of their full bathrooms are included in this comparison. Figure 13 shows that while many bathroom exhaust fans are manually controlled, such as by an on/off switch, automatic controls are becoming more common in newer homes.

Figure 13 Bathroom exhaust fan control type in homes built in different years.

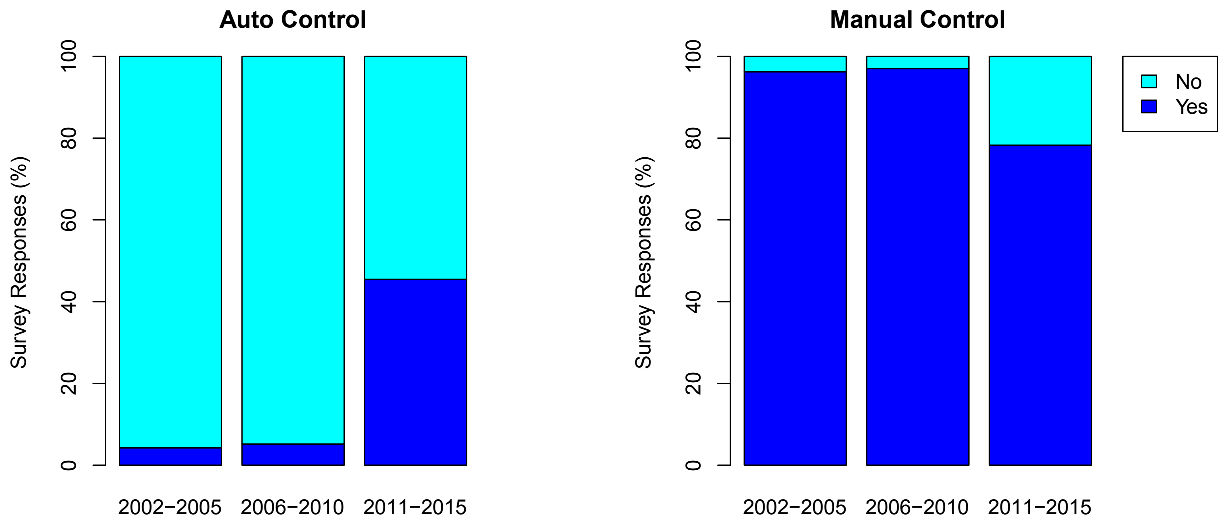


Table 11 shows the ordinal logistic regression results of selected house characteristics, including the number of bathroom exhaust fans, on survey respondents reported frequency of discomfort from musty odor in their homes. Results suggest that there is a negative association (OR < 1) between number of bath fans and frequency of discomfort due to musty odor (OR=0.94, P<0.05). On the other hand, increasing the number of occupants has a positive association (OR > 1) with the frequency of discomfort from musty odor in their homes (OR=1.18, P<0.05). These results suggest that bathroom exhaust fans may be helpful to reduce the frequency of musty odor causing discomfort in homes, whereas more occupants is a risk factor. To keep this analysis simple, the number of bathroom exhaust fans was not normalized by number of bathroom or floor area. Instead, floor area is included as one of the explanatory variables. However, floor area is not found to be statistically significant in this regression analysis. The number of occupants normalized by floor area is also not statistically associated with the frequency of discomfort from musty odor.

Table 11 Odds ratios of selected house characteristics on frequency of discomfort from musty odor.

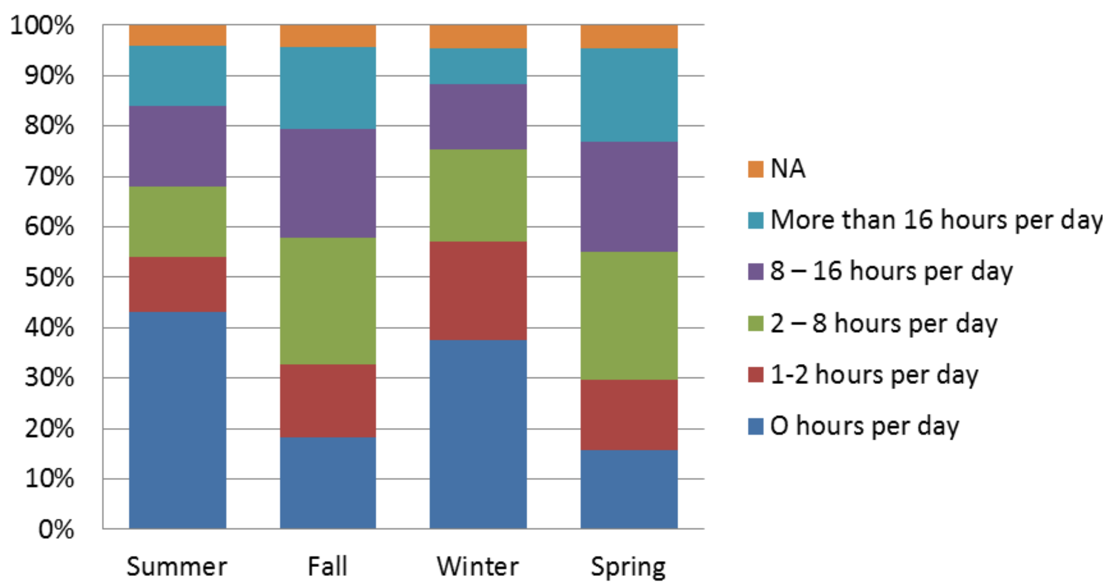
	Musty odor (N=2,622)			
	OR	**95% Confidence Interval**		**p-value**
		2.5%	**97.5%**	
Floor Area*	0.58	0.28	1.22	0.16
Number of occupants	1.18	1.11	1.24	3e-09
Number of bath fans	0.94	0.88	0.99	1.99e-02

*Floor area was transformed to a dimensionless parameter by a division of 929 m^2 (10,000 ft^2).

3.5 Window Opening

Survey respondents provided the number of hours per day on average they opened their windows in each of the four seasons. Survey respondents were asked "how many hours per day are your windows open?" The survey did not ask the number of windows open or the size of the openings. Results are summarized in Figure 14; see also Appendix A-3 for detailed statistics. In summer and winter, 43% and 38% of the people never open the windows, compared to 18% and 16% in fall and spring. In fall and spring, the majority of households (70%) opened their windows for at least 2–8 hours per day. In summer and winter, about 40% of people opened their windows for at least 2–8 hours per day. Compared to a previous study (CEC, 2007), in the fall and spring season, the results are similar but in summer, the previous study found more window opening. A previous LBNL study (Price and Sherman 2006) found broadly similar results with slightly more summer window opening, but less in the winter. Most of the survey respondents are located in southern California which is a hot and dry climate that may have an influence on window opening behavior because the previous studies collected the data from more diverse area.

Figure 14 Window opening frequency by season.



3.5.1 Correlation between window openings with IAQ/OAQ satisfaction

Table 12 shows regression results of IAQ and OAQ satisfaction predicting window opening. The result showed that except winter, the hours of window openings in all other seasons are statistically significant with regard to the satisfaction of OAQ (ORspring = 1.08, ORsummer = 1.18 and ORfall = 1.08, P<0.05). This suggests that survey respondents who rated OAQ positively would open their window more often, or in other words those who rated OAQ negatively would open their window less often. In comparison, the association between window openings and IAQ satisfaction is less clear, with ORwinter being the only statistically significant result. In winter, the negative association (OR<1) suggests that survey respondents who rated IAQ poorly would open their windows more often.

Table 12 Odds ratios of indoor and outdoor air quality satisfaction associated with window opening frequency.

Satisfaction with Air Quality	Spring (N=2,571)				Summer (N=2,574)			
	OR	95% CI		p-value	OR	95% CI		p-value
		2.5%	97.5%			2.5%	97.5%	
Indoor air quality	0.97	0.93	1.01	0.09	0.97	0.93	1.01	0.10
Outdoor air quality	1.08	1.04	1.11	2.4e-05	1.18	1.13	1.22	7.3 e-18
	Fall (N=2,574)				Winter (N=2,574)			
Indoor air quality	0.97	0.93	1.01	0.2	0.95	0.91	0.99	0.016
Outdoor air quality	1.08	1.04	1.12	1.6e-05	1.04	1.00	1.07	0.05

Table 13 shows the odds ratios of other indoor environmental parameters on window opening frequency. The results showed that for all four seasons, survey respondents' satisfaction with air movement was correlated with window opening. More frequent experience of not enough air movement was associated with more window opening and more frequent sensation of too much air movement was associated with less window opening, with both correlations appearing as statistically discernible in all seasons.

In the summer, survey respondents satisfaction with indoor air moisture level (Indoor air too dry, Indoor air too damp) is also statistically associated with window opening frequency. Survey respondents who perceived indoor air as too damp report opening windows more frequently. The other associations between indoor environmental conditions and window opening frequency are less clear statistically as indicated by the p-value close to 0.05. Collectively, these results are consistent with at least a fraction of the population using window opening to manage IAQ and comfort in a rational manner.

Table 13 Odds ratios of indoor environmental conditions on window opening frequency.

Indoor Environmental Conditions	Spring (N=2,571)				Summer (N=2,574)			
	OR	95% CI		p-value	OR	95% CI		p-value
		2.5%	97.5%			2.5%	97.5%	
Too much air movement	0.93	0.89	0.97	0.002	0.93	0.88	0.97	8.9 e-04
Not enough air movement	1.09	1.05	1.13	9.4e-08	1.05	1.02	1.08	0.003
Indoor air too dry	0.96	0.93	1.00	0.03	0.94	0.91	0.97	4.1e-04
Indoor air too damp	1.03	0.96	1.10	0.43	1.23	1.15	1.32	1.9e-09
Musty odor	0.97	0.91	1.02	0.22	0.94	0.89	1.00	0.04
	Fall (N=2,574)				Winter (N=2,574)			
Too much air movement	0.94	0.90	0.98	0.005	0.94	0.89	0.98	3.8e-03
Not enough air movement	1.09	1.06	1.13	1.15e-07	1.07	1.04	1.10	3.8e-05
Indoor air too dry	0.98	0.95	1.02	0.36	1.02	0.98	1.05	0.33
Indoor air too damp	1.03	0.96	1.09	0.44	1.01	0.95	1.08	0.70
Musty odor	0.94	0.89	1.00	0.03	0.99	0.93	1.04	0.60

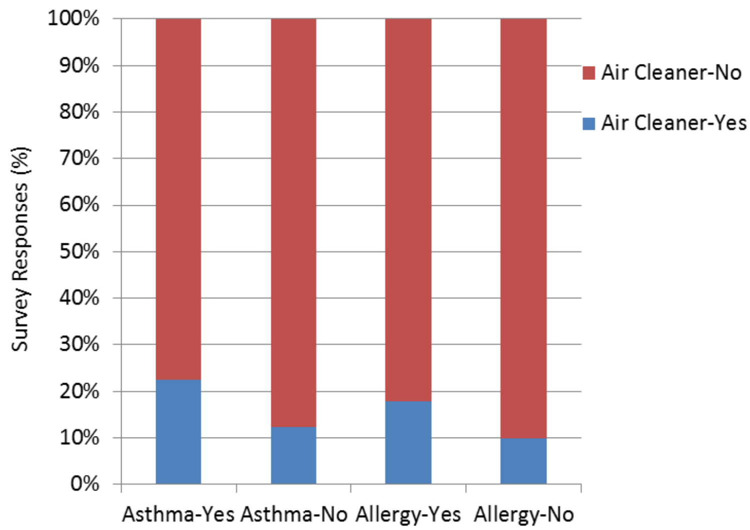
3.6 Use of air cleaners

Survey respondents were asked whether they use a stand-alone (portable) air filter, air purifier, or air cleaner in their homes. Only a small percentage (13%) of survey respondents reported using such a device, the majority of survey respondents (81%) do not (5% of survey respondents skipped this question, and 1% indicated they did not know the answer).

Survey respondents were also asked if anyone in the household has been diagnosed with asthma or allergies. Households with at least one person diagnosed with allergies are common: 53% of survey respondents reported at least one person has been diagnosed with allergies (41% reported no to this question), and 19% of survey respondents reported at least one person has been diagnosed with asthma (76% reported no to this question).

Figure 15 shows the percentage of survey respondents reporting the use of a stand-alone (portable) air filter, air purifier, or air cleaner in their homes, and comparing the percentages in households with and without at least one person diagnosed with asthma or allergy. The percentage of stand-alone (portable) air filter, air purifier, or air cleaner usage almost doubled in households with at least one person diagnosed with asthma or allergy compared to households without; see Appendix A-3 for detailed statistics.

Figure 15 Stand-alone (portable) air filter, air purifier, or air cleaner usage with and without at least one person in a household diagnosed of asthma or allergy.



3.6.1 Factors associated with air cleaner usage

Table 14 shows results of ordinal logistic regression of several factors that are potentially associated with use of an air cleaner in a household. As previously discussed, households that have at least one person diagnosed with asthma or allergies are more likely to use air cleaners. The odds ratios (allergy: OR=1.64, $P<0.05$; asthma: OR=1.55, $P<0.05$) in Table 14 quantify this positive association. In addition, satisfaction with outdoor air quality is also a factor that has statistical significance on air cleaner usage. The odds ratio (OR=0.92, $P<0.05$) suggests that survey respondents are more likely to use an air cleaner in their home if they give a lower rating on satisfaction with outdoor air quality. On the other hand, satisfaction with indoor air quality is not a statistically significant factor predicting air cleaner usage ($P=0.07$). These results suggest that poor outdoor air quality may be one of the factors why survey respondents use an air cleaner in their homes. The current survey did not ask survey respondents the reasons they use their air cleaner, so no cause-effect argument can be made. There are also numerous other possible reasons to use an air cleaner. For example, the perception of poor IAQ leads to air cleaner usage therefore it is expected to see a correlation between air cleaner usage and poor IAQ perception. However, it is possible that the air cleaner improved the IAQ, so the correlation between air cleaner usage and IAQ perception was not observed from the current survey.

Table 14 Odds ratios of diganosis with allergy or asthma in household, satisfaction with indoor and outdoor air quality, on air cleaner usage.

Parameters	Air Cleaner Usage (N=2,543)			
	OR	95% Confidence Interval		p-value
		2.5%	97.5%	
Allergy	1.64	1.27	2.13	0.00016
Asthma	1.55	1.19	2.02	0.0012
Indoor air quality	0.94	0.88	1.00	0.07
Outdoor air quality	0.92	0.87	0.98	0.007

4 Summary

An occupancy survey was conducted to obtain information about mechanical ventilation characteristics and occupant satisfaction of new homes in California. This report summarizes survey data on house and household characteristics, such as the types of mechanical ventilation equipment and gas appliances installed (and how they are used), occupant satisfaction with IAQ and other indoor environmental parameters, and other occupant activities related to IAQ, e.g., window opening and use of an air cleaner. Most of our survey participants are SoCalGas company customers so most of them have gas appliances.

Most surveyed homes are single-family detached homes, built between 2002 and 2006. The majority of survey respondents are homeowners. Most homes have floor areas between 140 and 279 m2 (1,500–3,000 ft^2), and are occupied by two to four occupants. The majority of heads of household of the surveyed homes had a college or more advanced degree. Almost half of the household had a combined income of above $100,000.

Most surveyed homes have a central gas furnace, gas water heater, and gas cooktop. Gas clothes dryer, gas oven, and gas fireplace are also common. Survey respondents indicated that most of them have a kitchen range hood and bathroom exhaust fans in their home. Most survey respondents indicated that they have a particle air filter in their central forced air system. Over half of the homes characterized the air filter as either a medium (MERV 8-11) or high (MERV $\geqslant$ 12) efficiency.

A comparison of floor area, number of stories, number of occupants, types of gas appliances, mechanical ventilation systems, and particle air filter in the central forced air systems of homes were presented by year built: 2002–2005, 2006–2010, 2011–2015. Overall, homes are similar in terms of these characteristics. For the 28 homes built after 2011, there is a trend of slightly larger floor area in 2011–2015 homes, more homes with gas ovens, fewer homes with gas fireplace, and more homes with continuous exhaust fan, fresh air vent, and/or whole house fan. The latter are to be expected given the code changes requiring these mechanical ventilation systems.

In addition to summarizing the survey data, statistical analyses were performed to characterize potential associations between IAQ satisfaction, comfort, and health indicators with house and household characteristics. The health indicators were items such as, any person in household with diagnosed allergy and/or asthma. The household characteristics considered were floor area, number of occupants, kitchen and bathroom ventilation, window opening, and use of an air cleaner. Ordinal logistic regression was used to characterize the relationship between a set of explanatory variables and the response parameter.

Survey respondents were generally more satisfied with the indoor air quality in their home than the outdoor air quality near where they live. But because survey respondents tend to associate indoor air quality with other indoor environmental conditions, such as thermal comfort, air movement, and dryness, the term "indoor air quality" potentially has many meanings that could complicate interpretation of the survey data. The most common complaint with regard to thermal comfort is some room(s) being too hot in the summer. More survey respondents complained about stagnant air (not enough air movement) than draftiness (too much air movement) in their homes. Occupants are generally satisfied with the moisture level in their homes. Results from ordinal logistic regression suggest that potential sources of indoor pollutants (e.g., number of occupants) and odor issues (e.g., musty odor) are negatively associated with IAQ satisfaction ratings. Occupant IAQ satisfaction may be influenced by other indoor environmental conditions, such as thermal comfort, not enough air movement, and dryness.

Kitchen range hoods and over-the-range microwaves that exhaust air to outside are the most common types of kitchen ventilation. Survey respondents who have a range hood that is exhausted to the outside use their range hood more frequently than those who have a range hood that blows air back into the kitchen. Almost 25% of survey respondents who have a range hood that blows air back into the kitchen indicated that they do not use their range hood because they are ineffective at removing cooking fumes or odors. In comparison, less than 10% of survey respondents who have a range hood that is exhausted to outside indicated that as a reason for not using the range hood. The most common reason by far (75%) for not using the range hood is "not needed for what is being cooked". Range hood being "too noisy" and "forget to turn it" are also some of the reasons why range hood is not used. Energy use by the range hood is not a common concern among users.

The most common bathroom exhaust fan control is by a manual on/off switch. Automatic controls, such as by a timer, humidity sensor, and/or occupancy sensor, are becoming more common in homes built since 2011. Ordinal logistic regression results suggest that an increase number of bath fans is statistically associated with a decrease in the frequency of discomfort due to musty odor. An increase in number of occupants is associated with an increase in frequency of musty odor in homes.

Window opening frequency varies by season. In fall and spring, the majority of homes (70%) open their windows for at least 2–8 hours per day. In summer and winter, about 40% of open their windows for at least 2–8 hours per day. In spring, summer, and fall, ordinal logistic regression results suggest that survey respondents who rated outdoor air quality positively tend to open their window more often. In all four seasons, "not enough air movement" is a significant parameter associated with more frequent window opening.

A small percentage (13%) of survey respondents reported that they use a stand-alone (portable) air filter, air purifier, or air cleaner in their homes. In households with at least one person diagnosed with asthma or allergies, the prevalence of air cleaner usage is about twice of that of households without. In addition, ordinal logistic regression results suggest that satisfaction with outdoor air quality is also a factor that has statistical significance on air cleaner usage. Survey respondents are more likely to use an air cleaner in their home if they give a lower rating on satisfaction with outdoor air quality. Satisfaction with indoor air quality is not a statistically significant factor associated with air cleaner usage.

Overall, analysis suggests that in this sample of largely pre-2008 homes, some of the mechanical ventilation systems (e.g., bathroom exhaust fan, fresh air vent) had a positive association with occupant satisfaction of indoor air quality and comfort. Homes with ventilation systems described as providing fresh air are correlated with higher indoor air quality satisfaction. In addition, having a vented range hood was associated with an increase in range hood usage, which suggests that new code requirements for effective kitchen exhaust may lead to better ventilation practices amongst occupants. Occupants are aware that a kitchen range hood exhausting to the outside is more effective than one that recirculates.

REFERENCES

ASHRAE. 2013. "ASHRAE Standard 62.2 Ventilation and Acceptable Indoor Air Quality in Residential Buildings", Atlanta, GA.

CEC. 2007."Study of Ventilation Practices and Household Characteristics in New California Homes." California Energy Commission.

CEC. 2008. "Building Energy Efficiency Standards for Residential and Nonresidential Buildings." Sacramento, CA, California Energy Commission.

Frontczak, M., S. Schiavon, J. Goins, E. Arens, H. Zhang, and P. Wargocki. 2012. "Quantitative Relationships between Occupant Satisfaction and Satisfaction Aspects of Indoor Environmental Quality and Building Design." Indoor Air 22 (2): 119–31. doi:10.1111/j.1600-0668.2011.00745.x.

Price, P. and Sherman, M. 2006. Ventilation Behavior and Household Characteristics in New California homes. LBNL59620, Berkeley, CA.

Zalejska-Jonsson, Agnieszka, and Mats Wilhelmsson. 2013. "Impact of Perceived Indoor Environment Quality on Overall Satisfaction in Swedish Dwellings." Building and Environment 63 (May): 134–44. doi:10.1016/j.buildenv.2013.02.005.

Appendix A-1

Survey Recruitment

SoCalGas A Sempra Energy utility

2015 California New Home Survey

Dear Customer,

SoCalGas is helping the Lawrence Berkley National Laboratory to conduct a research study on new homes in Southern California. We are inviting customers who live in a house, townhouse or duplex built in 2002 or later to complete a survey about their home.

The survey asks questions about your home, appliances, indoor air quality and demographics. All responses are confidential. Results will be used to help determine how homes can provide adequate ventilation and good indoor air quality, while improving energy efficiency. The survey has two sections. If you complete both sections it will take about 15-20 minutes.

Click this link to access the survey.

Or copy and paste the URL below into your internet browser:

https://hengh-survey.lbl.gov

Customers who complete the survey and enter their contact information will be entered into a drawing for $100. One winner will be announced each month starting June 1 through October 1, 2015.*

The survey will close on September 30, 2015, but we ask you to **please complete the survey by June 30th, 2015.** Customers who complete the survey by June 30th will be eligible for the July 1 drawing. If you complete the survey after June 30th, you will be entered into the drawing for the month you complete the survey.

Your data is very valuable to our understanding of new homes in Southern California. We thank you for your time and participation.

If you have questions about this research study, please contact:

Rengie Chan
Research Scientist, Indoor Environment Department
Lawrence Berkley National Laboratory
wrchan@lbl.gov (510) 486-6570

BERKELEY LAB

Sincerely,
SoCalGas Customer Research

*Click here to read the sweepstakes rules.

Appendix A-2

California New Homes Survey 2015

Welcome to the 2015 California New Homes Survey!

This survey is part of a research study on new homes in California. This research will help inform how new homes can provide adequate ventilation and good indoor air quality, while reducing air infiltration and energy use.

We invite your participation if you live in a single-family detached house, townhouse, or duplex, built in 2002 or later. The survey includes questions about your home, appliances, and indoor air quality.

This survey has two sections:

- A 5-minute survey about your home.
- Additional 15-minute survey on mechanical systems and appliances, household activities and demographics.

The first 3 questions are mandatory for determining eligibility. After that, you can skip questions that you do not want to answer.

At the end of each survey section, you can enter a chance to win $100 by submitting your contact information. You can double your chance of winning by completing both survey sections. One winner will be announced at the beginning of each month starting June 1 through October 1, 2015*. You will be entered into the drawing for the month you complete the survey.

This research is being conducted by Lawrence Berkeley National Laboratory (LBNL) with funding from the California Energy Commission. Results will be used only for research on how to provide adequate ventilation and improve indoor air quality. In order to protect your privacy, the data will be encrypted and password protected.

If you have questions about the research study, please contact:

Max Sherman, Ph.D.
Principal Investigator, Residential Building Systems Group
Lawrence Berkeley National Laboratory
mhsherman@lbl.gov (510) 486 4022

* Click here to read the sweepstakes rules.

Electronic Consent

By selecting Continue Survey below, you indicate that:

- You have read information about the survey.
- You are at least 18 years of age.
- You voluntarily agree to participate.

If you do not wish to continue, you may close this page by clicking the [Exit Survey] button below. You may still enter your contact information below for the chance to win $100.

[Continue Survey] or [Exit Survey]

(If Exit Survey is selected)

One winner will be announced at the beginning of each month starting June 1 through October 1, 2015. Please note that if you are among the lucky winners, we will contact you to get your name and full street address to send you the $100 in the form of a check.

You may also decline by clicking the No button below.

……. Yes! Enter to win.
……. No, I'm not interested.

(If selected yes)

Please provide contact information for how you would like to be contacted:

Name: ……………………………………

Please provide either your email or telephone number, or both.

Email: ……………………………………

Phone: …………………………………..

A. Eligibility Questions

Please answer <u>ALL</u> three questions to determine eligibility to participate in this survey.

1. Do you live in a single-family detached house, a townhouse, or a duplex?
   …….. Single-family detached house
   …….. Townhouse
   …….. Duplex
   …….. Other (e.g., apartment, mobile home) ………………

2. What year was your house built?
   Year Built: ………………

3. What is the first three digits of your zip code?
   Zip Code: ……………….

———————————————————

(If the dwelling is not eligible, the following message will be displayed and the survey will exit.)

Thank you for your interests in this study. Your home is not part of our targeted survey group.

If you would like to find out more about our work on ventilation and indoor air quality in homes, please visit our website at: http://hengh.lbl.gov/

———————————————————

(Survey will continue if the dwelling is eligible)

Yes! You live in a home that is eligible to participate in this survey.
Please answer to the best of your knowledge. You can skip any questions that you do not want answer.

B. Home and Household Characteristics

4. What is the size (floor area) of your home?
   Square Feet: ………………

5. How many people currently live in your home?
   Number of People: ……………..

6. Do you have any of the following natural gas (NOT propane or LPG) appliances? Select all that apply.
   …….. Central gas furnace for heating
   …….. Gas wall furnace for heating
   …….. Freestanding gas heater
   …….. Gas water heater
   …….. Gas cooktop
   …….. Gas oven
   …….. Gas clothes dryer
   …….. Gas fireplace/ log set
   …….. Other. Please describe: ………………………………
   …….. None
   …….. Don't know

   LPG = Liquefied petroleum gas

7. Do you have any of the following mechanical ventilation equipment (see **Illustration 1**)? Select all that apply.
   …….. Kitchen range hood or over the range microwave with exhaust fan
   …….. Kitchen exhaust fan separate from range hood
   …….. Bathroom exhaust fan

…….. Continuously operating ventilation exhaust fan
…….. Fresh air vent connected to heating and cooling system
…….. HRV (Heat Recovery Ventilator) or ERV (Energy Recovery Ventilator)
…….. Whole house fan
…….. Radon control system
…….. Other. Please describe: ……………………………………………
…….. None
…….. Don't know

C. Air Quality In and Around Your Home

8. To what extent are you satisfied or dissatisfied with the indoor air quality in your home?

Very Dissatisfied				Neutral				Very Satisfied
☐	☐	☐	☐	☐	☐	☐	☐	☐

9. How would you rate the outdoor air quality near where you live?

Very Poor				Neutral				Excellent
☐	☐	☐	☐	☐	☐	☐	☐	☐

10. How would you rate your home in protecting you from outdoor air pollution?

Very Ineffective				Neutral				Very Effective
☐	☐	☐	☐	☐	☐	☐	☐	☐

D. Comfort Level in Your Home

11. In winter, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times in a month	Few times a week	Every day
Too hot in some room(s).	☐	☐	☐	☐	☐
Too cold in some room(s).	☐	☐	☐	☐	☐

12. In summer, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too hot in some room(s).	☐	☐	☐	☐	☐
Too cold in some room(s).	☐	☐	☐	☐	☐

13. How often do the following conditions affect the comfort of occupants in your home?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too much air movement.	☐	☐	☐	☐	☐
Not enough air movement.	☐	☐	☐	☐	☐
Indoor air is too dry.	☐	☐	☐	☐	☐
Indoor air is too damp.	☐	☐	☐	☐	☐
Indoor air has musty odor.	☐	☐	☐	☐	☐

E. Submit Your Response

Thank you for filling out this survey!

Your data is very valuable to our understanding of indoor air quality and mechanical ventilation in new California homes. Please select one of the following.

……. Submit my responses
……. Exit survey and do not use my responses

__________________________________-

(If selected to exit without submitting responses)

The survey has ended. Your responses will not be used in this research.

If you have any questions about the survey, please contact:

Max Sherman, Ph.D.
Principal Investigator, Residential Building Systems Group
Lawrence Berkeley National Laboratory
mhsherman@lbl.gov (510) 486 4022

For more information about the results of this survey or the follow-up sampling study, please visit our website: http://hengh.lbl.gov/

(if selected to submit response)

To thank you for your help, please enter your contact information below to enter the chance to win $100.

One winner will be announced at the beginning of each month starting June 1 through October 1, 2015. Please note that if you are among the lucky winners, we will contact you to get your name and full street address to send you the $100 in the form of a check.

You may also decline by clicking the No button below.

……. Yes! Enter to win.
……. No, I'm not interested.

(If selected yes)

Please provide contact information for how you would like to be contacted:

Name: ……………………………………

Please provide either your email or telephone number, or both.

Email: ……………………………………

Phone: …………………………………..

F. Follow Up Study

(If the dwelling is a single-family detached house, was built in 2011 and after, and did not select "none" for natural gas appliance or mechanical ventilation equipment, the following recruitment information will appear.)

Your house may qualify for a follow-up study of indoor air quality and ventilation being conducted by Lawrence Berkeley National Laboratory (LBNL).

The study involves research teams visiting homes to measure the performance of ventilation equipment, and to set up air quality and ventilation monitoring devices that will remain in place for a one-week period.

Participants will receive up to $230 when completing the study. Homes from the eligible list will be selected based on geographic location, and home and household characteristics. The field study will begin in November 2015 and continue throughout 2016.

If you are interested to receive more information about the study, please enter your contact information below. A member of our research team will contact you to ask you more questions about your home to determine eligibility within 4 weeks.

For more information about the sampling study, please visit our website: http://hengh.lbl.gov/

Would you like to find out more about our follow-up study?

……. Yes! I want to find out more

……. Yes! I want to find out more. Contact me at email/telephone already provided for a chance to win $100.

……. No, I'm not interested.

(If selected yes to find out more about field study)

Please provide contact information for how you would like to be contacted:

Name: ……………………………………

Please provide either your email or telephone number, or both.

Email: ……………………………………

Phone: …………………………………..

G. Additional Survey Questions

In addition, we appreciate if you would answer a few more questions about your mechanical systems and appliances, household activities and demographics.

The additional questions take about 15 minutes to complete. Answering these additional questions will greatly increase the scientific value of the survey data.

You can also double your chance to win $100!

If you do not wish to continue, you may close this page by clicking the Exit button below.

[Continue Survey] or [Exit Survey]

(If exit survey)

Survey has ended.

Thank you for filling out this survey! Your data is very valuable to our understanding of indoor air quality and mechanical ventilation in new California homes.

If you have any questions about the survey, please contact:

Max Sherman, Ph.D.
Principal Investigator, Residential Building Systems Group
Lawrence Berkeley National Laboratory
mhsherman@lbl.gov (510) 486 4022

For more information about the results of this survey or the follow-up sampling study, please visit our website: http://hengh.lbl.gov/

(If continue survey)

H. Detail Home and Household Characteristics

Thank you for continuing with our survey!
Please answer to the best of your knowledge. You can skip any questions that you do not want to answer.

14. How many stories are at or above ground?
    Number Stories: …………………

    Half story or split-level counts as 0.5.

15. What type of foundation do you have? Select all that apply.
    …….. Concrete slab
    …….. Crawlspace
    …….. Basement
    …….. Don't know

    If your home is located above a garage, select the foundation of the garage.

16. How many bedrooms are in your home?
    Number Bedrooms: ……………….

17. How many bathrooms are in your home?
    Number Full Bathrooms: ……………….
    Number Half Bathrooms: ………………

    Half bathroom has a toilet and sink, but <u>NO</u> bath or shower.

18. Does your home have an attached garage? Yes / No

    If your home is located above a garage, select "Yes".

19. What year did you move into this home?
    Year Moved In: ………………

20. Do you own or rent your home?
    ……. Own (If yes → 21, skip otherwise)
    ……. Rent
    ……. Other

21. Are you the first owner of the property? Yes / No

I. Natural Gas Appliances for Space Heating

You indicated that your home has the following natural gas appliances.
(Show answers from 6)

22. The next few questions ask about the type and location of gas appliances if present. Do you want to change your answers before going forward?
    …….. Yes, change my answers. (If yes → 23)
    …….. No change.

23. Do you have the following natural gas appliances? Select all that apply.
    …….. Central gas furnace for heating (If yes → 24)
    …….. Gas wall furnace for heating
    …….. Freestanding gas heater
    …….. Gas water heater (If yes → 28)
    …….. Gas cooktop
    …….. Gas oven
    …….. Gas clothes dryer (If yes → 29)
    …….. Gas fireplace/ log set
    …….. Other. Please describe: ………………………………
    …….. None
    …….. Don't know

24. You indicated that your have a central natural gas furnace for heating.
    Where is your furnace located?
    ……. Attic
    ……. Basement or crawlspace under the living space
    ……. Attached garage
    ……. Interior closet
    ……. Other space <u>inside</u> the home. Please describe: ……………………………
    ……. Other space <u>outside</u> the home (e.g., furnace located in detached garage). Please describe: ………………………….
    ……. Don't know

25. You indicated that you do <u>NOT</u> use natural gas for heating.
    Which of the following heating appliances are used in your home? Select all that apply.
    ……. Central electric heating or heat-pump
    ……. Baseboard electric wall heater

……. Freestanding electric heater
……. Wood fireplace
……. Wood or pellet stove
……. Freestanding propane heater
……. Freestanding kerosene heater
……. No, I use natural gas for heating my home
……. Other. Please describe: ..…………………………
……. Don't know

(If central gas furnace or central electric heating or heat-pump → 26)

26. You indicated that you have a central forced air heating system.
Does your central forced air heating system have a particle air filter (**Illustration 2**)?

……. Yes
……. No, system does NOT have a particle air filter
……. No, my home does NOT have a central forced air heating system
……. Don't know

(If 26 is yes →27)

27. What kind of particle air filter does your central forced air heating system have (see **Illustration 2**)?
……. Traditional inexpensive filter
……. Medium efficiency filter
……. High efficiency filter
……. Electrostatic filter
……. Other. Please describe: …………………………
……. Don't know

J. Other Natural Gas Appliances

28. You indicated that you have a natural gas water heater.
Where is your water heater located?
……. Attic
……. Basement or crawlspace under the living space
……. Attached garage
……. Interior closet
……. Other space <u>inside</u> the home. Please describe: ……………………………
……. Other space <u>outside</u> the home (e.g., water heater located in detached garage).
Please describe: ………………………….
……. Don't know

29. You indicated that you have a natural gas clothes dryer.
Where is your clothes dryer located?
……. Laundry room
……. Basement or crawlspace under the living space

……. Attached garage
……. Interior closet
……. Other space inside the home. Please describe: ……………………………
……. Other space outside the home (e.g., clothes dryer located in detached garage). Please describe: ………………………….
……. Don't know

K. Mechanical Ventilation Systems

You indicated that your home has the following mechanical ventilation equipment. *(Show answers from 7)*

30. The next few questions ask about your mechanical ventilation equipment (see **Illustration 1**) if present. Do you want to change your answers before going forward?
    …….. Yes, change my answers. (If yes → 31)
    …….. No change.

31. Do you have the following mechanical ventilation equipment (see **Illustration 1**)? Select all that apply.
    …….. Kitchen range hood or over the range microwave with exhaust fan (If yes → 32, 33)
    …….. Kitchen exhaust fan separate from range hood (If yes → 33)
    …….. Bathroom exhaust fan (If yes → 35)
    …….. Continuously operating ventilation exhaust fan
    …….. Fresh air vent connected to heating and cooling system (If yes → 38)
    …….. HRV (Heat Recovery Ventilator) or ERV (Energy Recovery Ventilator) (If yes → 38)
    …….. Whole house fan
    …….. Radon control system
    …….. Other. Please describe: ……………………………………………
    …….. None
    …….. Don't know

L. Kitchen Range Hood and/or Exhaust Fan

32. What type of kitchen range hood or over the range microwave do you have?
    ……. Kitchen range hood exhausts air to outside
    ……. Kitchen range hood blows air back into kitchen
    ……. Over-the-range microwave exhausts air to outside
    ……. Over-the-range microwave blows air back into kitchen
    ……. Don't know

33. How often is the kitchen range hood or kitchen exhaust fan used when cooking with a cooktop?

……. Always (5 out of 5 times)
……. Most of the Time (4 out of 5 times)
……. Sometimes (2 to 3 out of 5 times)
……. Rarely (1 out of 5 times)
……. Never (0 out of 5 times)
……. Don't know

(If range hood used sometimes or less frequently → 34)

34. If the kitchen range hood or kitchen exhaust fan is <u>NOT</u> always used, what are the reasons for not using it? Select all that apply.

……. Forget to turn it on
……. Not needed for what is being cooked
……. Too noisy
……. Doesn't seem to remove cooking fumes or odors
……. Open window instead
……. Uses too much energy
……. Other. Please describe: ……………...

M. Bathroom Exhaust Fan

35. What type(s) of bathroom exhaust fan control do you have?
Enter number of full and half bathroom(s) with the control types.

Types of Exhaust Fan Control	Number of Full Bathrooms	Number of Half Bathrooms
Auto-on timer control	………..	………..
Auto-on humidity sensor	………..	………..
Auto-on occupancy sensor	………..	………..
Comes on when light is turned on	………..	………..
Manual on/off switch	………..	………..
On all the time	………..	………..
No exhaust fan	………..	………..

Half bathroom has a toilet and sink, but <u>NO</u> bath or shower.

N. Particle Filtration in Mechanical Ventilation System

(If fresh air vent or HRV or ERV → 36)

36.) You indicated that you have a mechanical ventilation system that brings in outdoor air. Does the system have a particle air filter (see **Illustration 2**) that is separate from the central forced air system?
    ……. Yes
    ……. No, outdoor air system does NOT have a separate particle air filter
    ……. No, mechanical ventilation system does NOT bring in outdoor air
    ……. Don't know

    Examples of mechanical ventilation systems that bring in outdoor air include HRV (heat recovery ventilator), ERV (energy recovery ventilator), and fresh air vent connected to heating and cooling system.

(If 36 is yes →37)

37.) What kind of particle air filter does your mechanical ventilation system that brings in outside air have (see **Illustration 2**)?
    ……. Traditional inexpensive filter
    ……. Medium efficiency filter
    ……. High efficiency filter
    ……. Electrostatic filter
    ……. Other. Please describe: …………………………
    ……. Don't know

O. Mechanical Ventilation System Operation

(If 21 is yes, i.e. first owner of the property → 38)

38. Was the operation of the mechanical ventilation system explained to you when you bought or moved into the home?
    ……. Yes
    ……. No
    ……. Don't know

39. Do you feel you understand how to operate your mechanical ventilation system properly?
    ……. Yes
    ……. No
    ……. Not Sure

40. To what extent are you satisfied or dissatisfied with your mechanical ventilation system?

Very Dissatisfied				Neutral				Very Satisfied
☐	☐	☐	☐	☐	☐	☐	☐	☐

(If not very satisfied → 41)

41. If you are NOT very satisfied with your mechanical ventilation system, what are the reason(s) for dissatisfaction? Select all that apply.
    ……. Too noisy
    ……. Too drafty
    ……. Difficult to operate
    ……. Difficult to maintain
    ……. Uses too much energy
    ……. Brings in dust, odor, or air pollutants from outdoor
    ……. Not effective
    ……. Other. Please describe: …………………………………

P. Occupancy and Indoor Activities

The next few questions ask about indoor activities, such as cooking, that can affect the indoor air quality in your home.

42. On average, how many hours per day is your home occupied by at least one person, including day and night hours?

	Fewer than 8 hours per day	8 to 12 hours per day	12 to 16 hours per day	16 to 20 hours per day	More than 20 hours per day
Weekday	☐	☐	☐	☐	☐
Weekend	☐	☐	☐	☐	☐

43. On average, how many times per week is your cooktop and/or oven used for cooking, including boiling water?

	0 time per week	1 to 2 times per week	3 to 4 times per week	5 to 6 times per week	7 times per week
Breakfast	☐	☐	☐	☐	☐
Lunch	☐	☐	☐	☐	☐
Dinner	☐	☐	☐	☐	☐

	0 time per week	1 to 2 times per week	3 to 4 times per week	5 to 6 times per week	7 times per week
Other cooking	☐	☐	☐	☐	☐

44. On average, how many times per week do the following activities occur inside your home? Enter "0" if occurrence is less frequent than once a week.

Use shower	(Times per week) …………………
Use bath or indoor Jacuzzi	(Times per week) …………………
Use dishwasher	(Times per week) …………………
Use washing machine	(Loads per week) ………………..
Hang clothes to dry indoors	(Loads per week) ………………..

Q. Window Opening

45. On average, how many hours per day are your windows open?

	0 hour per day	1 to 2 hour per day	2 to 8 hours per day	8 to 16 hours per day	More than 16 hours per day
Summer	☐	☐	☐	☐	☐
Fall	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐
Spring	☐	☐	☐	☐	☐

R. Indoor Activities

46. On average, how often do the following activities occur inside your home?

	Never	Few times a year	Few times a month	Few times a week	Every day
Smoking	☐	☐	☐	☐	☐
Burn candle or incense	☐	☐	☐	☐	☐
Vacuuming	☐	☐	☐	☐	☐
Use cleaning agent for floor cleaning	☐	☐	☐	☐	☐

	Never	Few times a year	Few times a month	Few times a week	Every day
Use spray air freshener	☐	☐	☐	☐	☐
Use pesticide spray	☐	☐	☐	☐	☐
Use paints, glue, solvents (e.g., hobbies, home repairs)	☐	☐	☐	☐	☐
Use humidifier	☐	☐	☐	☐	☐
Use dehumidifier	☐	☐	☐	☐	☐

S. Other Indoor Sources

47. Are plug-in or stick air fresheners, or other scented decorations, used in your home?
    ……. Yes
    ……. No
    ……. Don't know

48. Do occupants wear shoes in your home?
    ……. Yes
    ……. No
    ……. Don't know

49. How many dogs, cats, or other furry pets are in the home?
    Number of Pets: ………………

T. Use of Air Cleaners

50. Do you use a stand-alone (portable) air filter, air purifier, or air cleaner in the home?
    ……. Yes
    ……. No
    ……. Don't know

(If 50 is yes →51)

51. Where is your stand-alone (portable) air filter, air purifier, or air cleaner located in your home? Select all that apply.
    ……. Master bedroom
    ……. Other bedroom(s)
    ……. Living room
    ……. Home office
    ……. Other. Please describe: ……………......................................

52. Has anyone in the household been diagnosed with asthma?
……. Yes
……. No
……. Don't know

53. Has anyone in the household been diagnosed with allergies?
……. Yes
……. No
……. Don't know

U. Demographic Information

The next questions will help us interpret the results of the survey. All responses will be kept confidential.

54. Please indicate the number of household member(s) in the following age categories.

	Number of household member(s)
0 to 17 Years Old	……………………
18 to 65 Years old	……………………
Over 65 Years old	……………………

55. What is the highest education level of head of household?
…….. No schooling completed
…….. 1 to 8th grade
…….. 9th to 12th grade
…….. Completed high school (high school diploma, GED credential)
…….. Some college
…….. Associate's degree
…….. College degree (Bachelor's degree)
…….. Graduate degree (Master's, Professional school, Doctorate degree)

56. Please indicate all races and/or ethnicities of people living in your household.
…….. American Indian, Alaska Native
…….. Asian or Pacific Islander
…….. Black, African American
…….. Hispanic/ Latino
…….. White, Caucasian
…….. Other, specify: ………………….
…….. Mixed race, specify: ………………….

57. What is the total income of all member(s) of your household combined?
- …….. Less than $35,000
- …….. $35,000 to $ 49,999
- …….. $50,000 to $ 74,999
- …….. $75,000 to $ 99,999
- …….. $100,000 to $150,000
- …….. Greater than $150,000

V. Submit Your Response

You have reached the end of the survey. Thank you for taking the time to help us with this important research!

Your data is very valuable to our understanding of indoor air quality and mechanical ventilation in new California homes.

Please select one of the following.
- ……. Submit my responses
- ……. Exit survey and do not use my responses

———————————————————-

(If selected to exit without submitting responses)

The survey has ended. Your responses will not be used in this research.

If you have any questions about the survey, please contact:

Max Sherman, Ph.D.
Principal Investigator, Residential Building Systems Group
Lawrence Berkeley National Laboratory
mhsherman@lbl.gov (510) 486 4022

For more information about the results of this survey or the follow-up sampling study, please visit our website: http://hengh.lbl.gov/

———————————————————-

(if selected to submit responses)

To thank you for your help, please enter your contact information below to enter the chance to win $100.

One winner will be announced at the beginning of each month starting June 1 through October 1, 2015. Please note that if you are among the lucky winners, we will contact you to get your name and full street address to send you the $100 in the form of a check.

You may also decline by clicking the No button below.

- ……. Yes! Enter to win.
- ……. Yes! Enter to win. I already entered my contact information.
- ……. No, I'm not interested.

(If selected yes)

Please provide contact information for how you would like to be contacted:

Name: …………………………………

Please provide either your email or telephone number, or both.

Email: …………………………………

Phone: ………………………………..

W. Follow Up Study

(If the dwelling is a single-family detached house, was built in 2011 and after, and did not select "none" for natural gas appliance or mechanical ventilation equipment, the following recruitment information will appear.)

Your house may qualify for a follow-up study of indoor air quality and ventilation being conducted by Lawrence Berkeley National Laboratory (LBNL).

The study involves research teams visiting homes to measure the performance of ventilation equipment, and to set up air quality and ventilation monitoring devices that will remain in place for a one-week period.

Participants will receive up to $230 when completing the study. Homes from the eligible list will be selected based on geographic location, and home and household characteristics. The field study will begin in November 2015 and continue throughout 2016.

If you are interested to receive more information about the study, please enter your contact information below. A member of our research team will contact you to ask you more questions about your home to determine eligibility within 4 weeks.

For more information about the sampling study, please visit our website: http://hengh.lbl.gov/

Would you like to find out more about our follow-up study?

- ……. Yes! I want to find out more
- ……. Yes! I want to find out more. Contact me at email/telephone already provided for a chance to win $100.
- ……. No, I'm not interested.

(If selected yes to find out more about field study)

Please provide contact information for how you would like to be contacted:

Name: ……………………………………

Please provide either your email or telephone number, or both.

Email: ……………………………………

Phone: …………………………………..

———————————————————-

X. End of Survey

Thank you for filling out this survey! Your data is very valuable to our understanding of indoor air quality and mechanical ventilation in new California homes.

If you have any questions about the survey, please contact:

Max Sherman, Ph.D.
Principal Investigator, Residential Building Systems Group
Lawrence Berkeley National Laboratory
mhsherman@lbl.gov (510) 486 4022

For more information about the results of this survey or the follow-up sampling study, please visit our website: http://hengh.lbl.gov/

Illustration 1

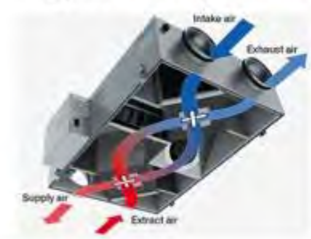
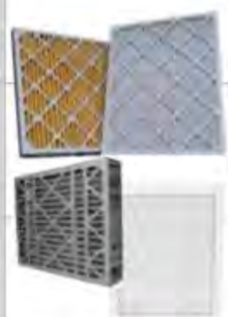
Mechanical Ventilation Equipment	
Kitchen range hood/ over-the-range microwave with exhaust fan  	Kitchen exhaust fan separate from range hood 
Bathroom exhaust fan 	Continuously operating ventilation exhaust fan  
Fresh air vent connected to heating and cooling system 	HRV (Heat Recovery Ventilator) or ERV (Energy Recovery Ventilator) 
Whole house fan 	Radon control system 

Illustration 2

Types of Air Filters		Air Filter Efficiency Ratings		
		MERV	MPR	FPR
Traditional inexpensive filter		0-4	--	--
		5-7	300 600	4-5
Medium efficiency filter		8-11	1000 1200 1500	6-7 8-9
High efficiency filter		≥12	1900 2200	10
Electrostatic filter		--	--	--

MERV = Minimum efficiency reporting value
MPR = Microparticle performance rating
FPR = Filter performance rating

Appendix A-3

Table A3-1 Occupant satisfaction with indoor air quality (IAQ), outdoor air quality (OAQ), and other indoor environmental conditions.

Parameter	Survey Response Counts (%)									
Overall IAQ satisfaction	-4 (Very Dissatisfied)	-3	-2	-1	Neutral	1	2	3	4 (Very Satisfied)	NA
	40 (1.4%)	33 (1.2%)	71 (2.6%)	124 (4.4%)	569 (20.5%)	224 (8%)	543 (20%)	572 (21%)	589 (21%)	6
Overall OAQ satisfaction	-4 (Very Dissatisfied)	-3	-2	-1	Neutral	1	2	3	4 (Very Satisfied)	
	121 (4.4%)	115 (4.2%)	201 (7.3%)	277 (10%)	503 (18%)	305 (11%)	548 (20%)	428 (15%)	268 (9.6%)	5
How often the following conditions affect the comfort?	Never	Few times a year	Few times in a month	Few times a week	Everyday	NA				
Winter (Too hot)	1331 (48%)	692 (25%)	277 (10%)	193 (7%)	95 (3%)	183 (7%)				

Parameter	Survey Response Counts (%)					
Winter (Too cold)	750 (27%)	922 (33%)	446 (16%)	352 (13%)	192 (7%)	109 (4%)
Summer (Too hot)	367 (13%)	764 (28%)	477 (17%)	623 (23%)	505 (18%)	35 (1%)
Summer (Too cold)	1460 (53%)	546 (20%)	228 (8%)	153 (6%)	96 (3%)	288 (10%)
Too much air movement	2006 (72%)	388 (14%)	150 (6%)	89 (3%)	36 (1%)	102 (4%)
Not enough air movement	1033 (37%)	754 (27%)	420 (15%)	334 (12%)	162 (6%)	68 (3%)
Indoor air is too dry	1363 (49%)	654 (24%)	344 (12%)	187 (7%)	127 (5%)	96 (3%)
Indoor air is too damp	2135 (77%)	385 (13.8%)	81 (3%)	49 (2%)	5 (0.2%)	116 (4%)
Indoor air has musty odor	**2048 (74%)**	**414 (14.9%)**	**126 (4.5%)**	**53 (1.9%)**	**19 (0.7%)**	**111 (4%)**

Table A3-2 Kitchen range hood type and usage frequency (N = 2,516).

Parameter	Survey Response Counts (%)					
Type of range hood?	Kitchen range hood exhausts air to outside	Kitchen range hood blows air back into kitchen	Over-the-range microwave exhausts air to outside	Over-the-range microwave blows air back into kitchen	Don't know	NA
	1081 (43%)	107 (4%)	901 (33%)	222 (8%)	131 (5%)	74 (3%)
How often do you use range hood when cooking with cooktop?						
Always	150 (14%)	11 (10%)	118 (13%)	14 (6%)	10 (8%)	
Most of the Time	293 (27%)	19 (18%)	181 (20%)	38 (17%)	14 (11%)	
Sometimes	347 (32%)	26 (24%)	289 (32%)	57 (26%)	43 (33%)	
Rarely	266 (25%)	42 (39%)	286 (32%)	96 (43%)	56 (43%)	
Never	23 (2%)	9 (8%)	21 (2%)	17 (8%)	5 (4%)	
Don't Know	2 (<0.1%)	0 (0%)	5 (0.5%)	0 (0%)	3 (2%)	
NA			1			

Table A3-3 Reasons for not using the range hood
(N = responses that answered range hood is used sometimes or less frequently).

Parameter	**Survey Response (%)**					
Type of range hood	Kitchen range hood exhausts air to outside	Kitchen range hood blows air back into kitchen	Over-the-range microwave exhausts air to outside	Over-the-range microwave blows air back into kitchen	Don't know	NA
N	638	77	596	170	107	
What are the reasons for not using the kitchen range hood or exhaust fan?						
Forget	108 (17%)	8 (10%)	108 (18%)	30 (18%)	17 (16%)	17
Not Needed	537 (84%)	56 (73%)	488 (82%)	120 (71%)	86 (80%)	64
Too Noisy	179 (28%)	17 (22%)	175 (29%)	42 (25%)	31 (29%)	20
Doesn't Work	45 (7%)	22 (29%)	54 (9%)	45 (26%)	7 (7%)	4
Open Window	59 (9%)	10 (18%)	70 (12%)	36 (21%)	20 (19%)	12
Uses Too Much Energy	6 (1%)	1 (2%)	8 (1.3%)	2 (1%)	3 (3%)	0
Other						

Table A3-4 Survey responses on frequency of window opening by season.

Window Opening						
	0 hours per day	1–2 hours per day	2–8 hours per day	8–16 hours per day	More than 16 hours per day	NA
Summer	1194 (43%)	303 (11%)	390 (14%)	439 (16%)	334 (12%)	111 (4%)
Fall	505 (18%)	400 (14%)	698 (25%)	596 (22%)	449 (16%)	123 (4%)
Winter	1044 (38%)	541 (20%)	506 (18%)	356 (13%)	198 (7%)	126 (5%)
Spring	437 (16%)	388 (14%)	699 (25%)	609 (22%)	510 (18%)	128 (5%)

Table A3-5 Survey responses on air cleaner usage in household with and without diagnosed case(s) of asthma and/or allergy.

Use of Air Cleaner	Asthma (N=2,587)		Allergy (N=2,569)	
	Yes	No	Yes	No
Yes	115 (23%)	255 (12%)	258 (18%)	111 (10%)
No	396 (77%)	1821 (88%)	1185 (82%)	1015 (90%)

APPENDIX B:
Title 24 Fan Sizing and Airtightness Requirements for New California Homes

Abstract

Since 2008, California has had building code (also known as Title 24) requirements for minimum ventilation. This simulation study is a companion to a field study of new California homes to determine if the ventilation requirements are resulting in acceptable indoor air quality (IAQ). The simulation study aims to look beyond current home performance to examine potential future changes to the California Code. The main objectives of this simulation study were to: (1) evaluate the IAQ and energy impacts of different whole house (or dwelling unit) fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH50 airtightness requirement in the Title 24 energy code. Energy, ventilation and IAQ performance were simulated in two prototype homes compliant with the 2016 prescriptive provisions of the Title 24 Building Energy Code, across a number of California climate zones (CZ 1, 3, 10, 12, 13 and 16) reflecting the variety of climate conditions in the state. Airtightness was varied between 0.6 and 5 ACH50, and whole house fans were sized according to six currently available or proposed compliance paths in Title 24 or ASHRAE Standard 62.2. Fan sizing methods either accounted for infiltration and fan type, or they used a fixed airflow approach, with no variability in the fan sizing by airtightness, climate zones, geometry and fan types. The simulations used the relative exposure approach to assess IAQ where the exposure to a generic continuously emitted indoor contaminant is compared to the exposure using a known fixed air flow – in this case the whole house target airflow (Q_{total}) required by ASHRAE Standard 62.2. The results for individual cases were combined using a weighting based on the fraction of new homes constructed in different climate zones to get statewide estimates of performance.

The whole house ventilation fan sizing methods with the poorest weighted average IAQ (highest relative exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method (T24 2008) and the Total Ventilation Rate Method (T24 2013). These had weighted average relative exposures of 1.3 and 1.4, respectively. Of all sizing methods, the adopted ***Title 24 2019*** sizing method with a sub-additivity adjustment for unbalanced fans maintained relative exposure closest to 1.0. The ASHRAE 62.2-2016 method and the ***Qtotal*** method were the next best approaches. The ASHRAE 62.2-2016 fan/infiltration superposition method consistently under-ventilated and had relative exposures in the range of 1.05 to 1.09, while the ***Qtotal*** method consistently over-ventilated, with relative exposures of about 0.93 to 0.97. ***Qtotal*** was the only sizing method that maintained exposure below 1.0 in all simulated cases. The best approaches from an IAQ standpoint were the T24 ***2019*** and ***Qtotal*** methods. They increased the weighted average energy use by 3 and 5% relative to the ASHRAE 62.2-2016 method. The difference in weighted average total energy consumption between any of these three sizing methods was roughly 350 kWh/year.

Most of the sizing methods had widely spread relative exposure values, meaning that most homes were either substantially under- or over-ventilated relative to target rates in 62.2 and Title 24. This inconsistency increases the risk of either poor IAQ or excess energy consumption for individual homes, even when the weighted average results are acceptable. The ASHRAE 62.2-2016 fan sizing method, which accounts fully for infiltration and fan type, had the most consistent pollutant exposure and ventilation rates across all cases, irrespective of climate zone, fan type, airtightness or house prototype. This sizing method had average exposure of 1.09, due to biases in the exhaust fan sub-additivity calculations in ASHRAE 62.2-2016. If desired, the CEC could adopt an alternative sub-additivity formulation that would eliminate most of this bias, and should reduce average exposure very close to 1.0. The 2019 Title 24 fan sizing method resulted in exposure values nearly as tightly clustered as the ASHRAE 62.2-2016 method, though it consistently over-ventilated leaky homes relative to the target airflows in the standard and energy code, with increased site energy consumption ranging from 70 to, 1,400 kWh/year, when averaged across climate zones.

An airtightness requirement of 3 ACH50 in new California homes was found to have predicted weighted average energy savings of about 1 to 5% of total HVAC energy use. Most of these savings were from reducing the ventilation rate and worsening IAQ. The fixed airflow fan sizing methods saved more energy (roughly 3 to 5%) but worsened IAQ (increasing exposure to a generic indoor contaminant by 5 to 24%). The energy savings are low because the majority of new home construction is in mild climates, and the interactions between unbalanced mechanical ventilation and natural infiltration lead to small changes in total airflow when we tighten to this limit. Energy use decreased as weighted average exposure increased, essentially trading off poor IAQ for improved energy performance. The sizing methods that accounted for infiltration and/or fan type had substantially reduced weighted average energy savings (1%) under an airtightness requirement, while they marginally improved IAQ (reduced exposure by roughly 3 to 4%). Airtightness savings were roughly double in the 2-story vs. 1-story prototype homes, because of their increased natural infiltration rates due to having greater natural infiltration airflows. Savings were also higher in climates with the harshest weather (CZ16 and CZ1), but the lack of new construction in these zones nearly eliminated their effect on the weighted average results. When HVAC energy use was normalized such that pollutant exposure was the same in all cases, the energy savings attributable to a 3 ACH50 airtightness limit dropped to well below 1%.

The determination of which fan sizing method is most appropriate for new homes in California will largely depend on whether or not the state decides to impose an airtightness requirement in the building energy code (and require HERS raters to measure it). Our results suggest that unless occupant pollutant exposure is allowed to increase by 5-10% relative to target rates, then an airtightness limit will have very marginal savings of roughly 1% of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5% are possible through airtightening. On average, the adopted 2019 fan sizing method for Title 24 performed similarly to the more complicated ASHRAE 62.2-2016 method under current airtightness conditions. The adopted fan sizing method gave weighted average exposure very near to 1.0 under both current and hypothetical airtightened scenarios, though exposure would increase roughly 5% under a hypothetical airtightness requirement in the energy code.

1 Introduction

The provision of air exchange in residences to dilute indoor pollutants was traditionally provided by weather-induced natural infiltration and operation of windows and doors, as seen fit by the occupants (Janssen, 1999; Sundell, 2004). Most homes were exceptionally leaky and maintained much more air exchange throughout the year than was required to maintain acceptable indoor conditions, which wasted large amounts of energy. As builders and consumers became conscious of the energy consumed by homes in the late 1970s, air sealing of the building envelope became a very early 'low-hanging fruit' target of energy efficiency efforts. Aggressive airtightening and insulating efforts were initially performed without adding any intentional ventilation to the homes, and reports of mold, moisture and poor IAQ were promulgated throughout the building community (Less, Mullen, Singer, & Walker, 2015).

Many building energy professionals realized that mechanical ventilation was required in airtightened homes in order to maintain air quality that was acceptable to occupants. Mechanical ventilation mandates slowly spread across the world, with strong government requirements for new homes in Canada (Gusdorf & Hamlin, 1995; Gusdorf & Parekh, 2000; Riley, 1987) and internationally, and in the U.S. certain energy efficiency programs and jurisdictions incorporated ventilation into regional construction practice and codes (Mudarri, 2010). Currently, the need for mechanical ventilation in new homes is recognized in model codes, by many local jurisdictions and by programs such as the US DOE weatherization.

The ventilation standard in the United States—ASHRAE Standard 62.2 (ANSI/ASHRAE, 2016)—currently specifies a target whole house ventilation rate that varies by floor area and occupancy, and is closely aligned with the rule of thumb air exchange target that energy and air quality professionals have long touted as the ideal energy-IAQ compromise—roughly 0.3 to 0.35 air changes per hour (hr^{-1}).

California's Building Energy Efficiency Standards (Title 24) has recognized the need for builders to install continuous mechanical ventilation in new homes (and some remodeled homes) since 2008. The 2008 updates to Title 24 included a mandatory requirement that new residences and additions >1,000 ft^2 provide mechanical ventilation meeting the requirements of the ASHRAE Standard 62.2-2007. Reliance on operable windows for compliance was explicitly prohibited. This change in IAQ ventilation requirements was spurred by an IAQ field study in new California homes that showed low ventilation rates in new (at the time) California homes with moderately high formaldehyde concentrations (Offermann, 2009). A companion survey study also demonstrated that a substantial minority of new California homes had windows closed continuously during heating and cooling seasons (Price, Sherman, Lee, & Piazza, 2007). Together, these studies were used to support mandatory inclusion of mechanical ventilation in new California homes for IAQ.

Airtightness in new homes has also increased with improved construction methods and technologies, and the International Energy Conservation Code (IECC) now recognizes a 3 ACH_{50} airtightness target for U.S. DOE Climate Zone 3 and above (5 ACH_{50} in zones 1 and 2), which includes most of California (ICC, 2012). The Title 24 requirements and paths to compliance, as well as the mandates of the ASHRAE Standard 62.2, have also continued to evolve over the past decade. As such, there are currently a number of different ways to comply with the IAQ provisions of Title 24. None of these compliance paths align perfectly with the current requirements in the ASHRAE 62.2-2016 ventilation standard. As in the past, we anticipate that the California Energy Commission may adopt the current 62.2 standard in part, with California-specific provisions or adjustments. Builder practice around Whole house fan sizing and installation in California (Chan et al. 2018 and Stratton et al 2012a) is to install systems with considerable excess capacity (by 40-50%), which does not align with any of the specified options. This indicates that builders are not deliberately designing systems to operate at minimum airflows required by code. For this reason we will include this current builder practice as a fan sizing option in this study.

This simulation study is being performed in parallel with a field study of pollutant concentrations in new California homes built to the 2008 Title 24 building energy code (Chan et al. 2018). The main goals of this simulation effort are to quantify the energy, ventilation and IAQ impacts of airtight residences under current and proposed IAQ compliance paths available in the Title 24 building energy code and the ASHRAE 62.2 ventilation standard. Specifically, we will examine how different levels of envelope airtightness and methods of sizing Whole house fans affect exposure to pollutants and HVAC energy use. This will to provide information that will help to guide the California Energy Commission's decision whether or not to include an airtightness requirement in the Title 24 Building Energy Code, as well as an IAQ ventilation specification that compliments this requirement without causing harm.

The two primary objectives are:

- Assess the energy and IAQ impacts of different fan sizing methods currently available or proposed for California Title 24 compliance in new homes.
- Determine the impacts of a proposed 3 ACH50 airtightness requirement under the various fan sizing methods.

2 Background

2.1 IAQ and Relative Exposure

In this work, IAQ impacts are assessed using the metric of relative exposure. This metric was first proposed as an approach for assessing intermittent ventilation, based on equivalent dose and exposure to a generic, continuously emitted indoor contaminant. Equivalence was assessed relative to a fixed airflow ventilation system (Sherman, Mortensen, & Walker, 2011; Sherman, Walker, & Logue, 2012). The metric of relative exposure is now the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard.

The relative exposure reflects the real-time ratio between the concentrations of a generic, continuously emitted, indoor contaminant, under two different ventilation rates. First, is a fixed ventilation rate that represents the target airflow for the home (in this study we used ASHRAE 62.2-2016), and second is the time-varying airflow actually experienced by the house.

At a given time step, a relative exposure equal to 1 means the two ventilation rates lead to identical pollutant concentrations. When averaged over a period of time (e.g., annually), a value of 1 means the two rates provide equivalent pollutant exposure. A relative exposure of one-half suggests the real-time ventilation rate is double the reference ventilation rate, and a relative exposure of two indicates a real-time ventilation rate that is half the reference rate. Annually, the average during occupied hours of the relative exposure must be less than or equal to one in order to satisfy ASHRAE 62.2-2016 requirements.

The relative exposure can be interpreted as a multiplier that could be applied to any generic contaminant emitted uniformly and continuously from only indoor sources. For example, a value of 1.2 reflects a 20% increase in pollutant concentration, relative to the concentration if the home's ventilation (Q_i) was at the target ventilation rate (Q_{total}). Or a value of 0.66 would reflect a 34% reduction in the pollutant concentration, relative to the concentration at the target ventilation rate.

In general, the pollutant concentration is inversely related to the ventilation rate. As a result, the increased airflow required to reduce the concentration is much greater than the reduction in airflow needed to result in a similar increase in the concentration. For example, a home at 0.5 ACH hr^{-1} and a formaldehyde concentration of 30 ppb would need to double its airflow to 1 ACH hr^{-1} in order to halve the concentration to 15 ppb. But the house would reach 45 ppb (30 + 15) after only a 33% reduction in the ventilation rate, from 0.5 to 0.23 ACH hr^{-1}. The end result of this is that it requires more airflow more to reduce a pollutant concentration than is saved by allowing the concentration to increase.

2.2 Airtightness, IAQ and Energy Consumption

Overall, reducing air leakage while mechanically ventilating to maintain equivalent IAQ is expected to save energy for two reasons: (1) it reduces the variability in the ventilation rate throughout the year, shifting airflows to milder weather conditions, and (2) this reduction in variability means the same exposure can be maintained with a lower total airflow. Both of these effects reduce the heating and cooling loads associated with ventilation, even when the same relative exposure is maintained.

A principle of equivalent ventilation is that as the airflow gets more variable, a higher average flow is required to maintain equivalent exposure. For this reason, in addition to shifting ventilation to milder periods, the airtight, mechanically vented home requires a lower annual average ventilation rate to achieve the same exposure as a leaky home. The most airtight cases effectively have a fixed house airflow that is equal to the fan airflow. Their flows do not increase or decrease with outside conditions. In contrast, a leaky home has widely varying ventilation rates determined by weather conditions, and it will require substantially higher total annual airflow to achieve relative exposure equal to that of the airtight home.

3 Method

The REGCAP simulation tool is used to predict the ventilation and energy performance. It combines detailed models for mass-balance ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. The details of this model have been presented elsewhere (Iain S. Walker, 1993; Iain S. Walker & Sherman, 2006; I.S. Walker, Forest, & Wilson, 2005), along with validation summaries of house and attic air, mass and moisture predictions. Two zones are simulated: the main house and the attic. REGCAP is implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance.

3.1 Prototype Descriptions

Two CEC prototype homes were simulated—one- and two-story, referred to throughout as "med" (or "medium") and "large", respectively (Nittler & Wilcox, 2006). These were made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 energy code. Thermostat schedules were set to meet those specified in the 2016 ACM (see Table 1). HVAC equipment was sized using ACCA Manual J load calculation procedures. Current deviations from the Title 24 prescriptive path prototypes include no whole house economizer fans, internal gains based on RESNET calculation method, HVAC equipment efficiencies and elimination of duct leakage to outside. Equipment efficiency was increased beyond prescriptive minimums to SEER 16 A/C and 92 AFUE gas furnaces in order to align with standard new construction practice encountered in the parallel field study of new California homes (Chan et al. 2018) and based on input from the project's Technical Advisory Committee.

Table 2 summarizes the prototype home parameters that were exercised in this study. The climate zones were chosen to capture a range of heating and cooling loads. The airtightness ranged from current practice of 5 ACH_{50} down to passive house levels of 0.6 ACH_{50}. This included an airtightness of 3 ACH_{50} that could be adopted as a maximum level for the state to align with the requirements of the International Energy Conservation Code that is increasingly being used elsewhere in the country. The ventilation fan for Title 24 compliance was sized according to seven different calculation methods, which are discussed in detail in Section 3.4. Each case was simulated with both balanced and unbalanced Whole house fans. A baseline case with no Whole house fan operating was simulated for each combination of prototype, airtightness and climate zone. The ventilation energy use was the difference in total annual HVAC consumption between the fan and no fan cases, which includes changes in fan energy and thermal loads from air exchange.

Table 1 HVAC thermostat schedule per Title 24 ACM Table 19

Hour of Day	Heating Set-Point (°F)	Cooling Set-Point (°F)
0:00	65	78
1:00	65	78
2:00	65	78
3:00	65	78
4:00	65	78
5:00	65	78
6:00	65	78
7:00	68	83
8:00	68	83
9:00	68	83
10:00	68	83
11:00	68	83
12:00	68	83
13:00	68	82
14:00	68	81
15:00	68	80
16:00	68	79
17:00	68	78
18:00	68	78
19:00	68	78
20:00	68	78
21:00	68	78
22:00	68	78
23:00	65	78

Table 2 Summary of the parameters that were varied in HENGH simulations.

Prototype Home	1-story, 2,100 ft^2			2-story, 2,700 ft^2			
CEC Climate Zone	1 (Arcata)	3 (Oakland)	10 (Riverside)	12 (Sacramento)	13 (Fresno)	16 (Blue Canyon)	
Envelope Airtightness (ACH_{50})	0.6	1	2	3	5		
Whole house fan Sizing Method	None	T24_2008	T24_2013	Qtotal	ASHRAE 62.2-2016	T24_2019	Builder Practice
Fan Type	Exhaust			Balanced			

3.2 Weighted Average Calculations

To scale these individual cases up to statewide estimates, we developed weighting factors that represent our best estimate of the current distribution of parameters. A second series of weighting factors were developed to represent a proposed envelope leakage requirement of 3 ACH_{50}.

Each case is weighted according to the expected distribution of the parameter in new homes throughout the state. The weighted average parameters used in our analysis included climate zone (see Table 7), envelope airtightness (Table 3), house prototype (Table 4) and fan type (Table 5). Each factor is briefly discussed below. This is an imperfect approach to characterizing the entire new California single-family building stock, but it does give us a way to generalize and summarize our results. For example, this method gives greater weight to results from the mild climate zones in Southern and Central California where most new home development occurs in the state, and it reduces the effect of the larger energy impacts in sparsely populated zones, like CZ1 (Arcata) or 16 (Blue Canyon). The average result under these weights for each fan sizing method was calculated using Equation 1.

$$\bar{x} = \frac{\sum_{i=1}^{n}(x_i * w_{prototype,i} * w_{cz,i} * w_{ACH50,i} * w_{fantype,i})}{\sum_{i=1}^{n} w_{prototype,i} * w_{cz,i} * w_{ACH50,i} * w_{fantype,i}} \qquad (1)$$

x = Variable in question (e.g., relative exposure, ventilation energy use)

$w_{prototype}$ = house prototype weight

w_{cz} = climate zone weight

w_{ACH50} = airtightness weight

$w_{fantype}$ = fan type weight

The airtightness weights used to estimate the impacts of an air leakage requirement in new California homes are shown in Table 3. The airtightness weights are designed to roughly estimate the airtightness distribution in new California homes, with most new construction achieving roughly 5 ACH_{50}, and diminishing numbers of new homes achieving 3 ACH_{50} and very low numbers with greater airtightness. The weighting factors are based on the results of the following field studies. Proctor, Chitwood, & Wilcox (2011) reported median envelope leakage in 38 new CA homes of 4.66 ACH_{50}. They found that only 7.8% of homes were below 3 ACH_{50}. The HENGH field study (Chan et al. (2018)) in new California homes has found very similar airtightness results, with a median of 4.5 ACH_{50}; 6% of HENGH homes were below 3 ACH_{50}, 26% were between 3 and 4 ACH_{50}, and 68% exceeded 4 ACH_{50}. Consistent with these field studies, we placed 93% of airtightness weight in the 3 and 5 ACH_{50} homes, and 7% of airtightness weight in the 2 ACH_{50} or less categories. The weights under the proposed 3 ACH_{50} airtightness requirement (Table 3, Row 2) simply shift these down (e.g., from 5 to 3, 3 to 2, etc.), such that nearly all new homes achieve either 3 or 2 ACH_{50}, with very small numbers that are more airtight or non-compliant with the limit. We do not have real-world estimates of what happens to home airtightness under a code-imposed air leakage limit, but we estimate that a small fraction of homes will miss the target, and all others will be fairly tightly clustered below the code requirement.

Table 3 Envelope airtightness weighting factors

Envelope airtightness weighting factors	Envelope Airtightness (ACH_{50})				
	5	3	2	1	0.6
Current	0.63	0.30	0.05	0.01	0.01
Proposed 3 ACH_{50}	0.01	0.63	0.30	0.05	0.01

Prototype weights (Table 4) match those provided in the description of the single-family Title 24 prototype buildings that are used for analysis supporting development of Title 24 (Nittler & Wilcox, 2006). Fan type weights (Table 5) prioritize exhaust fans, with a modest 10% of new homes having balanced ventilation systems. This is consistent with findings from the companion field study to this simulation effort (Chan et al. (2018)), where 64 of 70 homes used an exhaust fan to comply with Title 24 ventilation requirements. This aligns with prior assessments of ventilation in new California homes, which found that the vast majority of new homes use unbalanced exhaust ventilation systems to comply with Title 24 (Stratton, Walker, & Wray, 2012a).

Table 4 Prototype weighting factors

Prototype	1-story, 2,100 ft^2	2-story, 2,700 ft^2
Weighting Factor	0.45	0.55

Table 5 Fan type weighting factors.

Fan Type	Exhaust	Balanced
Weight Factor	0.90	0.10

Climate zone weights (Table 6 and Table 7) are based on the fraction of total projected new housing starts in 2017 in each CEC climate zone, using data provided to the 2016 CASE teams by the CEC Demand Analysis office. We have reproduced exactly the estimates provided by Rasin & Farahmand (2015) in Table 14 of the Residential High Performance Walls CASE report. Yet, we simulated only climate zones 1, 3, 10, 12, 13 and 16, and we attribute projected housing starts in non-simulated climate zones based on geography and overall heating/cooling degree days (see Table 6 for our assignment of non-simulated climates to those we simulated, for example, the CZ4 and CZ5 weights were added to the CZ12 weight). The combined weights for zones 1, 3, 10, 12, 13 and 16 are provided in Table 7.

Table 6 New construction estimates for single-family homes in 2017 and weighting assignments for un-simulated climate zones.

CZ	City	2017 New Single-Family Homes	2017 New Homes Fraction	Rough HDD_{65} Range	Rough CDD_{80} Range	CZ Weight Assignment
1	Arcata	695	0.006	3800-4500	0-50	1
2	Santa Rosa	2602	0.024	2600-4200	200-900	3
3	Oakland	5217	0.048	2500-3800	10-500	3
4	San Jose-Reid	5992	0.055	2300-2900	200-1000	12
5	Santa Maria	1164	0.011	2300-3000	200-900	12
6	Torrance	4142	0.038	700-1900	500-1200	10
7	San Diego-Lindbergh	6527	0.060	1300-2000	500-1100	10
8	Fullerton	7110	0.066	1300-1800	700-1300	10
9	Burbank-Glendale	8259	0.076	1100-1700	1300-1600	10
10	Riverside	16620	0.154	1600-1900	1400-1900	10
11	Red Bluff	5970	0.055	2500-4300	600-1900	3
12	Sacramento	19465	0.180	2400-2800	900-1600	12
13	Fresno	13912	0.129	2000-2700	1000-2200	13
14	Palmdale	3338	0.031	1900-2700	2000-4200	13
15	Palm Spring-Intl	3885	0.036	1000-1300	4000-6600	10
16	Blue Canyon	3135	0.029	4300-6000	200-1000	16

Table 7 Climate zone weighting factors.

	1 (Arcata)	3 (Oakland)	10 (Riverside)	12 (Sacramento)	13 (Fresno)	16 (Blue Canyon)
Total Weight Factor	0.006	0.128	0.431	0.246	0.160	0.029

3.3 Energy Use Normalization with Relative Exposure

Most of the results presented in this work are raw simulation outputs in which the IAQ provided in each case is not the same. When assessing energy savings from an airtightness requirement, this means the results presented in Section 4.1 conflate changes in airtightness with changes in the ventilation rate and relative exposure. To isolate the energy associated with ventilation from other envelope loads, we simulated cases with no fan operation and no envelope leakage. The energy use for these envelope-only cases was subtracted from the total to get the ventilation-only component. We used these ventilation-only energy use estimates to determine estimates of energy savings normalized by relative exposure. This is achieved by simply multiplying the ventilation-only energy estimates by the relative exposure in this case. E.g., a relative exposure of 1.2 would lead to a 20% increase in energy use to correct to a relative exposure of 1. While this assumed linear response my not be exactly true in all cases it is the only way to achieve comparisons at the same relative exposure without considerable manual iteration. The total HVAC energy use was then calculated for each case by adding the adjusted ventilation energy use back onto the envelope-only HVAC energy use to provide an estimate of energy use for each case when they are forced to provide the same exposure. These exposure-adjusted adjusted total energy use values are presented separately in Section 4.2.

3.4 Whole House Mechanical Ventilation in Title 24

Since the 2008 code cycle, California's Title 24 building energy code has required whole house mechanical ventilation in new homes and in additions >1,000 ft^2. The code requirements have evolved to include multiple calculation methods for sizing the fans. In this study, we examined six fan sizing methods available to designers and to the Energy Commission in specifying requirements of the 2019 Title 24. There are sizing methods that explicitly account for natural infiltration and those that do not (described in detail in Section 3.4.1 and 3.4.2). The fan sizing methods are summarized in Table 9. All calculated fan sizes are illustrated for each sizing method in Appendix B-1 (Figure 28 through Figure 33).

3.4.1 Whole house fan Size Calculation Without Natural Infiltration

We assessed three fan sizing methods that include no direct estimates of natural infiltration, and their calculated fan airflows do not vary by the factors that affect infiltration, namely airtightness, house geometry and climate zone.

3.4.1.1 Fan Ventilation Rate Method (T24_2008)

The Fan Ventilation Rate method (referred to as ***T24_2008***) was added as a requirement in the Title 24 (2008) Residential Compliance Manual Section 4.6.2. It calculates Whole house fan airflow from conditioned floor area and occupancy, as shown in Equation 2. This was the fan sizing equation in the version of ASHRAE 62.2 at the time the requirement was written. This fan sizing approach implicitly assumed a background infiltration rate equivalent to 0.02 cfm per ft^2 of conditioned floor area. This is an appropriate natural infiltration rate assumption for homes in the 5-7 ACH_{50} range, but it is inadequate for substantially airtight homes. The T24_2008 method results in fan sizes that do not vary by either airtightness or location. This fan sizing method continues to be available in the current 2016 Title 24, and it is the default sizing method for IAQ ventilation in the prescriptive and performance path homes.

$$Q_{fan} = \frac{A_{floor}}{100} + 7.5 \times (N_{br} + 1) \qquad (2)$$

Q_{fan} = calculated Whole house fan airflow, cfm

A_{floor} = conditioned floor area, ft^2

N_{br} = number of bedrooms

3.4.1.2 Current Builder Practice Method (BuilderPractice)

Field research suggests that current builder practice in California homes results is to install a Whole house fan that is oversized relative to the T24_2008 airflow requirement by roughly 40%[1]. We refer to this fan sizing as ***BuilderPractice*** and use a 40% oversized fan in the simulations (calculated using Equation 3). We hypothesize that this over-sizing is the result of builders rounding up the required airflow rates to match that of the nearest retail fan.

$$Q_{fan} = 1.4 \times Q_{fan,T24\_2008} \qquad (3)$$

[1] The 70 homes studied in the companion field study (Chan e al. (2018)) had an average measured fan flow 50% above the minimum requirement. However all these data were not available at the time of performing the simulations and a 40% value was used based on the initial field study results and the results of Stratton et al. (2012) in 15 California homes.

3.4.1.3 Total Ventilation Rate Method (Qtotal)

In 2013, an alternative IAQ compliance path for airtight, low-infiltration homes was added to Title 24 named the Total Ventilation Rate method. Homes using the Total Ventilation Rate method would typically calculate a fan size by subtracting an infiltration estimate from a whole house target airflow. This is based directly on changes to ASHRAE 62.2 that explicitly changed the basic equations to from fan sizing (based on an assumed natural infiltration air flow of 2 cfm/100 sq. ft. of floor area) to a total ventilation target. In this no-infiltration sizing method (referred to as ***Qtotal***), we simply set the Whole house fan airflow equal to the whole house ventilation airflow target, as in Equation 4, where the fan airflow is equal to Q_{tot}.

$$\mathbf{Q_{tot} = 0.03\ A_{floor} + 7.5 \times (N_{br} + 1)} \qquad \textbf{(4)}$$

3.4.2 Whole house fan Size Calculation With Natural Infiltration

Four Whole house fan sizing methods are examined that include natural infiltration estimates with varying levels of sophistication, all of which are based on the methods in the ASHRAE 62.2 ventilation standard. ASHRAE 62.2-2016 is structured to help ensure that all compliant homes have similar whole house airflows that are consistent with the target airflow set by the standard (Q_{tot}). We begin by outlining the general process of calculating a whole house target airflow (Q_{total}), an infiltration estimate (Q_{inf}) and a resulting Whole house fan airflow (Q_{fan}). We then highlight where specific fan sizing methods diverge from this general approach.

3.4.2.1 Total Ventilation Rate Method Including Infiltration (T24_2013)

Here we take the Total Ventilation Rate method and account for natural infiltration in the Whole house fan sizing (referred to as ***T24_2013***).

A target ventilation airflow (Q_{total}) for the combined natural and mechanical flows is calculated using Equation 4. The natural infiltration airflow (Q_{inf}) is estimated from blower door air leakage, house geometry and climate data. The normalized leakage is calculated using the effective leakage area from a blower door measurement, combined with the conditioned floor area and height of the building using Equation 5. The annual effective natural ventilation airflow (Q_{inf}) is calculated using Equation 6 using the weather and shelter factor (*wsf*). The *wsf* is designed to give an annual average infiltration airflow estimate that would provide pollutant exposure equivalent to that under time-varying infiltration airflows and includes on assumptions about wind shelter and envelope leakage distribution. A *wsf* value for each TMY3 climate file location is provided in Normative Appendix B-1 to ASHRAE 62.2-2016. The weather file locations and *wsf* values used in the HENGH simulations are reproduced in Table 8. Turner et al. (2012) describe the methods used to calculate the *wsf* factors for the 62.2 standard.

The fan airflow (Q_{fan}) is calculated as the difference between the target ventilation rate and the natural infiltration rate using Equation 7.

$$\mathbf{NL} = \mathbf{1000} \times \left[\frac{\mathbf{ELA}}{\mathbf{A_{cond}}}\right] \times \left[\frac{\mathbf{H}}{\mathbf{H_{ref}}}\right]^{\mathbf{Z}} \quad \mathbf{(5)}$$

NL = normalized leakage
ELA = effective leakage area, ft^2
H = vertical distance between the lowest and highest above-grade points within the pressure boundary, ft
H_{ref} = reference height for one-level of home, 8.2 ft

$$\mathbf{Q_{inf}} = \frac{\mathbf{NL \times wsf \times A_{floor}}}{\mathbf{7.3}} \quad \mathbf{(6)}$$

Q_{inf} = Effective annual infiltration rate, cfm
NL = normalized leakage
wsf = weather and shielding factor from Normative Appendix B-1 62.2-2016
A_{floor} = floor area of residence, ft^2

$$\mathbf{Q_{fan}} = \mathbf{Q_{total}} - \mathbf{Q_{inf}} \quad \mathbf{(7)}$$

Q_{fan} = required mechanical ventilation rate, cfm
Q_{total} = Total required ventilation rate, cfm
Q_{inf} = Effective annual infiltration rate, cfm

Table 8 CEC climate zones, representative cities, selected TMY3 id and site locations, and weather and shielding factors (wsf) for fan sizing in HENGH simulations.

CZ	Representative City	TMY3 ID	TMY3 Site Name	wsf
1	Arcata	725945	ARCATA AIRPORT	0.56
2	Santa Rosa	724957	SANTA ROSA (AWOS)	0.49
3	Oakland	724930	OAKLAND METROPOLITAN ARPT	0.54
4	San Jose-Reid	724945	SAN JOSE INTL AP	0.48
5	Santa Maria	723940	SANTA MARIA PUBLIC ARPT	0.52
6	Torrance	722950	LOS ANGELES INTL ARPT	0.42
7	San Diego-Lindbergh	722900	SAN DIEGO LINDBERGH FIELD	0.38
8	Fullerton	722976	FULLERTON MUNICIPAL	0.34
9	Burbank-Glendale	722880	BURBANK-GLENDALE-PASSADENA AP	0.39
10	Riverside	722869	RIVERSIDE MUNI	0.42
11	Red Bluff	725910	RED BLUFF MUNICIPAL ARPT	0.5
12	Sacramento	724830	SACRAMENTO EXECUTIVE ARPT	0.51
13	Fresno	723890	FRESNO YOSEMITE INTL AP	0.45
14	Palmdale	723820	PALMDALE AIRPORT	0.57
15	Palm Spring-Intl	747187	PALM SPRINGS THERMAL AP	0.46
16	Blue Canyon	725845	BLUE CANYON AP	0.44

3.4.2.2 ASHRAE 62.2-2016 Ventilation Standard Method (ASH622_2016)

The current ASHRAE 62.2-2016 ventilation standard (referred to as ***ASH622_2016***) builds on the T24_2013 calculation approach described in Equations 5-7, but it adds a superposition adjustment (∅) to account for the sub-additivity of unbalanced mechanical airflows with natural infiltration. Inclusion of superposition reduces the effective infiltration airflow (Q_{inf}, Equation 6) used in mechanical fan sizing when the Whole house fan is unbalanced, as in Equations 8 and 9. This increases the required mechanical airflow.

$$\emptyset = \frac{\mathbf{Q_{inf}}}{\mathbf{Q_{total}}} \quad \textbf{(8)}$$

∅ = sub-additivity factor, 1 if balanced Whole house fan
Q_{inf} = annual effective infiltration airflow, cfm
Q_{total} = target combined natural and mechanical airflow, cfm

$$\mathbf{Q_{fan}} = \mathbf{Q_{total}} - \emptyset(\mathbf{Q_{inf}}) \quad \textbf{(9)}$$

Superposition refers to the sub-additive combining of unbalanced airflows in homes, such as exhaust or supply ventilation fans with natural infiltration. When an unbalanced fan turns on, its airflow does not add directly to the existing infiltration, rather it is sub-additive, so that the resulting total flow is less than the sum of the two individual flows. Unbalanced fans interact with the envelope pressures in the home, shifting the neutral pressure plane vertically, which leads to this sub-additive combination of the fan and infiltration airflows. 50 l/s infiltration flow plus 50 l/s fan airflow does not lead to 100 l/s of house airflow, rather some total airflow less than 100 results. Balanced ventilation fans do not interact with the house pressure balance, so they add simply and directly to infiltration. The standard method for combining these flows historically was quadrature (ASHRAE, 2013; Wilson & Walker, 1990). But recent work has developed new relationships that have been incorporated into ASHRAE 62.2-2016 (Hurel, Sherman, & Walker, 2016). As such, fan sizing in 62.2-2016 can account for this sub-additivity, requiring a larger unbalanced fan than balanced fan. Real-time ventilation rate calculations for equivalence also include this sub-additivity for unbalanced ventilation fans.

3.4.2.3 Adopted 2019 Title 24 Method (T24_2019)

Finally, we include the Whole house fan sizing method that has been adopted in the 2019 code cycle for the Title 24 building energy code (T24_2019). The adopted fan sizing procedure is identical to the ASH622_2016 method described in Section 3.4.2.2, except envelope leakage is treated differently. IAQ fans in homes with envelope leakage greater than 2 ACH50 are sized using a default 2 ACH_{50} envelope leakage value. Homes with reduced envelope leakage below the 2 ACH_{50} limit use the actual leakage rate in fan sizing calculations. So, for very airtight homes, the calculated IAQ fan sizes are identical to those using the ASH622_2016 sizing procedure, while leakier homes have larger fan airflows, because of lower natural infiltration estimates resulting from the default leakage rate of 2 ACH_{50}.

Table 9 Whole house fan sizing methods for Title 24 assessment

Name	Abbreviation Used	Description / Notes	Inputs	Account for Infiltration?	Parameters Included in Infiltration Estimate		
					Envelope Airtightness	Climate Zone and Geometry	Superposition
Fan Ventilation Rate Method	T24_2008	Use floor area and occupancy to calculate fan flow rate based on assumed infiltration (2 cfm per ft^2 floor area). Fan sizing method initially adopted in 2008 T24 Section 4.6.2 of the Residential Compliance Manual. Used as default fan sizing in Performance Path compliance and in prescriptive homes. Most likely compliance path for new homes. Assumed infiltration is roughly correct for homes in the 5-7 ACH_{50} range. More airtight homes will be under-vented.	Floor area; number of bedrooms	No			
Current Builder Practice Method	BuilderPractice	40% is added to the T24_2008 sizing method Whole house fan airflows. This reflects current builder practice based on field studies in California homes. To demonstrate compliance, fans are sized to the T24_2008, but installed airflows are commonly 40% higher, likely due to limitations in available fan airflows on the market (typically 50-80-110 cfm, for example). Builders round up for compliance.	Floor area; number of bedrooms	No			
Target Ventilation Rate Method	Qtotal	Fan sized to the target ventilation rate from the T24_2013 method using floor area and occupancy.	Floor area; number of bedrooms	No			
Total Ventilation Rate Method	T24_2013	Calculate fan flow required to achieve target total ventilation rate using floor area, occupancy and infiltration calculated from blower door measurement of envelope airtightness. Fan sizing method added to T24 in 2013, alongside T24_2008. A small subset of new homes may be complying using this path, especially very airtight homes (e.g., Passive Houses).	Floor area; number of bedrooms; CZ; Airtightness; # of stories	Yes	X	X	
ASHRAE 62.2-2016 Ventilation Standard Method	ASH622_2016	Same as T24_2013, but with the superposition adjustment requiring larger sized unbalanced fans. This is the new default method for calculating mechanical fan size in the 2016 version of ASHRAE 62.2.	Floor area; number of bedrooms; CZ; Airtightness; # of stories; Whole house fan type	Yes	X	X	X
Adopted 2019 Title 24 Method with Adjustment by Fan Type	T24_2019	Same as ASH622_2016, envelope leakage is fixed at 2 ACH_{50} for all cases with leakage greater than 2 ACH_{50}. This leads to larger IAQ fan sizes than calculated with ASH622_2016. Actual envelope leakage is used in cases with leakage below 2 ACH50. Fan flows are identical to ASH622_2016 in these cases.	Floor area; number of bedrooms; CZ; Airtightness; # of stories; Whole house fan type	Yes	X (in cases <2 ACH_{50})	X	X

3.4.3 Calculation of Relative Exposure

The relative exposure for a given time step is calculated from the relative exposure from the prior step (R_{i-1}), the target ventilation rate (Q_{tot}) and the current ventilation rate (Q_i) using Equation 10, unless the real-time or scheduled ventilation is zero, then Equation 11 is used.

$$\mathbf{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t / V_{space}}} \quad \textbf{(10)}$$

R_i = relative exposure for time-step i
R_{i-1} = relative exposure for previous time-step i-1
Q_{tot} = Total ventilation rate from ASHRAE 62.2-2016 (see Equation 4), cfm
Q_i = Ventilation rate from the current time-step, cfm
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, ft^3

$$\mathbf{R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \quad \textbf{(11)}$$

The target ventilation rate, Q_{tot} is calculated using Equation 4. The real-time ventilation rate (Q_i) is the combined airflow of the Whole house fan and natural infiltration, predicted by the REGCAP mass balance model.

4 Results

A total of 960 annual simulations were run using the REGCAP building simulation tool. The parametrically varied parameters included 7 Whole house fan sizing methods, 5 levels of airtightness (0.6, 1, 2, 3, 5), 6 CEC climate zones (1, 3, 10, 12, 13, 16), 2 building prototypes (large, 2-story and medium, 1-story), and 2 fan types (balanced and exhaust). Tabular summaries of energy end-uses, normalized total HVAC energy, Whole house fan airflows, whole house air exchange rates and relative exposure are provided for each of 960 simulations in Appendix B-1 Table 14.

4.1 Raw (not exposure corrected) Results

4.1.1 Weighted Average Exposure and Energy Use Under An Airtightness Requirement in Title 24

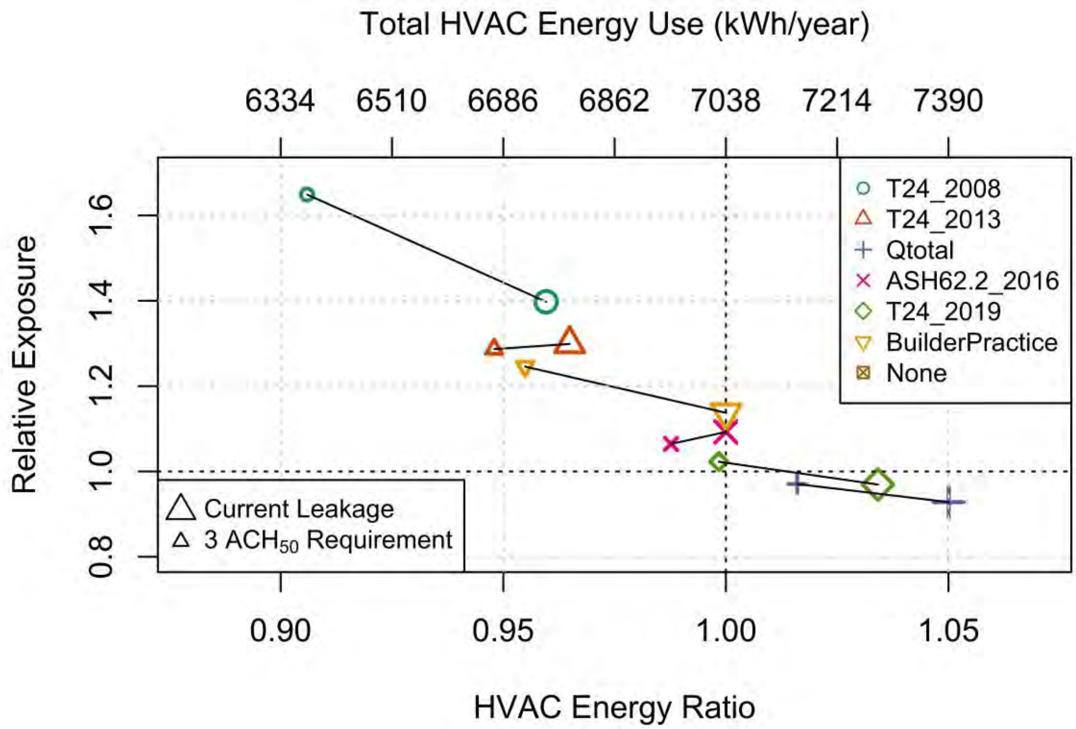
We calculated weighted average IAQ and energy results, based on assigned weightings for the prototype house, climate zone, ventilation fan type and envelope airtightness (see Section 3.2 for details on the applied weights). These were assessed under two scenarios—the current airtightness distribution and a future distribution with a 3 ACH_{50} envelope requirement in the

Title 24 (see airtightness distribution weights in Table 3 from Section 3.2). These weighted average results are summarized in Table 10 and illustrated in Figure 1. Results are further refined by prototype (2-story large vs. 1-story medium homes) in Table 11 to highlight substantial differences between 1- and 2-story homes. We report HVAC energy use in two ways. First, is in absolute kilowatt-hour consumption (referred to as "HVAC Energy Use" in Table 10). Second, we report consumption that is normalized against cases with a Whole house fan sized to the ASH622_2016 method under the current airtightness distribution (referred to as "HVAC Energy Ratio" in Table 10). These estimates allow comparisons between fan sizing methods, as well as between airtightness scenarios for the same fan sizing method or between methods. For example, the T24_2019 fan sizing method has weighted average estimated HVAC savings of 3.6% under an airtightness requirement in the code. This is calculated as the difference between current and future HVAC Energy Ratio Values (1.034 – 0.998 = 0.036). Similarly, we can compare weighted average HVAC energy use under the current Fan Ventilation Rate Method (T24_2008) with the newly adopted T24_2019 sizing method. The new adopted fan sizing will increase estimated HVAC energy use by 7.4% (0.960 – 1.034 = -0.074), and will reduce exposure by 43% (1.40 – 0.97 = 0.43).

Table 10 Weighted average relative exposure, ventilation energy and HVAC energy, with current airtightness and under potential future airtightness requirement.

Fan Sizing Method	Relative Exposure			HVAC Energy Use (kWh/year)			HVAC Energy Ratio		
	Current	Future	Change	Current	Future	Savings	Current	Future	Savings
T24_2008	1.40	1.65	25%	6754	6376	378	0.960	0.906	5.4%
T24_2013	1.30	1.29	-1%	6791	6672	119	0.965	0.948	1.7%
Qtotal	0.93	0.97	4%	7390	7151	239	1.050	1.016	3.4%
ASH62.2_2016	1.09	1.06	-3%	7038	6951	87	1.000	0.988	1.2%
T24_2019	0.97	1.02	5%	7279	7027	252	1.034	0.998	3.6%
BuilderPractice	1.14	1.25	11%	7039	6721	318	1.000	0.955	4.5%
None	2.75	4.20	155%	6126	5735	391	0.870	0.815	5.6%

Figure 1 Weighted average population level HVAC energy and relative exposure when airtightening new California homes under different fan sizing methods. Small symbols are the future, airtightened results, and the large symbols are the existing results.



Overall, our results show that none of the Whole house fan sizing methods are perfect, and that all of them have weighted average relative exposure either above or below 1.0 under both current and future airtightness weightings. In the presence of Whole house fan ventilation, a new airtightness limit in the Title 24 would lead to relatively marginal whole house HVAC energy savings of 1-5% of total HVAC consumption (averaging roughly 100 to 300 kWh/year). The magnitude of these effects and the change in relative exposure depend on the fan sizing method and house prototypes, as discussed below. The greatest savings are for the fan sizing methods that do not vary Whole house fan sizing by airtightness (T24_2008, T24_2019, Qtotal and BuilderPractice). Notably, T24_2019 does increase the required fan size in cases with leakage below 2 ACH_{50} (i.e., the 0.6 and 1 ACH_{50} cases), but the weighting factors for these cases amount to only 6% of total weight. These sizing methods do not increase the required Whole house fan airflow in response to increased airtightness. When fan sizes remain constant and infiltration is reduced, HVAC energy and ventilation rates are reduced while exposure increases. In Figure 1, these cases have lines that slope up and to the left, indicating reduced HVAC energy use and increased relative exposure. For fan sizing methods that use infiltration adjustment (ASH62.2_2016 and T24_2013), the airtightness savings are still larger than the increased ventilation energy, but net-savings are small (roughly 1%). These methods maintain relative exposure very close to one, rather than increasing it. In Figure 1, these cases have short lines tracking slightly down and to the left, indicating small HVAC energy savings and very slightly reduced exposure.

Under a hypothetical 3 ACH_{50} airtightness requirement, the infiltration-adjusted sizing methods have larger fan airflows and slightly reduced exposure (and increased energy use), while the other fan sizing methods have the same fan airflows and increased exposure (and reduced energy use). The cases with no Whole house fan have the worst exposure under an airtightness requirement (4.37), which illustrates the necessity of Whole house fan ventilation as homes become more airtight. This equates to more than a quadrupling of contaminant concentrations in non-mechanically ventilated homes. The only fan sizing method with weighted average exposure below 1.0 under a 3 ACH_{50} airtightness requirement was the Qtotal method (0.97), whose exposure was also below 1.0 under current airtightness weightings. All other fan sizing methods have weighted average exposure above 1.0 under an airtightness requirement. Of these methods, those that are closest to 1.0 are the T24_2019 and ASH622_2016 methods (1.02 and 1.06, respectively), with energy savings associated with airtightening of 3 and 1%, respectively. The T24_2013 method would have lower exposure under the airtightness requirement, though still greatly above 1.0 (at 1.29). All other sizing methods have similarly high exposure under the airtightness requirement, generally falling in the 20 to 60% worse range (for BuilderPractice (1.25) and T24_2008 (1.65)). This worsened IAQ buys these cases roughly 5% total HVAC energy savings from airtightening relative to current airtightness weightings.

Based on these results, the T24_2019 fan sizing method has the weighted average exposure closest to 1.0 with both current and future airtightness weightings (at 0.97 and 1.02). The two closest competitors that maintain exposure close to 1.0 under both airtightness weighting are the current ASH622_2016 and the Qtotal methods. The ASH622_2016 method has consistently higher exposure (at 1.09 and 1.06), while the Qtotal method has consistently lower exposure (at 0.93 and 0.97). Under current airtightness weights, the T24_2019 and Qtotal methods increase energy use by 3 and 5% relative to the ASH622_2016 method (and by 1 and 3% under future airtightness weights). The difference in weighted average total consumption between any of these three sizing methods is roughly 350 kWh/year (though absolute kWh differences are greater in harsher climate zones).

Performance was substantially affected by house prototype, so we also show the weighted averages disaggregated by prototype house in Table 11. The differences are due to the different number of stories and increased infiltration rates with the 2-story homes. Overall, weighted average savings from airtightening are much higher for the 2-story large prototypes, between 3 and 7% (200 to 500 kWh/year) across all fan sizing methods. In contrast, the 1-story medium homes average only 0 to 3% (roughly 0 to 200 kWh/year) savings across fan sizing methods.

Table 11 Weighted average relative exposure and HVAC energy, by fan sizing method and house prototype, with current airtightness and under potential future airtightness requirement.

Fan Sizing Method	Prototype	Relative Exposure			HVAC Energy Use (kWh/year)			HVAC Energy Ratio		
		Current	Future	Change	Current	Future	Savings	Current	Future	Savings
T24_2008	2-story	1.28	1.59	30%	7193	6684	509	0.972	0.903	6.9%
	1-story	1.54	1.73	19%	6218	5999	218	0.943	0.910	3.3%
T24_2013	2-story	1.26	1.32	6%	7149	6921	228	0.966	0.935	3.1%
	1-story	1.35	1.25	-10%	6354	6367	-14	0.964	0.966	-0.2%
Qtotal	2-story	0.90	0.97	6%	7834	7470	364	1.058	1.009	4.9%
	1-story	0.96	0.98	2%	6848	6761	87	1.038	1.025	1.3%
ASH62.2_2016	2-story	1.08	1.08	0%	7402	7214	187	1.000	0.975	2.5%
	1-story	1.11	1.04	-7%	6594	6630	-36	1.000	1.005	-0.5%
T24_2019	2-story	0.95	1.03	8%	7699	7310	388	1.040	0.988	5.2%
	1-story	0.99	1.01	2%	6765	6681	84	1.026	1.013	1.3%
Builder Practice	2-story	1.08	1.24	16%	7481	7020	461	1.011	0.948	6.2%
	1-story	1.21	1.26	5%	6499	6355	143	0.986	0.964	2.2%
None	2-story	2.25	3.43	117%	6508	6001	507	0.879	0.811	6.9%
	1-story	3.36	5.14	178%	5659	5410	249	0.858	0.820	3.8%

4.1.2 Relative Exposure

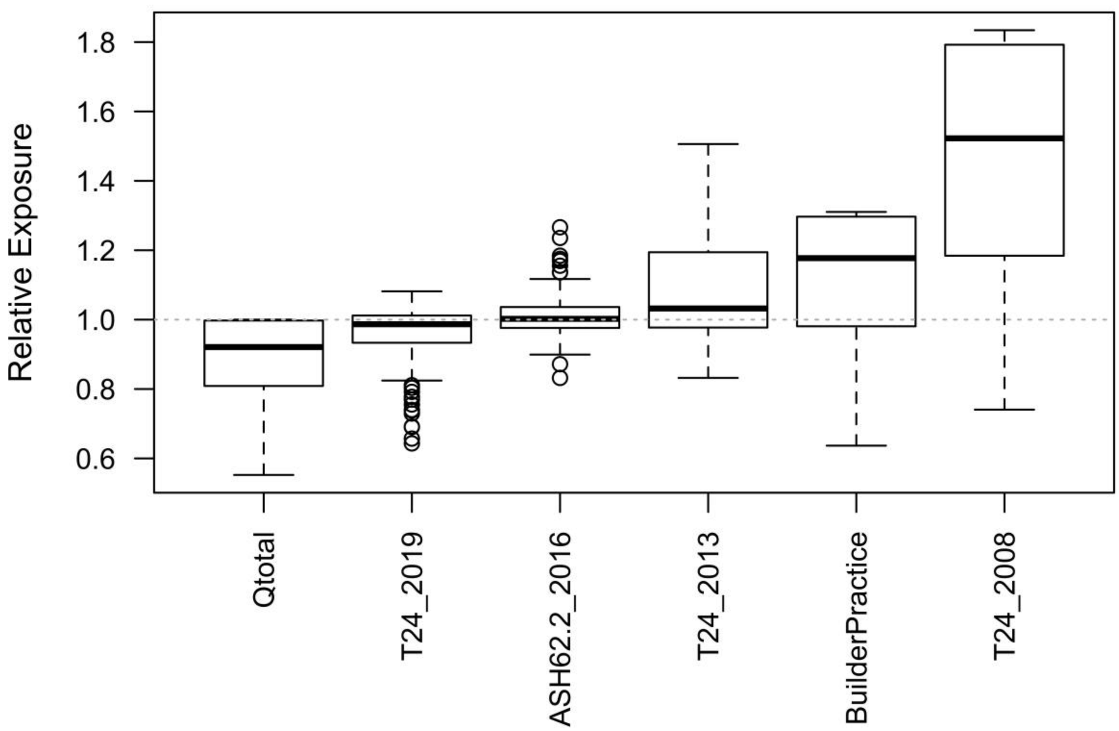
From an IAQ perspective, the relative exposure is the primary outcome of this work. As noted above, the fan sizing methods are imperfect and none achieved weighted average exposure equal to 1.0 and most of them had higher exposures. In addition to weighted averages, the distributions of relative exposure values are also critical. It is desirable for exposures to be tightly clustered around the mean value of 1.0, which ensures the homes are neither under- nor over-ventilated, which limits either poor IAQ or increased energy consumption.

We show how relative exposure distributions change with fan sizing method in Figure 2[2]. The ASHRAE 62.2-2016 fan sizing method, which accounts for all factors affecting infiltration, as

[2] In the boxplots in this report the middle bar represents the median, the boxes the 25th and 75th percentile, the whiskers are range. The circles/dots represent outliers that are more than one and half times the interquartile range from the median.

well as fan type (balanced vs. exhaust), has the tightest distribution of relative exposures and averages close to 1.0. The T24_2019 sizing method is also tightly clustered, with slightly greater variance. The outlier cases with low exposure when using T24_2019 are the 3 and 5 ACH_{50} homes whose fans are sized assuming envelope leakage of only 2 ACH_{50}. This results in higher air flow IAQ fans resulting in lower exposure and higher energy use. All other sizing methods have the potential to substantially under- or over-ventilate any given home, depending on its location, airtightness, prototype and fan type because they do not account for these interactions. Variability was greater when using the other sizing methods that did not include a sub-additivity adjustment for unbalanced fans.

Figure 2 Boxplots of annual relative exposure, by fan sizing method.



Air exchange rates and relative exposure aggregated by airtightness and fan sizing method are compared in Figure 3 and Figure 4. These figures show trends averaged over house prototype, fan type and climate zone. We then assessed individual cases and the relationship between fan sizing method, house prototype, fan type, airtightness and exposure. Figure 5 shows these case-by-case results for CZ10 (Riverside). Climate zone does not substantially affect any of the patterns and trends with airtightness, or comparisons across fan sizing methods, so we use CZ10 as a frame for discussion (other climate zone plots are provided in the Appendix B-1 Figure 15 through Figure 19).

Figure 3 Mean air exchange rates by envelope airtightness and fan sizing method, aggregated across prototype, fan type and climate zone.

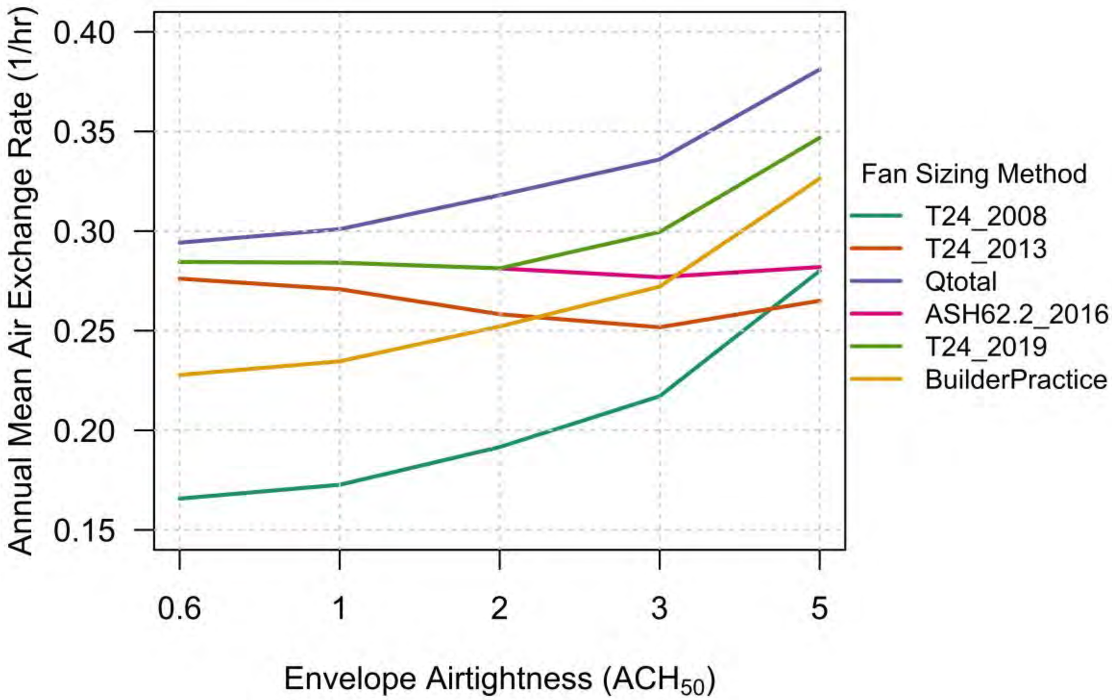


Figure 4 Mean relative exposure by envelope airtightness and fan sizing method, aggregated across prototype, fan type and climate zone.

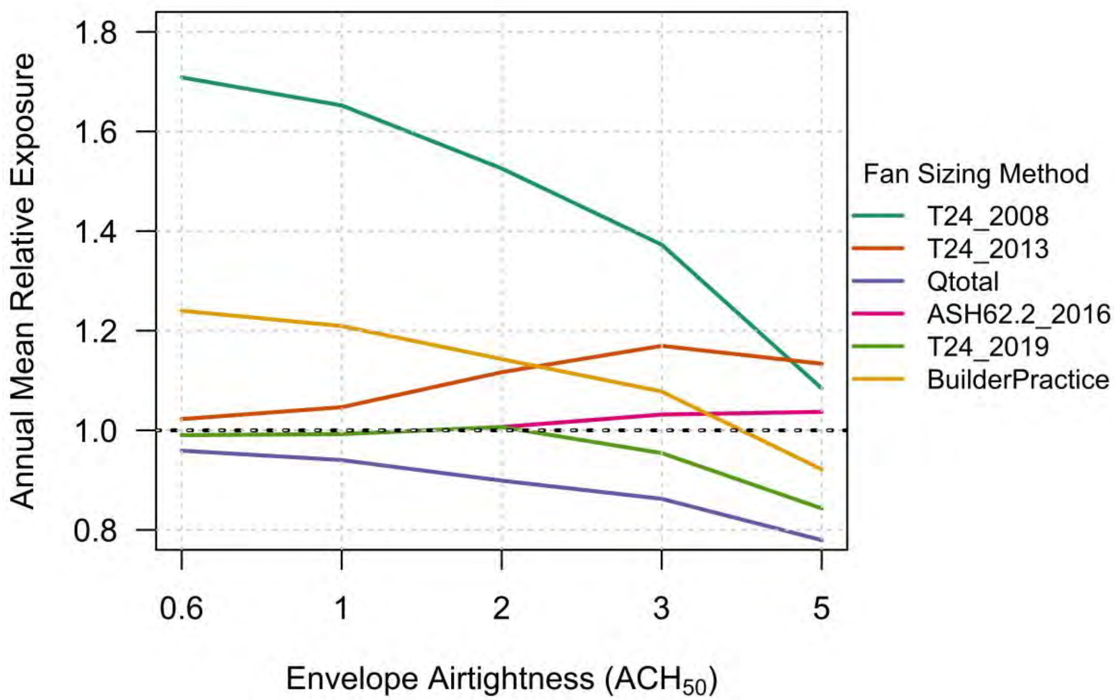
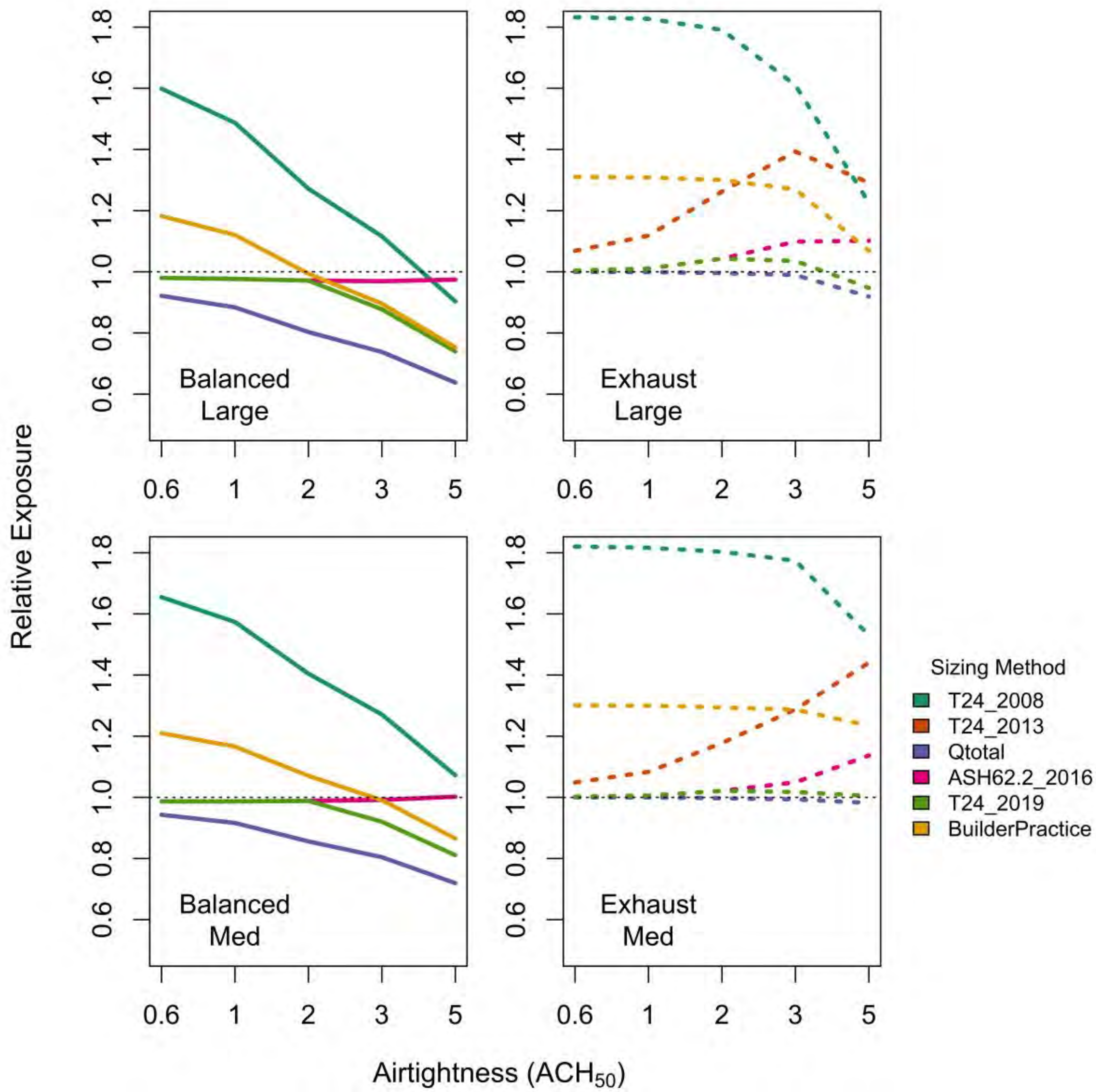


Figure 5 Variability of relative exposure with airtightness in CZ10, by prototype, fan type and fan sizing method.



These results show the following trends: (1) exposure is reduced (and ventilation rates increase) as air leakage increases, (2) the ASH622_2016 sizing method provides the most consistent exposure across these factors, (3) exhaust fans have higher exposure than balanced fans, (4) for exhaust fans sized using fixed airflow methods, there is little change in exposure between 0.6 and 3 ACH_{50}, and (5) exposure is higher in 1-story medium prototype homes.

For most fan sizing methods, this inconsistency translates to either unnecessarily high energy use or pollutant exposure for the occupants. For the majority of fan sizing methods and fan types, relative exposure goes down as air leakage increases, with the 5 ACH_{50} cases generally having the lowest exposure (and highest ventilation rates and energy use).

Balanced fan cases have overall lower exposure compared to exhaust fans because balanced fans simply add to infiltration while exhaust fans are sub-additive resulting in higher air flows for homes with balanced fans. For fixed airflow sizing methods using balanced Whole house fans (T24_2008, Qtotal, T24_2019, and BuilderPractice), increasing air leakage leads to higher ventilation rates and reduced exposure. As a result, exposure varies widely above and below 1.0 depending on leakage. The infiltration adjusted sizing methods (ASH622_2016 and T24_2013) are flat across airtightness levels with balanced Whole house fans, because they reduce Whole house fan airflow in response to increased infiltration estimates. These results again illustrate that the current ASH62.2_2016 sizing method has the most consistent relative exposure—neither under- nor over-ventilating the homes. For exhaust fans, the 2019 proposed sizing method with sub-additivity (T24_2019) and the Qtotal sizing methods provide exposure most consistently at or below 1.0, though this consistency falls apart in balanced fan cases, where the fixed airflow sizing methods either strongly under- or over-ventilate the homes.

For exhaust fan cases all sizing methods that don't scale with envelope leakage are under-ventilating the home relative to the ASHRAE standard target airflow. The worst of the sizing methods is the current default method used in Title 24 compliance—T24_2008 fan ventilation rate method—with exposure 50-80% higher in this climate zone. For fixed airflow sizing methods, there is little change in exposure (or ventilation rates) between 0.6 and 3 ACH_{50}. In the 1-story exhaust fan cases, there is not even substantial change when at 5 ACH_{50}. In these exhaust fan cases, the whole house airflows are fully dominated by the mechanical exhaust fans, and natural infiltration contributes almost no airflow. As a result, changing leakage area does not affect ventilation rates, exposure or energy use.

4.1.3 HVAC Energy Savings from Increasing Airtightness

From an energy perspective, there is a benefit to reducing the ventilation rates in homes and increasing relative exposure (and worsening IAQ), as has traditionally been done when air sealing homes. Yet, even for cases with the same exposure, we expect the airtightening of homes to save energy, because airtightening and mechanically ventilating shifts ventilation airflows to mild weather periods, and it reduces the annual average airflow required for a given exposure target (see Section 2.2). This time-shifting will have the most impact in locations with the harshest weather conditions. These effects of changing ventilation rates and exposure (IAQ), as well as changing when ventilation occurs and how much is needed, interact to determine changes in energy consumption from airtightening with mechanical ventilation. For some cases, these effects will interact additively to increase savings, and in others, we expect these effects to cancel out to some extent, limiting potential savings.

All fan sizing methods are imperfect. As a result, when changing airtightness, the ventilation rate and relative exposure are also changed. This is critical when assessing energy savings from airtightening because the IAQ is different between the cases. The fixed airflow fan sizing methods make no attempt to account for these changes with air leakage, while the infiltration-adjusted sizing methods try (albeit imperfectly) to maintain similar ventilation rates and exposure in all homes.

In fixed airflow sizing methods, balanced fans have much higher exposure and lower ventilation in more airtight cases (compared with balanced fans in leakier homes), so saving energy through airtightening is straightforward, albeit at the cost of poorer IAQ. Fixed airflow exhaust fan cases also tended to have higher exposure (and lower ventilation rates) at lower leakage levels, but this was static between 0.6 and 3 ACH_{50}, and in some 1-story cases, it remained static up to 5 ACH_{50}. As noted before (and discussed in Section 4.3), these cases were strongly mechanical fan dominated, such that natural infiltration contributed almost no additional airflow. As a result, changing the airtightness did not change ventilation rates, exposure or energy use. These cases may show some energy savings by going from 5 to 3 ACH_{50}, but very little for further tightening.

For infiltration-adjusted sizing methods, balanced fans had very little variability in ventilation rates or exposure across airtightness levels. Exposure was in fact very slightly lower (higher ventilation rates) in the most airtight cases. This same pattern was generally true for infiltration-adjusted exhaust fan cases, where the highest exposure (and lowest ventilation rates) were in the leakiest homes. For both exhaust and balanced fans sized with infiltration-adjustment, we expect that airtightening will reduce exposure and actually increase ventilation rates, which will counteract the potential energy savings from time-shifting ventilation to milder periods.

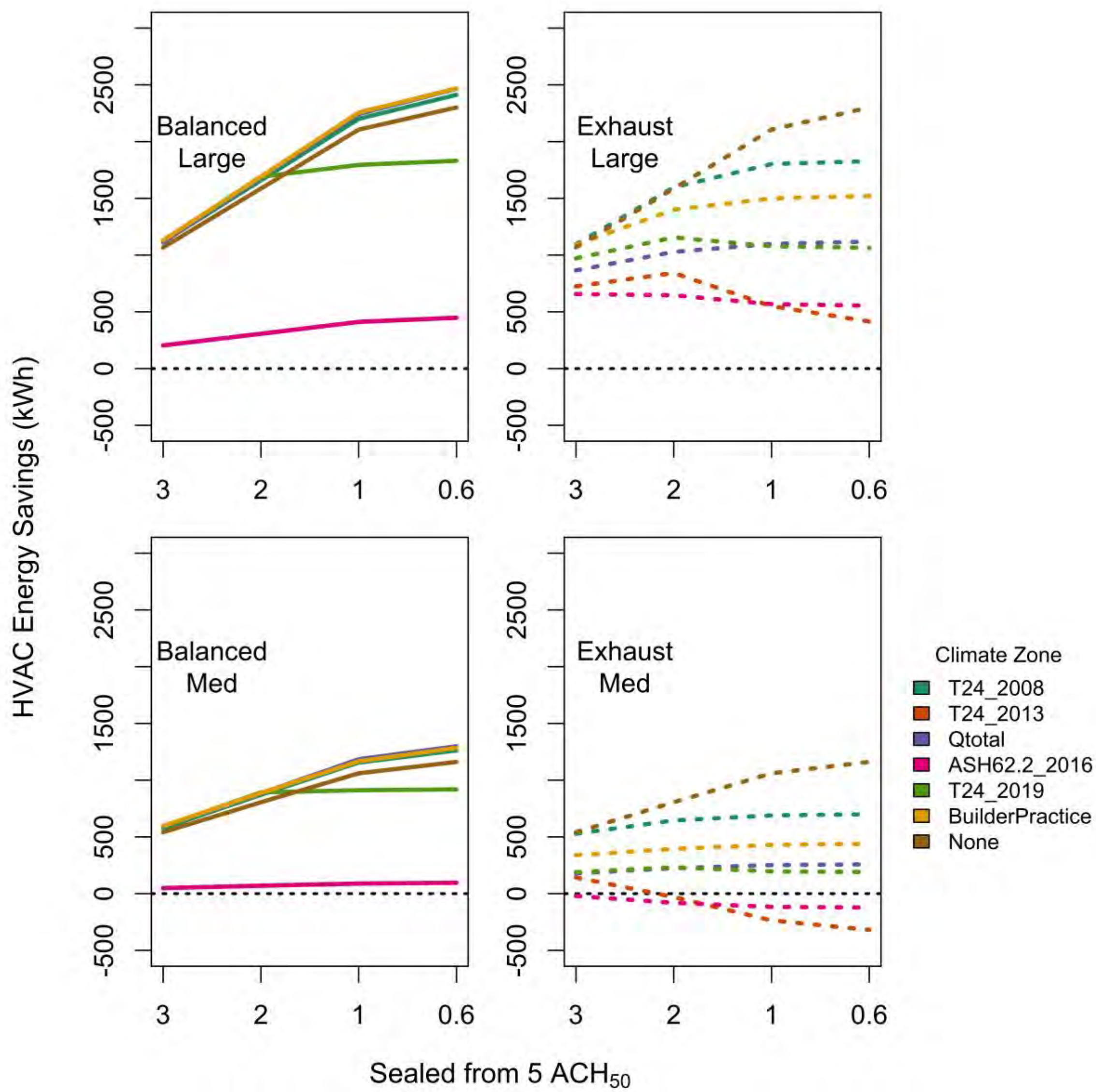
Consistent with these observations, the weighted average results in Section 4.1 suggest that marginal annual HVAC savings on the order of 1-5% can be expected if a 3 ACH_{50} or less airtightness requirement were included in the Title 24 for new homes. A distinction was seen between fan sizing methods that adjusted fan size by airtightness, climate zone and fan type, compared with fixed airflow methods, where fan size is independent of house airtightness. The fixed airflow sizing methods had higher weighted average HVAC savings of 3 to 5% (and generally higher occupant exposure), while the variable fan sizing methods had very low savings of roughly 1% (but reduced exposure marginally).

These weighted average results are useful for a statewide assessment of priorities, but we are also interested in the impacts of airtightening individual homes, which we expect will align with the trends in exposure discussed above. First, we average the results across climate zones and show the potential savings for each fan sizing method in Figure 6. Overall, the predicted savings from air leakage reductions increases as fan airflows get smaller. So, savings are generally greatest in cases with no IAQ fan ventilation, followed by the under-vented T24_2008, then BuilderPractice, etc. In these cases, predicted energy savings grow as leakage is incrementally reduced down to 0.6 ACH_{50}. As fan sizes increase, the whole house airflows become more fan dominated, and there is less impact from changing background envelope leakage levels. The fan sizing methods that account fully for infiltration in fan calculations have limited energy savings from air sealing, and the savings are often static or reduced as envelope leakage is tightened below 3 ACH_{50}.

Second, we show results for individual cases (with no averaging). For each unique combination of airtightness, climate zone and fan type, we assessed the annual energy savings of tightening from a baseline of 5 ACH_{50} to the reduced airtightness levels (3, 2, 1 and 0.6 ACH_{50}). The no fan cases are plotted in Figure 7 (Section 4.1.3.1) to show the impacts of airtightening without mechanical ventilation. To illustrate the impact of Whole house fans on airtightening savings , the ASH62.2_2016 and the T24_2019 cases are shown in Figure 8 and Figure 9 (Sections 4.1.3.2 and 4.1.3.3), respectively. All other fan sizing methods are plotted in the Appendix B-1 Figure 20 through Figure 23.

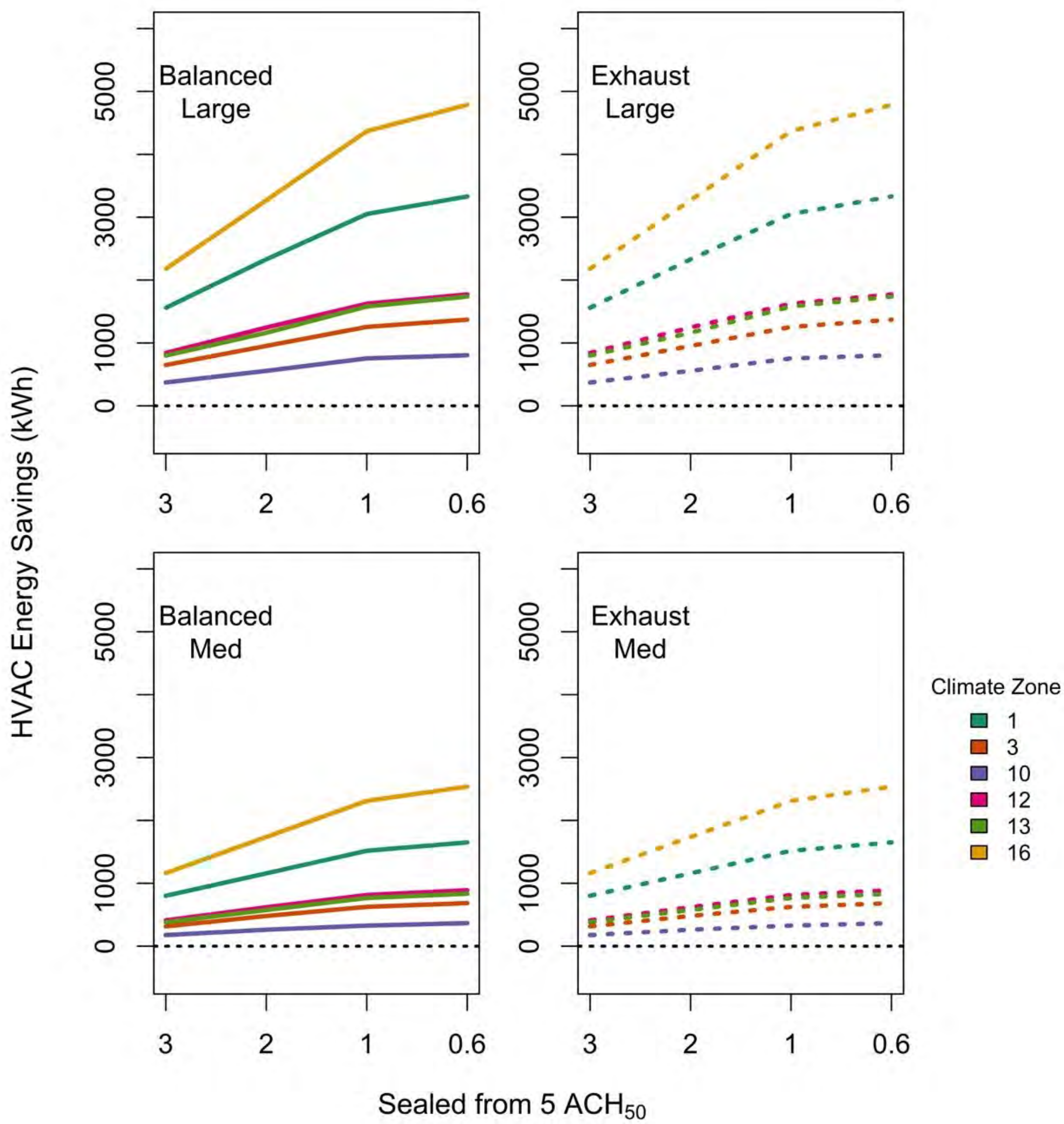
Finally, we present energy savings estimates that are normalized based on all cases having an exposure of 1.0 (i.e., the same IAQ), in an attempt to isolate the impacts of airtigthtening while providing equivalent IAQ (see Section 4.2). Both raw and normalized HVAC energy savings estimates when sealing from 5 ACH_{50} are tabulated for each case and airtightness target in Appendix Table 15.

Figure 6 All cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}. Results averaged across climate zones.



4.1.3.1 No Whole house fan Airtightness Savings

Figure 7 No fan cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

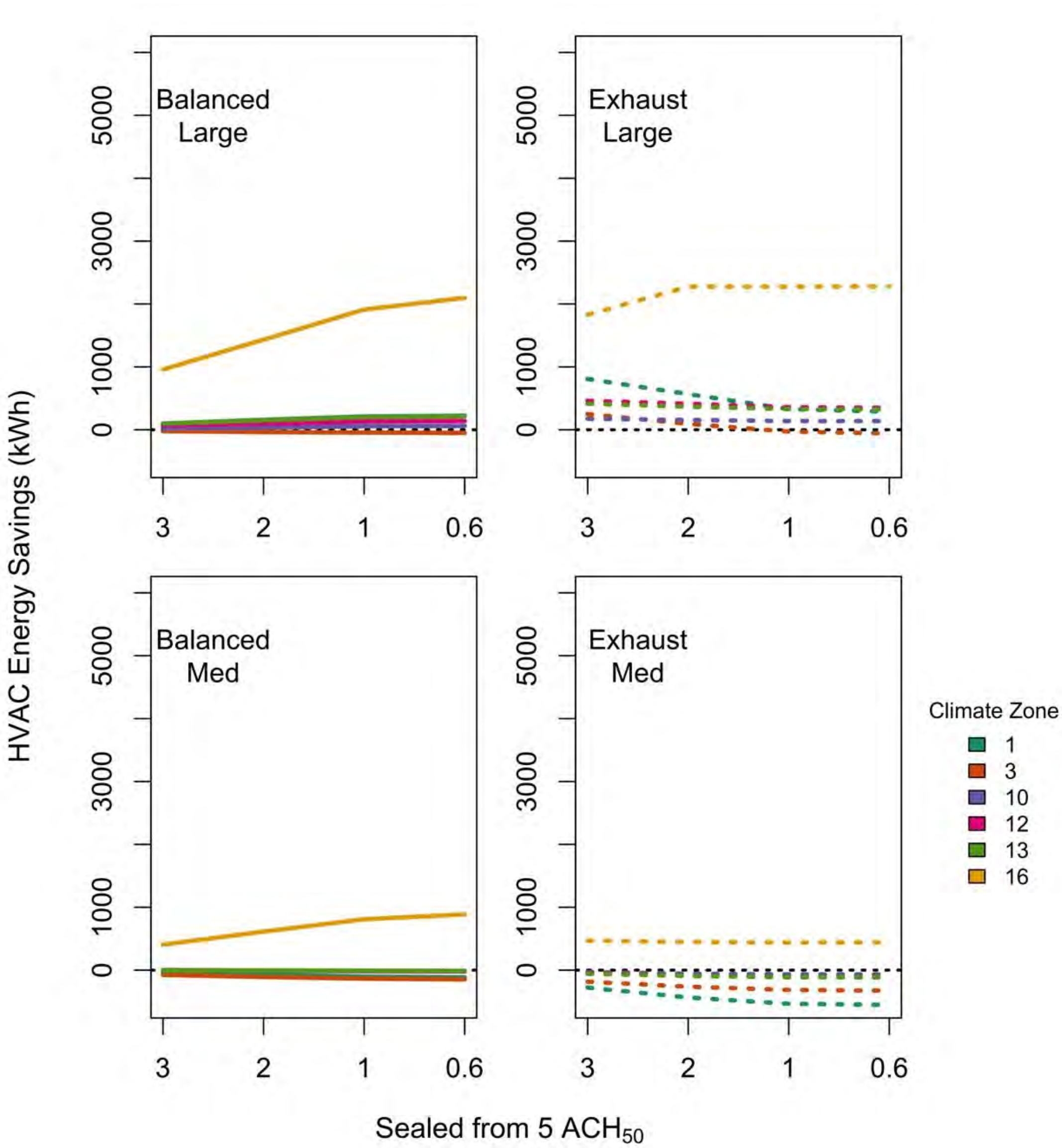


With no Whole house fan, most climates showed substantial energy savings from increased airtightness, and savings increased incrementally as homes became more airtight. The predicted energy savings are much greater in the 2-story large prototype homes than in their 1-story counterparts, irrespective of fan sizing method (or presence of a Whole house fan). This is consistent with the weighted average results in Table 11.

Savings varied from roughly 200-5,000 kWh/year, with strong climate zone and house prototype effects. Far and away, the greatest savings from airtightening accrued in the coldest locations—Blue Canyon CZ16 and Arcata CZ1. The lowest savings were in CZ10 (Riverside), while the other Central Valley and Bay Area climates were in the middle. Note: in the no fan cases, the 'balanced' and 'exhaust' figures are identical, because there are no fans.

4.1.3.2 ASH622_2016 Airtightness Savings

Figure 8 ASH62.2_2016 cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

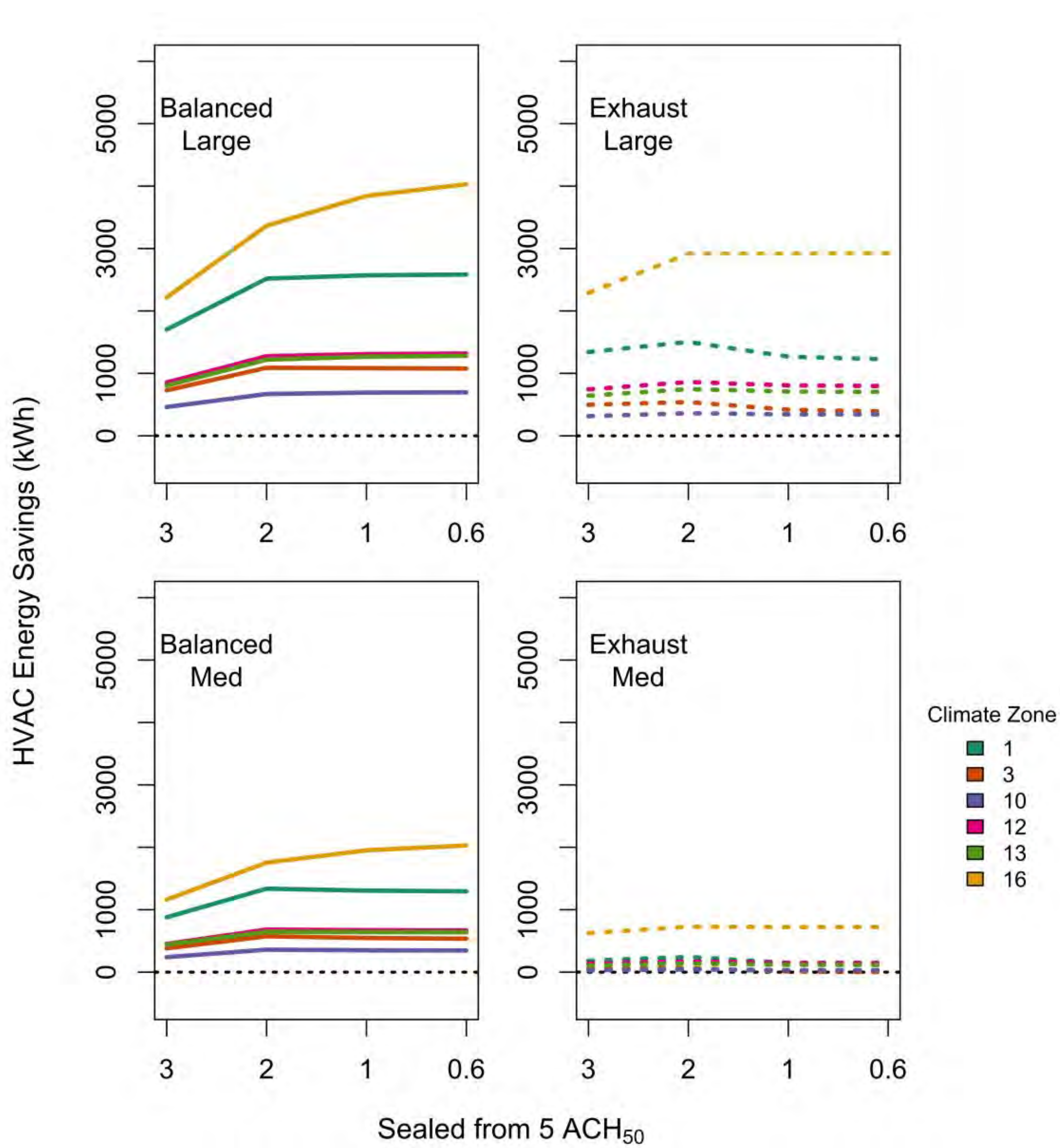


Adding ventilation fans sized according to ASH62.2_2016, which includes infiltration and fan type adjustments (Figure 8) shows much lower savings or increased consumption with airtightening and only CZ16 has appreciable savings. This is because the ASHRAE sizing approach tends to keep total air flows the same with climate and airtightness changes.

For the exhaust fan cases there are changes with airtightness that are greatest in CZ16. This is the result of imperfections in the fan sizing method on ASHRAE 62.2-2016.

4.1.3.3 T24_2019 Airtightness Savings

Figure 9 T24_2019 cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.



In Figure 9, we show the energy savings due to airtightening when the fans are sized using the proposed 2019 sizing method plus a sub-additivity adjustment for unbalanced fans (T24_2019). The fan airflows for these cases do not change with airtightness, with the exception of the cases below 2 ACH_{50}, whose IAQ fan airflows are increased as in ASH622_2016. In the homes with envelope leakage greater than 2 ACH_{50}, the envelope is fixed at 2 ACH_{50}, which leads to oversized fans in leaky homes. Since the fan airflows do not change with air leakage, the only change is reduced natural infiltration, which saves energy.

Here there are much larger savings in the balanced fan cases, and substantial savings for the exhaust fans in 2-story, large prototype homes with no increased consumption for any of the prototypes or climate zones. This is expected based on the exposure and ventilation results for this sizing method, because as homes become progressively more airtight, their ventilation rates go down and exposure increases. We also observe that for exhaust fan cases, energy savings do not increase with further airtightening beyond 3 ACH_{50}. As noted in the exposure section, ventilation rates and exposure were nearly static across these airtightness levels when using exhaust fans, such that reducing envelope leakage area had very little effect on the home's ventilation rate. Since reducing leakage areas only very marginally reduced ventilation rates, little additional energy savings are recorded beyond 3 ACH_{50}. In the harshest climates and in 2-story homes, we see some increasing savings with further airtightening, which is likely the result of shifting ventilation airflows to milder weather periods.

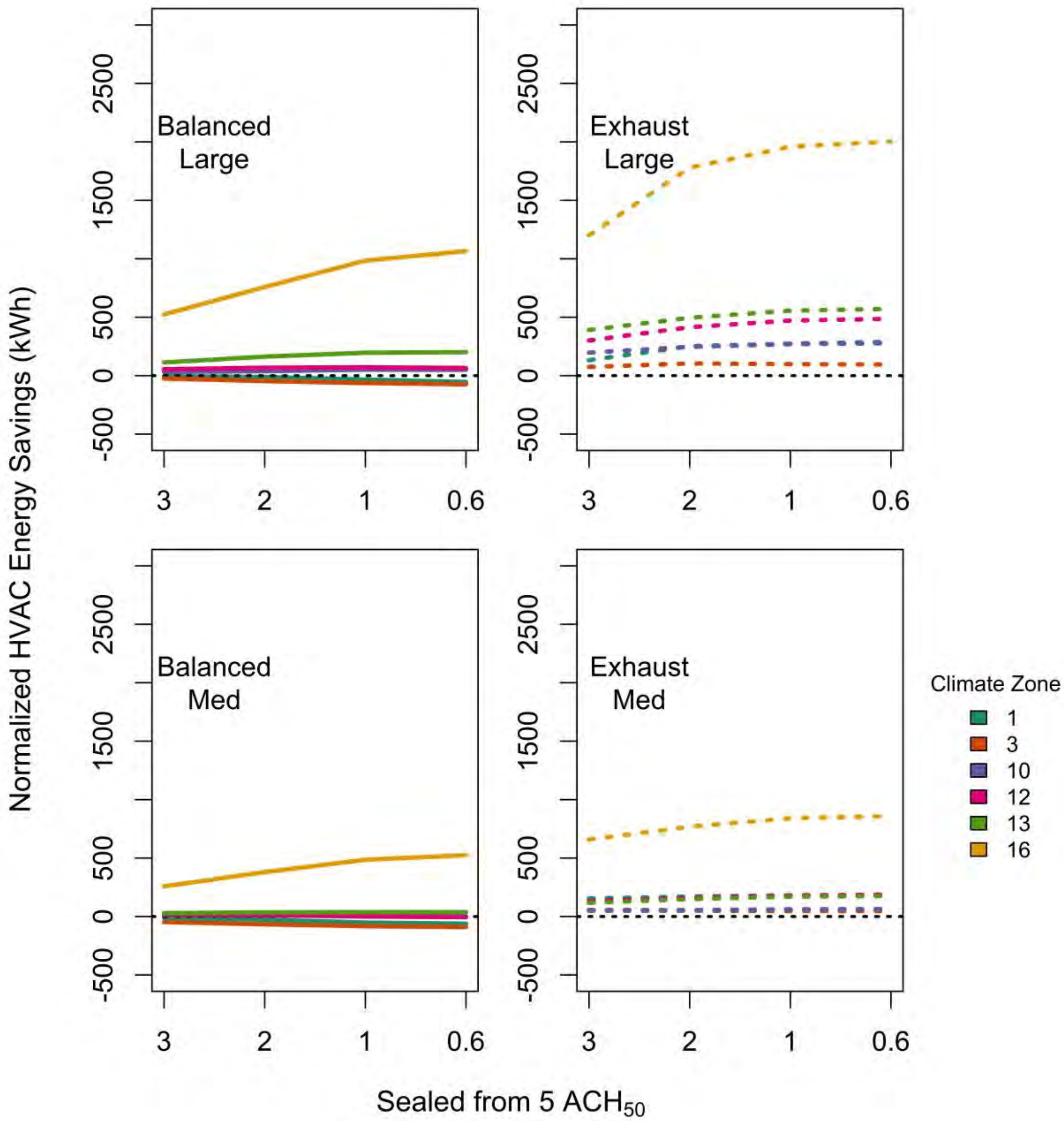
4.2 Exposure-Normalized Airtightness Savings

The raw results in Section 4.1.3 showed that the impacts of airtightening continuously ventilated new California homes depend greatly on fan sizing method, number of stories in the home, fan type and climate zone. Yet, it is critical to note that the air exchange rates and relative exposures were not the same for these cases. When reducing air leakage, the exposure was also changing. Due to differences in exposure and ventilation rates across levels of airtightness, fixed airflow cases tended to consistently save energy by reducing ventilation and increasing exposure, while infiltration-adjusted cases sometimes saved and sometimes increased energy consumption.

To account for these differences in exposure we normalized annual HVAC energy use by relative exposure, treating each individual case as if its relative exposure averaged precisely 1.0. The goal is to identify the benefits of airtightening, if all cases were providing the same service (i.e., identical annual average exposure/IAQ).

The normalized HVAC energy savings from airtightening is shown for the ASH62.2_2016 sizing cases in Figure 10 (normalized HVAC savings for all other fan sizing methods are plotted in Appendix B-1 (Figure 24 through Figure 27). With the exception of CZ16, the resulting energy savings were very small (typically 200 kWh or less). Nearly all cases of increased consumption were eliminated. For this sizing method, the raw, unormalized results were close to 1.0, so normalization had fairly small impacts on energy savings estimates attributable to air sealing for the ASHRAE 62.2-2016 sizing method. This was not the case for other sizing methods, where exposure corrections were larger and previously inflated savings were reduced. As was the case with the raw results, CZ16 is the only location with substantial normalized energy savings resulting from an airtightness requirement. Normalized energy savings are still greater in the 2-story prototypes, and exhaust fan savings are marginally higher than for balanced fans.

Figure 10 ASH62.2_2016, Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.



In Figure 11, we compare mean raw and normalized HVAC energy savings by climate zone and house prototype for sealing from 5 to 3 ACH_{50}. These values are averaged across the different fan sizing methods. The normalization of energy savings by relative exposure reduced energy savings substantially. This suggests that for most cases, the vast majority of energy savings presented in Sections 4.1.3.1 through 4.1.3.3 resulted from worsened IAQ (higher exposure) in the more airtight cases.

When energy is normalized by relative exposure, energy savings from a 3 ACH_{50} airtightness requirement in Title 24 are generally very low (i.e., <200 kWh/year), irrespective of fan sizing method. Climate zone 16 is the sole exception where substantial savings remain after normalization, though these savings are less than half those predicted from the raw simulation results.

Normalized energy savings distributions are provided for each climate zone in Figure 12, which again confirm that CZ16 is the only location with substantial normalized savings potential when sealing to 3 ACH_{50}. This is because CZ16 is the coldest location, which means the shifting of ventilation toward mild weather periods has a major impact. In the milder zones of the state, the impact of this seasonal shifting is quite small. In climate zones other than CZ16, the maximum normalized HVAC savings from airtightening to 3 ACH_{50} was less than 400 kWh/year. Normalized savings distributions are also provided by target airtightness level in Figure 13, which confirms that normalized HVAC energy savings increase very modestly with each incremental reduction in envelope leakage. Despite this marginal increase, and with the exception of the harshest climates, there is little normalized savings for airtightening home envelopes to anywhere from 3 to 0.6 ACH_{50}. Even when sealing from 5 to 0.6 ACH_{50}, more than 75% of the cases have normalized HVAC energy savings less than 500 kWh/year.

Figure 11 Comparison of median raw and normalized HVAC energy savings for sealing from 5 to 3 ACH_{50}, aggregated by climate zone and house prototype. Medians include all fan sizing methods and fan types.

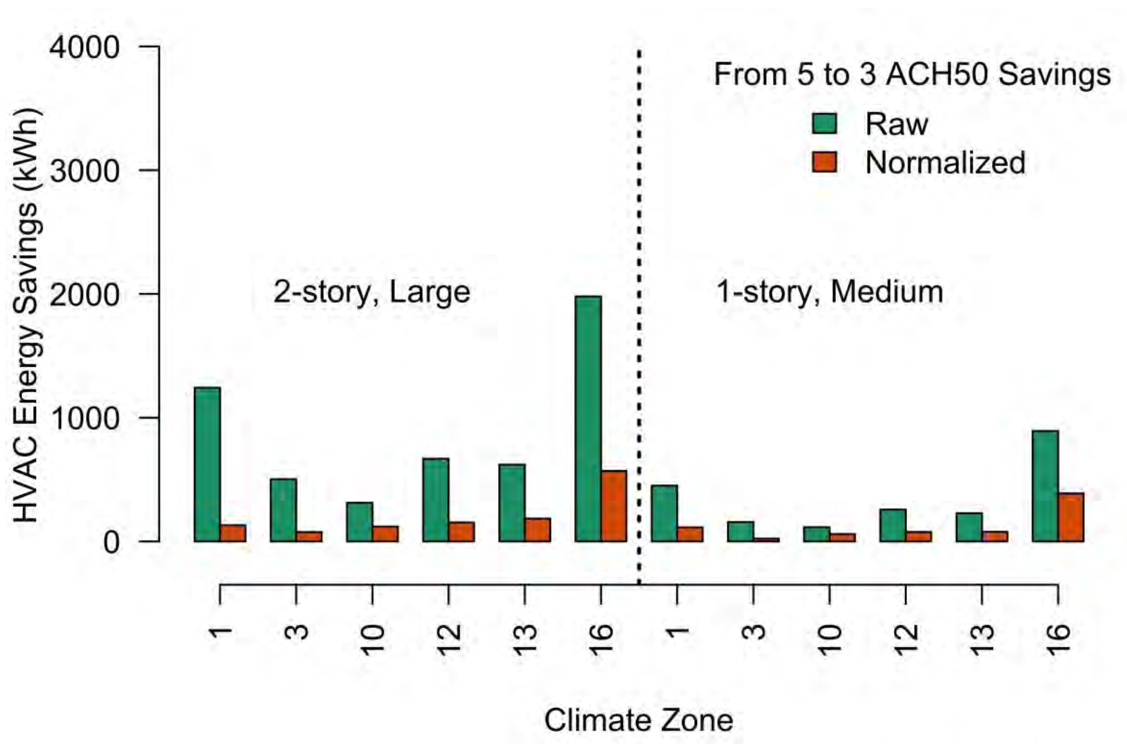


Figure 12 Distributions of normalized HVAC energy savings by climate zone, when sealing building envelope from 5 to 3 ACH_{50}.

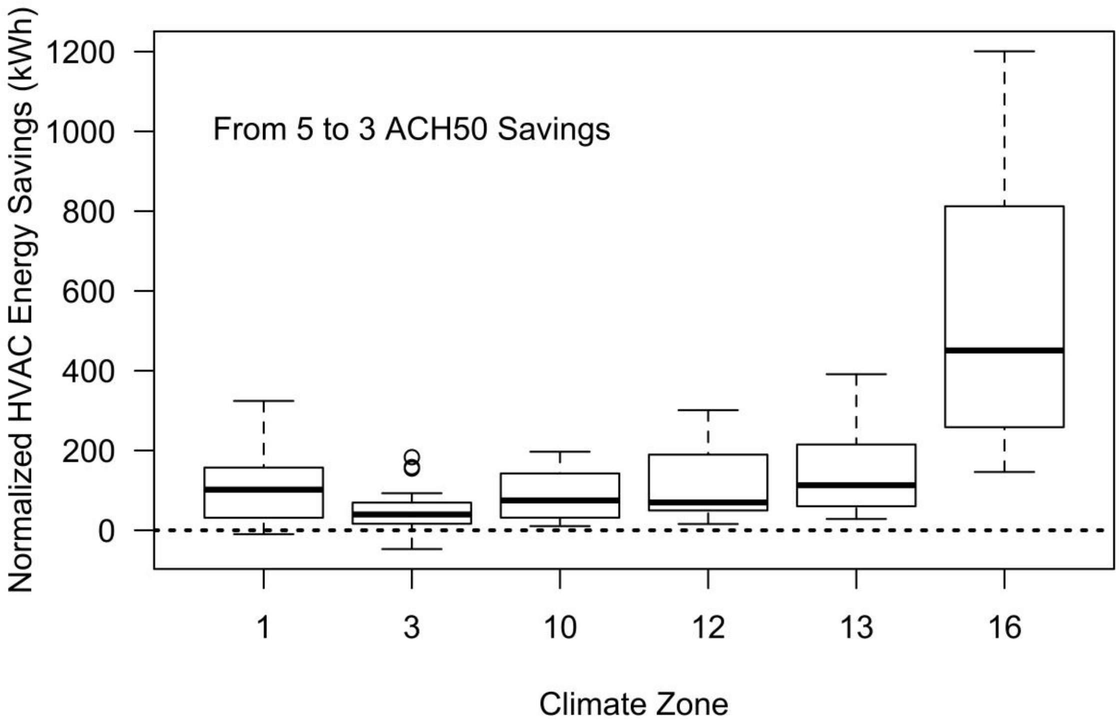
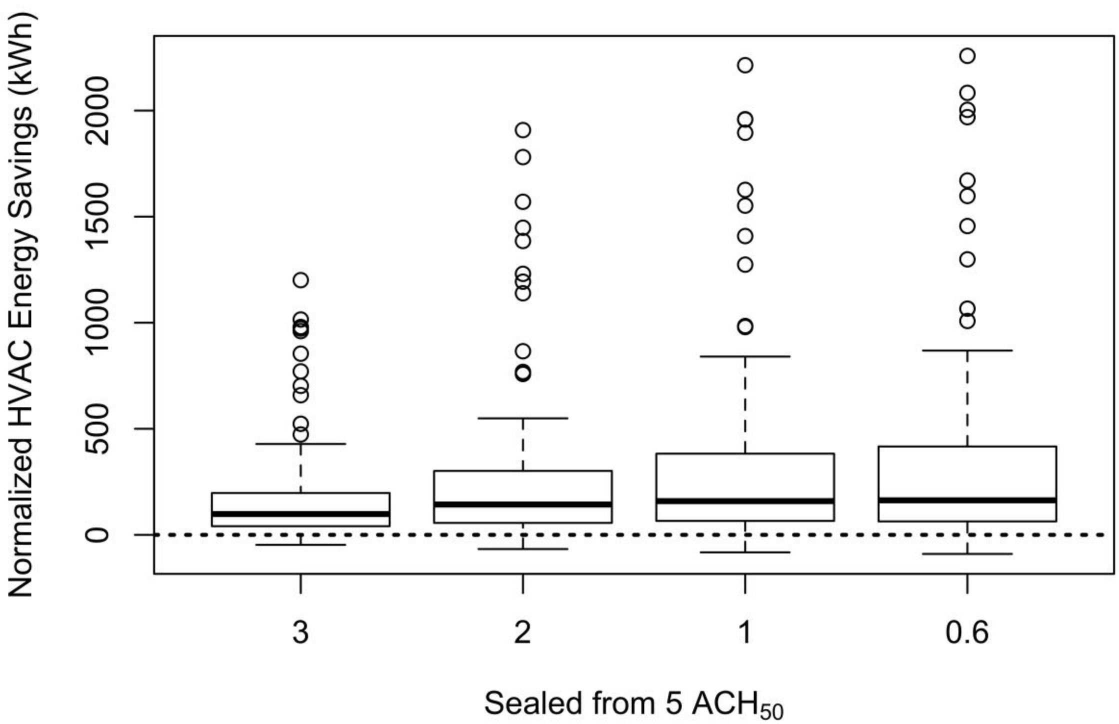


Figure 13 Distributions of normalized HVAC energy savings by airtightness, when sealing building envelope from 5 to 3, 2, 1 or 0.6 ACH_{50}.



4.3 Sub-Additivity and Infiltration in REGCAP and ASHRAE 62.2-2016

In the prior sections, we have established how balanced and exhaust fans perform very differently in terms of exposure, ventilation and energy use across fan sizing methods. The two most notable issues were as follows: (1) weighted average exposure for the ASHRAE 62.2-2016 sizing method was 1.1 (instead of 1.0), varying from 0.8 to 1.2, even though the method accounts for infiltration and fan type; and (2) fixed airflow sizing methods had nearly unchanging exposure, ventilation rates and energy use across envelope leakages from 0.6 to 3 ACH_{50} in 2-story homes and from 0.6 to 5 ACH_{50} in 1-story homes.

After an examination of factors affecting predicted infiltration rates in REGCAP and in ASHRAE 62.2-2016 (see Appendix B-1), we have determined that these results are due to the sub-additive combination of mechanical and natural airflows. For the first issue, differences in weather, envelope leakage distributions and the use of the simplified linearized approach to sub-additivity calculations in the ASHRAE fan sizing calculations leads to exposures not being equal to 1. The second factor is the result of how unbalanced natural infiltration combines with mechanical ventilation.

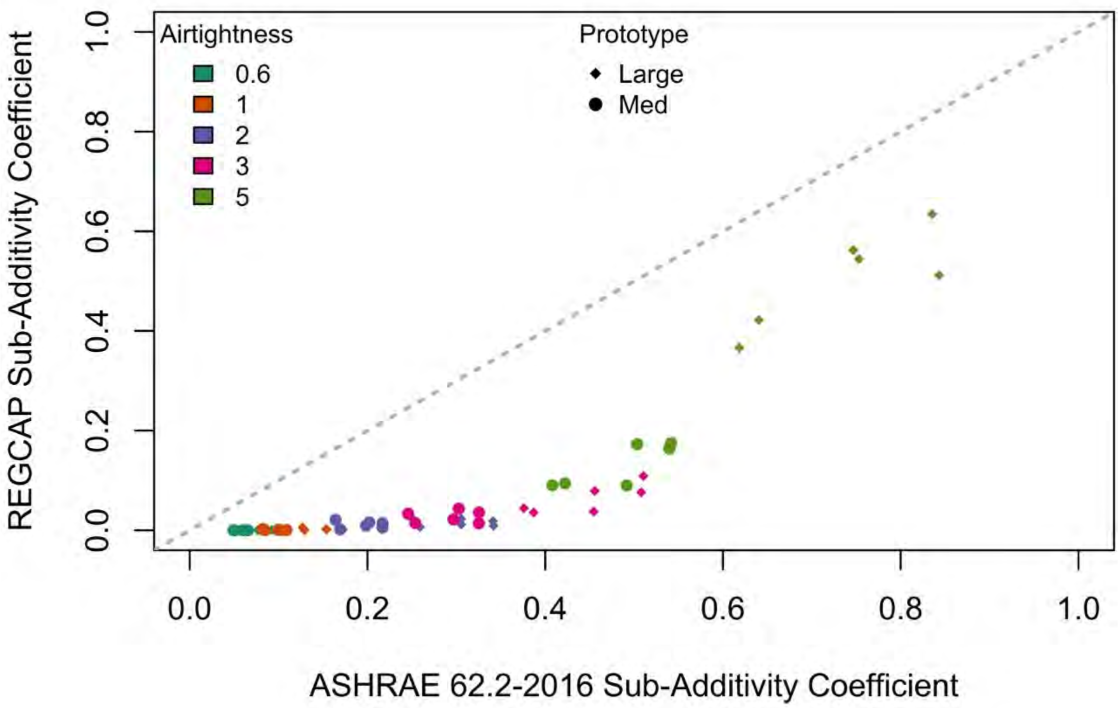
To assess this issue, we compared the sub-additivity coefficients (phi) from ASHRAE 62.2-2016 (based on the results in Hurel at al. (2016)) with those derived from the full mass-balance REGCAP model results from this study. The results are plotted in Figure 14 comparing the actual sub-additivity occurring in the REGCAP model mass balance with the estimates from the equations in ASHRAE 62.2-2016. For exhaust fans, less infiltration is contributed in the REGCAP model than is assumed by the standard for fan sizing. This was the case for all levels of airtightness and house prototypes. In fact, for most cases assessed, the sub-additivity coefficient was less than 0.1, which means that only 10% of the natural infiltration rate was added on top of the mechanical fan airflow. For many of the most airtight cases, the contribution was essentially zero. Values became clearly non-zero for the 3 and 5 ACH_{50} cases, though they are still well below the values assumed in the 62.2 fan sizing equations.

Hurel et al. (2016) reported that the sub-additivity model used in the standard is biased high at low infiltration rates (i.e., predicts more infiltration contribution than actually occurs), due to the use of the simple linear model in the ASHRAE standard, rather than the more accurate (though complicated) exponential model formulation (see Figure 5 in Hurel et al. for illustration of this bias). In addition, in Appendix E, Hurel et al. showed that relative to supply fans, exhaust fans had lower infiltration contributions. Exhaust fan sub-additivity predictions are expected to be biased low relative to the model used in 62.2, which was based on a mixture of exhaust and supply fans. Finally, Hurel et al.'s results show effectively zero infiltration contribution at 0.6 ACH_{50}, and they did not simulate any additional leakages between 0.6 and 3 ACH_{50}. HENGH simulations show near zero contributions for 0.6 and 1 ACH_{50} and very low contributions at 2 ACH_{50}. The sub-additivity behavior is clearly non-linear at very low leakage rates, and even the exponential model is at best an approximation of this.

For the simulations in this study, fan dominated airflow is occurring in the airtight exhaust fan cases. Essentially, no natural infiltration occurs whatsoever when the wind and stack pressures across leaks in the building envelope are less than the pressure induced by the exhaust fan, which can be very substantial in airtight homes. As a result, infiltration on top of fan airflow only occurs when it is particularly hot, cold or windy (or not at all in the 0.6 and 1 ACH_{50} cases). We have found similar results (i.e., infiltration is contributing much less than suggested by the ASHRAE standard) from the Title 24 leakage distribution in another study currently underway for the California Energy Commission that is using EnergyPlus and CONTAM in a co-simulation set-up.

Overall, these details support our finding that infiltration contributions are biased high in the ASHRAE 62.2-2016 sizing calculations relative to the HENGH REGCAP simulations. This results in under-sized Whole house fans, which is why our weighted average exposure was roughly 1.1 and not 1.0. Similarly, this very limited contribution of natural infiltration when combined with an exhaust fan explains why ventilation rates, exposures and energy usages were unchanging over the range from 0.6 to 3 ACH_{50} for exhaust fans sized using fixed airflow methods.

Figure 14 Comparison of sub-additivity coefficients between ASHRAE 62.2-2016 and REGCAP simulations.



An additional difference between the assumptions used to create the values of ϕ for ASHRAE 62.2 and the REGCAP calculations is in the envelope leakage distribution. The ASHRAE 62.2 approach is based on an average of one, two and three story homes where the fraction of leakage in the ceiling varies from 25% to 12.5% (Turner et al. (2012)). In the REGCAP simulations for this study we are using the leakage distribution assumptions of Title 24 with 50% of house leakage in the ceiling. These leakage distribution differences change both the estimates of infiltration and how unbalanced fans interact with building envelope lair flows (due to different natural infiltration pressures occurring across different parts of the building envelope). We re-ran a set of simulations using the leakage distributions reported in Table 16 for only 1-story homes using the 62.2-2016 fan sizing method. The sub-additivity coefficients we calculated for this new leakage distribution averaged 118% greater than those from the simulations using the Title 24 leakage distribution, but the new values were still 89% below the 62.2 model predictions (lower errors of 39% were found for the 5 ACH_{50} cases, as would be expected from the discussion above on the bias at low leakages). More details of these comparisons can be found together with additional discussion on differences between the weather files used to develop the ASHRAE 62.2 factors (TMY3) and the weather used in the current study (California Title 24-specific).

5 Discussion

In Section 5.1 through 5.7, we address the impacts of the simulation parameters that were varied, and through these discussions, we attempt to provide some guidance to the CEC in its specification of a Whole house fan sizing procedure and its option to include an airtightness requirement in the Title 24 code.

5.1 Prototype (1 story medium sized home and 2 story large home)

The differences in natural infiltration rates in 2- vs. 1-story homes had an important impact on energy and IAQ performance. The 2-story homes had substantial energy savings from airtightening, nearly double the savings in the 1-story homes, across all fan sizing methods. In fact, the 1-story homes sometimes increased energy consumption when airtightening and mechanically ventilating using the fan sizing methods in this work. Consistent with the energy savings in 2-story homes, these cases experienced the greatest changes in air exchange rates when air leakage was reduced, and their relative exposures increased as a result. After normalizing each case to have relative exposure equal to 1.0, the energy savings were very small for both 1 and 2 story prototype homes, though the two-story larger homes still had greater energy savings, by roughly a factor of two.

5.2 Fan Type (balanced or exhaust)

Fan type was a very important variable in this work. Overall, balanced fans had higher ventilation rates and energy consumption, with lower relative exposure and more variable exposure overall, because they do not interact in a sub-additive way with infiltration. These differences were much less pronounced for fan sizing methods that explicitly accounted for fan type (ASH622_2016 and T24_2019); these sizing methods were able to maintain reasonably consistent exposure near 1.0 across fan types, prototypes, climate zones, and airtightness.

It is prudent to leave fan type specification up to designers and builders. Yet, the code should not use fan calculation procedures that systematically worsen IAQ based on installed fan type. Comparing the current T24_2013 and the ASH622_2016 methods illustrates this well. The only difference between these sizing methods is that the ASH622_2016 requires larger exhaust fans due to their sub-additivity with infiltration. This results in weighted average exposure of 1.1 for ASH622_2016 vs. 1.31 for T24_2013. Failure to increase the required exhaust fan airflow due to sub-additivity worsens IAQ by 20% on average. In this context, it is notable that the adopted fan sizing method in the 2019 Title 24 includes a sub-addivity adjustment for unbalanced IAQ fans. This requirement will ensure there is no structural bias towards higher pollutant exposure in homes using unbalanced ventilation systems.

5.3 Climate Zone

Climate zones in California are generally mild, which limits the potential energy savings of reducing air leakage. Nevertheless, all climates in the state have varying temperature and wind driving forces that determine the natural infiltration rate of a home. As such, the fixed airflow fan sizing methods that did not adjust airflow based on estimated infiltration, and have fixed fan airflows across all climates, had widely varying relative exposures and air exchange rates. The fan sizing methods that account for infiltration in some way (ASH62.2_2016, T24_2019,, T24_2013) maintained much more consistent exposure and air exchange across climates. Energy savings from air leakage reduction were greatest in the coldest locations: CZ16 (Blue Canyon) and CZ1 (Arcata). When using an exhaust fan in a 1-story home sized to ASH62.2_2016, only CZ16 showed energy savings from reducing air leakage, while all other cases had unchanged or increased energy consumption.

5.4 Airtightness

Airtightness of the building envelope is of critical importance to the energy use and infiltration rates of a home. Yet, many of the fan sizing methods that we assessed ignored airtightness when designing the ventilation system (T24_2008, Qtotal, BuilderPractice, and to varying degrees, T24_2019). For these methods, a reduction in air leakage meant a reduction in house airflow and energy use, along with an increase in relative exposure and worsening IAQ. In these scenarios, reducing air leakage was shown to have consistent though modest whole house HVAC energy savings on the order of 4 to 5%, at the expense of higher pollutant exposure to occupants. In addition, these fan sizing methods were more likely to either under- or over-ventilate the homes relative to the target airflow, because they did not account for variable infiltration. For example, the 2019 adopted fan sizing method (T24_2019) tended to substantially over-ventilate all homes leakier than 2 ACH_{50} and to properly ventilate those below this level, due to use of the actual envelope leakage in fan sizing calculations. Other fan sizing methods explicitly accounted for infiltration, and adjusted fan airflows based on measured airtightness, climate zone and house type (ASH62.2_2016, T24_2013), and while still imperfect, these cases had more consistent ventilation rates, exposure and energy use across the parameters varied in our simulations.

When infiltration is accounted for in Whole house fan sizing, savings are roughly 1%, while fixed airflow sizing methods have 3 to 5% savings. This is because natural infiltration rates are low in California due to low driving forces, and for unbalanced fans, they interact non-linearly to further reduce air infiltration impacts on total airflow.

5.5 Fan Sizing Method

Ideally, a fan sizing method would ensure similar exposure and energy impacts across house types, fan types, airtightness and location. The ideal method would not predictably burden any homes in the state with either poor IAQ or artificially high energy use.

The first distinction between sizing methods is their treatment of infiltration. Fixed airflow methods do not account for infiltration at all, including T24_2008, Qtotal and BuilderPractice. These all have different fixed airflows, but they are similar in that they do not vary across any of our simulation parameters except house prototype. The adopted 2019 Title 24 sizing method accounts for infiltration driving forces as they vary by climate zone and house type (i.e., number of stories), but fails to account for critical differences in envelope leakage (e.g., 5 vs. 1 ACH_{50}), except for cases with leakage below 2 ACH_{50}. Finally, there are those sizing methods that attempt to account for all factors affecting infiltration rates—house leakage, climate zone and prototype—the current ASH62.2_2016 and the Total Ventilation Rate Method in the Title 24 (T24_2013).

Fan sizing methods also varied by their treatment of fan types, namely balanced vs. unbalanced fans. Nearly all methods treat the fan types as identical from an airflow calculation perspective, and as a result, the balanced fan cases tend to have higher overall airflow and energy use, along with lower exposure. Exhaust fans using these methods were shown to have higher exposure, due to their failure to account for sub-additivity with infiltration. It is notable that most new homes use simple exhaust ventilation systems to comply with Title 24 IAQ requirements. Some sizing methods (ASH62.2_2016 and T24_2019) include sub-additivity factors that effectively increase the required fan airflow if it is unbalanced, based on the magnitude of predicted infiltration relative to the target whole house airflow. These methods achieve more consistent whole house airflows and exposures across fan types.

The sizing methods with the poorest weighted average IAQ (highest exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method (T24_2008) and the Total Ventilation Rate Method (T24_2013). These had weighted average relative exposure 30 and 40% worse than target levels, respectively. The only sizing method to maintain exposure below 1.0 in all cases was to simply size the Whole house fan to the whole house target airflow (Qtotal). The sizing method with weighted average exposure closest to 1.0 under current and future airtightness conditions was the adopted T24_2019 method. Current builder practice at current air tightness levels (about 5 ACH_{50}) has a mean relative exposure less than one and 3% less energy use than ASH622_2016 (and 10% less energy use when correct for equivalent exposure equal to one).

The ASH62.2_2016 sizing method accounts for all factors affecting infiltration and it adjusts airflow based on fan type. While imperfect, it achieves the greatest consistency across all our metrics of interest—ventilation airflow, energy use and relative exposure. Its weighted average exposure was 1.09, meaning it under-ventilated homes on average. The CEC could consider future development of customized sub-additivity coefficients for use in Title 24 fan sizing that would achieve average exposure very nearly equal to 1.0 in most cases. For example, an improvement would be to use the exponential sub-additivity model formulation described by Hurel et al., which mostly eliminates the bias in sub-additivity at low infiltration rates.

The adopted T24_2019 sizing method maintained weighted average relative exposure quite close to 1.0 under current air leakage and with a hypothetical 3 ACH_{50} leakage requirement in the energy code. Its weighted average energy use was higher than for the ASH622_2016 sizing method, but this was largely because exposure was lower with the T24_2019 method. In some cases this is desirable, but in the most common cases—with leakage of 3 and 5 ACH_{50}—the T24_2019 sizing method substantially over-ventilates the homes, with relative exposure in the range of 0.8 to 0.95, depending on the fan type and house prototype. The simplification of not requiring measured air leakage to be used in fan sizing leads to increased energy consumption in the most common homes with leaky envelopes. The median increases (across climate zones) in HVAC site energy use for the adopted T24_2019 relative to the ASH622_2016 method are shown by prototype, fan type and envelope leakage level in Table 12. Only 3 and 5 ACH_{50} cases are shown, as the fan sizing methods are identical for the 2, 1 and 0.6 ACH_{50} cases. The increased consumption for the T24_2019 method ranges from roughly 70 to 1,400 kWh/year. The energy differences are largest for the 5 ACH_{50}, which are the most over-ventilated relative to 62.2 targets. Balanced fans have larger energy penalties, as do the larger, 2-story prototype homes. On a weighted average basis, this incremental energy use for the T24_2019 sizing method was 241 kWh greater than for the ASH622_2016 sizing method.

Table 12 Median Increased HVAC Site Energy Use for T24_2019 vs. ASH622_2016, by Envelope Leakage, Prototype and Fan Type. Averaged across climate zones.

Envelope Leakage (ACH50)	Prototype	Fan Type	Increase HVAC Energy Use (kWh), T24_2019 vs. ASH622_2016
3	Large	B	573
3	Large	E	285
3	Med	B	222
3	Med	E	73
5	Large	B	1375
5	Large	E	677
5	Med	B	668
5	Med	E	337

5.6 Selecting a Fan Sizing Method and Considering an Airtightness Limit

We have shown that some energy savings are available through imposing an airtightness limit on new California homes, generally at the cost of worsened IAQ. The new construction-weighted average savings are modest—1 to 5% of annual HVAC consumption—and they depend on the fan sizing method used and other factors. Overall, only very modest savings are available (1%) from an airtightness limit, unless occupant pollutant exposure is also allowed to increase by 4-10% on a weighted average basis (i.e., higher in some cases and lower in others). Reducing air leakage can also be costly. In Table 13, we provide estimated costs for reducing leakage from 5 to 3 ACH_{50} for the two CEC prototype homes, based on estimates from the National Residential Efficiency Measures Database (NREL, n.d.). The Energy Commission will need to assess these potential energy savings in light of the costs and the statutory requirement for a negative declaration for measures in the building energy code.

Table 13 Estimated costs to seal the two CEC single-family prototype buildings from 5 to 3 ACH_{50}.

Prototype	Cost per ft^2 to Seal Home from 5 to 3 ACH_{50}		
	$0.22 (Low)	**$0.52 (Average)**	**$0.82 (High)**
1-story, 2,100 ft^2	$462	$1,092	$1,722
2-story, 2,700 ft^2	$594	$1,404	$2,214

There are three primary paths forward in terms of airtightness policy for new homes in the state: (1) Do nothing, (2) Impose a numeric air leakage limit for new homes (e.g., 3 ACH_{50}) and require blower door testing, or (3) Specify prescriptive measures designed to achieve increased airtightness and evaluate compliance via a checklist (or the like), similar to what has already been required in Section 110.7 of Title 24 since 2013. Each of these scenarios might lead to a different choice as to the most appropriate fan sizing method for the code. Overall, we recommend the CEC consider: (1) the consistency of the sizing method (i.e., its tendency to achieve similar whole house ventilation rates across houses and climates), and (2) the relative exposure currently and under an airtightness requirement in the code.

The adopted Title 24_2019 fan sizing method provides weighted average relative exposure very close to one under current air leakage weights, as well as under a hypothetical 3 ACH_{50} leakage limit in the energy code. This suggests that on average, the adopted fan sizing method is robust against policy decisions regarding air leakage requirements in new California homes. As noted elsewhere, the main downside of the adopted fan sizing method is its tendency to require over-sized IAQ fans in homes leakier than 2 ACH_{50}, with associated increased energy use. This bias towards over-ventilating leaky homes will reduce pollutant exposure in these cases, at the expense of increased energy use, which is consistent with the requirement of a negative declaration for Title 24 measures. An air leakage limit of 3 ACH_{50} would lead to a weighted average increase in exposure of 5% with the adopted fan sizing method, though the exposures are still below those maintained using the ASHRAE 62.2-2016 sizing method. This worsened IAQ would be greater in 2-story homes, averaging 8%, though again less than the exposure maintained in 2-story homes with fans sized to ASHRAE 62.2-2016. If an air leakage limit were imposed while using the adopted fan sizing method, weighted average site energy savings would be 3.6% (252 kWh/year). Savings would be greater in 2-story, larger homes, at 5.2% vs. 1.3% in 1-story.

If the energy savings are normalized so that all approaches have relative exposure of one then the savings of tightening from 5 ACH_{50} to 3 ACH_{50} are all reduced because the savings are at the expense of increased exposure. The resulting energy savings are less than 200 kWh/year except for CZ16 where savings are about 500 kWh/yr (about 5% of total HVAC energy use).

5.7 Additional Considerations

There are some additional considerations not included directly in this work, but that the CEC might consider in selecting a fan sizing method, and in deciding whether or not to impose airtightness requirements.

Before imposing air tightness limits, we need to consider that the companion field study (Chan et al. 2018) found that like Whole house fans used for Title 24 compliance are turned off permanently in about three quarters of new California homes (similar results have been found in other parts of the country (Sonne, Withers, & Vieira, 2015). While technically out of control of code officials, the decision of whether or not to impose an air leakage limit in new homes should include consideration of this very real phenomenon. Under an airtightness limit, the impacts on human health of having the Whole house fan turned off worsen. Our weighted average results show that these homes would increase their relative exposure by a factor of roughly 1.5, to over 4 times the target exposure for new homes with Whole house fans operating continuously. The CEC should consider additional safeguards and/or homeowner education requirements that encourage occupants to keep their fans turned on. Labeling of fan control switches, elimination of occupant-controlled switches, further reductions in minimum noise-level requirements, etc. are all options that might ensure that more fans are operated as intended.

Second, is that installed ventilation airflows commonly exceed the code-minimum specification, by about 40-50%. Data from the companion field study indicate that this is likely due to limited fan airflow options on the market. The proposed fan sizing methods under serious consideration here (i.e., ASH62.2_2016 and T24_2019), substantially increase the minimum airflows required to satisfy Title 24 relative to the current prescriptive fans sized using the Fan Ventilation Rate method (T24_2008), and align within a few cfm of current builder practice. The state should consider available options to ensure that installed fan airflows are either aligned with the calculated values in the code (modulating fans that are set by installers or use of timers), or demonstration of compliance should include these increased airflows, such that other efficiency measures are used to offset increased ventilation energy.

6 Conclusions

Energy, ventilation and IAQ performance were simulated in two prototype homes compliant with the 2016 prescriptive provisions of Title 24, across a number of California climate zones (CZ 1, 3, 10, 12, 13 and 16) reflecting the variety of climate conditions in the state. Airtightness was varied between 0.6 and 5 ACH_{50}, and Whole house fans were sized according to six currently available or proposed compliance paths in Title 24 or ASHRAE Standard 62.2. Fan sizing methods either accounted for infiltration and fan type, or they used a fixed airflow approach, with no variability in the fan sizing by airtightness, climate zones, geometry and fan types. The objectives of this work were to: (1) evaluate the IAQ and energy impacts of different Whole house fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH_{50} airtightness requirement in the Title 24 energy code.

None of the fan sizing methods were perfect, despite the efforts made in some cases to account for all the major factors affecting house air exchange (e.g., house geometery, airtightness, fan type, location). The sizing methods with the poorest weighted average IAQ (highest exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method (T24_2008) and the Total Ventilation Rate Method (T24_2013). These had weighted average relative exposures 30 and 40% worse than target levels, respectively. Of all sizing methods, the adopted Title 24 2019 sizing method with a sub-additivity adjustement for unbalanced fans (T24_2019) maintained relative exposure closest to 1.0 under both current and future airtightness weightings (with exposures of 0.97 and 1.02, respectively). The two closest competitors were the current ASHRAE 62.2-2016 method (ASH622_2016) and the Qtotal method that sizes the fan to the total target ventilation rate in the ASHRAE standard. The ASH622_2016 method was consistently under-ventilated (at 1.09 and 1.06 under current and future airtightness weights), while the Qtotal method was consistently over-ventilated (at 0.93 and 0.97). Qtotal was the only sizing method that maintained exposure below 1.0 in all simulated cases. Under current airtightness weights, the T24_2019 and Qtotal methods increased weighted average energy use by 3 and 5% relative to the ASH622_2016 method (and by 1 and 3% under future airtightness weights). The difference in weighted average total consumption between any of these three sizing methods was roughly 300 kWh/year (these absolute differences were greater in harsher climate zones)

When all cases are examined individually, most of the sizing methods had widely spread relative exposure values, meaning that most homes were either substantially under- or over-ventilated relative to target rates in 62.2 and Title 24. This inconsistency increases the risk of either poor IAQ or excess energy consumption for individual homes, even when the weighted average results are acceptable (as they were for the T24_2019 method, for example). Exposure was generally higher in more airtight homes, in homes with exhaust fans, and in 1-story homes. The ASHRAE 62.2-2016 fan sizing method, which accounts fully for infiltration and fan type, had the most consistent pollutant exposure and ventilation rates across all cases, irrespective of climate zone, fan type, airtightness or house prototype. This sizing method had average exposure of 1.09, due to biases in the exhaust fan sub-additivity calculations in ASHRAE 62.2-2016. If desired, the CEC could adopt an alternative sub-additivity formulation that would eliminate most of this bias, and should reduce average exposure very close to 1.0. The adopted Title 24_2019 fan sizing method also had quite consistent exposure values, though it tended to over-ventilate leakier homes. Unlike the ASHRAE 62.2-2016 method, other sizing methods had drastically different performance for balanced vs. exhaust fans, as well as at differing airtightness levels and climate zones.

An airtightness requirement of 3 ACH_{50} in new California homes was found to have marginal predicted weighted average energy savings (1 to 5% of total HVAC) when also providing continuous mechanical ventilation. Most of these savings were from reducing the ventilation rate and worsening IAQ. The fixed airflow fan sizing methods saved more energy (roughly 3 to 5%) but worsened IAQ (increased exposure by 5 to 24%). Energy use increased as weighted average exposure was reduced, essentially trading off poor IAQ for improved energy performance. If the changes in exposure are accounted for by normalizing to the same exposure, these energy savings are substantially reduced to typically less than 1% savings apart from CZ16 where savings are about 5%. The sizing methods that accounted for infiltration and/or fan type had substantially reduced weighted average energy savings (1%), while they marginally improved IAQ (reduced exposure by roughly 3 to 4%) under an airtightness requirement. In fact, for the ASH622_2016 sizing method, energy use increased under an airtightness regime for 1-story homes with exhaust fans in all climate zones except CZ16. Airtightness savings were roughly double in the 2-story vs. 1-story prototype homes, because of their increased natural infiltration rates (due to greater building height). Savings were also higher in select climates with the harshest weather (e.g., CZ16 in Blue Canyon and CZ1 Arcata), but the lack of new construction in these zones nearly eliminated their effect on the weighted average results. The estimated costs for air sealing from 5 to 3 ACH_{50} averaged $1,092 and $1,404 for the 1- and 2-story prototypes, respectively.

The adopted fan sizing method in the 2019 Title 24 energy code is fairly robust against policy decisions regarding air leakage limits in the energy code, as it provided weighted average exposure nearly equal to 1 under both airtightness scenarios (existing and airtightened). Weighted average exposure would increase 5% with an air leakage limit in the energy code, though it would still be less than exposure achieved using the ASH622_2016 sizing method. Our results suggest that unless occupant pollutant exposure is allowed to increase by 5-10% relative to target rates, then an airtightness limit will have very marginal savings of roughly 1% of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5% are possible through airtightening. Consistent with this, when all cases were normalized to have the same IAQ, the HVAC energy savings from an airtightness limit in the code were reduced to well below 1%.

7 References

ANSI/ASHRAE. (2016). Standard 62.2-2016 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. Atlanta, GA: ASHRAE.

ASHRAE. (2013). 2013 ASHRAE Handbook - Fundamentals (SI). Atlanta, GA: ASHRAE.

Chan, Wanyu R.; Kim, Yang-Seon; Singer, Brett C.; Walker, Iain S. (Lawrence Berkeley National Laboratory). 2018. Ventilation and Indoor Air Quality in New California Homes with Gas Appliances and Mechanical Ventilation. California Energy Commission. Publication number: CEC-500-YYYY-XXX.

Gusdorf, J., & Hamlin, T. (1995). Indoor Air Quality and Ventilation Rates in R-2000 Houses (No. 23440-95–1037). Energy Technology Branch, CANMET, Department of Natural Resources Canada. Retrieved from http://publications.gc.ca/collections/Collection/M91-7-347-1995E.pdf

Gusdorf, J., & Parekh, A. (2000). Energy Efficiency and Indoor Air Quality in R-2000 and Conventional New Houses in Canada. In Efficiency and Sustainability. Pacific Grove, CA: ACEEE. Retrieved from http://www.aceee.org/proceedings-paper/ss00/panel01/paper09

Hurel, N., Sherman, M. H., & Walker, I. S. (2016). Sub-additivity in combining infiltration with mechanical ventilation for single zone buildings. Building and Environment, 98, 89–97. https://doi.org/10.1016/j.buildenv.2015.12.020

ICC. (2012). International Energy Conservation Code. International Code Council.

Janssen, J. E. (1999). The history of ventilation and temperature control. ASHRAE Journal, 41(10), 48–70.

Less, B., Mullen, N., Singer, B., & Walker, I. (2015). Indoor air quality in 24 California residences designed as high-performance homes. Science and Technology for the Built Environment, 21(1), 14–24. https://doi.org/10.1080/10789669.2014.961850

Mudarri, D. H. (2010). Building Codes and Indoor Air Quality. US EPA. Retrieved from http://earth1.epa.gov/iaq/pdfs/building_codes_and_iaq.pdf

Nittler, K., & Wilcox, B. (2006). Residential Housing Starts and Prototypes: 2008 California Building Energy Efficiency Standards. Sacramento, CA: California Energy Commission. Retrieved from http://www.energy.ca.gov/title24/2008standards/prerulemaking/documents/2006-03-28_workshop/2006-03-27_RES_STARTS-PROTOTYPES.PDF

NREL. (n.d.). NREL: National Residential Efficiency Measures Database - Retrofit Measures for Air Leakage (v3.1.0). Retrieved June 13, 2018, from https://remdb.nrel.gov/measures.php?gId=10&ctId=376&scId=6160&acId=6162

Offermann, F. (2009). Ventilation and Indoor Air Quality in New Homes (No. CEC-500-2009-085). California Energy Commission. Retrieved from http://www.energy.ca.gov/2009publications/CEC-500-2009-085/CEC-500-2009-085.PDF

Price, P. P., Sherman, M., Lee, R. H., & Piazza, T. (2007). Ventilation Practices and Household Characteristics in New California Homes (Final Report No. CEC-500-2007-033). California Energy Commission. Retrieved from http://www.google.com/url?sa=t&rct=j&q=%22ventilation%20practices%20and%20household%

20characteristics%22&source=web&cd=1&ved=0CE4QFjAA&url=http%3A%2F%2Fwww.energy.ca.gov%2F2007publications%2FCEC-500-2007-033%2FCEC-500-2007-033.PDF&ei=anjrT72LFYbm2AXC0Yy7AQ&usg=AFQjCNH_HsNFC4J7UTstGYGW_nTZjlrOig&cad=rja

Proctor, J., Chitwood, R., & Wilcox, B. (2011). Efficiency Characteristics and Opportunities for New California Homes (ECO) (Final Project Report No. CEC-500-2012-062). Sacramento, CA: California Energy Commission, PIER Energy-Related Environmental Research Program. Retrieved from http://www.energy.ca.gov/2012publications/CEC-500-2012-062/CEC-500-2012-062.pdf

Rasin, J., & Farahmand, F. (2015). Residential High Performance Walls (Codes and Standards Enhancement Initiative (CASE) No. 2016- RES-ENV2- F). Sacramento, CA: California Energy Commission. Retrieved from http://title24stakeholders.com/wp-content/uploads/2015/02/2016-T24-CASE-Report-High-Perf-Walls-Feb2015.pdf

Riley, M. (1987). An Overview of the R-2000 Home Program Design and Installation Guidelines for Ventilation Systems. In AIVC Conference. AIVC.

Sherman, M. H., Mortensen, D. K., & Walker, I. S. (2011). Derivation of Equivalent Continuous Dilution for Cyclic, Unsteady Driving Forces. International Journal of Heat and Mass Transfer, 54(11–12), 2696–2702.

Sherman, M. H., Walker, I. S., & Logue, J. M. (2012). Equivalence in ventilation and indoor air quality. HVAC&R Research, 18(4), 760–773. https://doi.org/10.1080/10789669.2012.667038

Sonne, J., Withers, C. R. J., & Vieira, R. K. (2015). Investigation of the Effectiveness and Failure Rates of Whole-House Mechanical Ventilation Systems in Florida (No. FSEC-CR-2002-15). Cocoa, FL: Florida Solar Energy Center. Retrieved from http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-2002-15.pdf

Stratton, C., Walker, I. S., & Wray, C. P. (2012). Measuring Residential Ventilation System Airflows: Part 2 - Field Evaluation of Airflow Meter Devices and System Flow Verification (No. LBNL-5982E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://homes.lbl.gov/sites/all/files/lbnl-5982e.pdf

Sundell, J. (2004). On the history of indoor air quality and health. Indoor Air, 14, 51–58.

Turner, W. J. N., Sherman, M. H., & Walker, I. S. (2012). Infiltration as ventilation: Weather-induced dilution. HVAC&R Research, 18(6), 1122–1135. https://doi.org/10.1080/10789669.2012.704836

Walker, Iain S. (1993, Spring). Attic Ventilation, Heat and Moisture Transfer. University of Alberta, Edmonton, Alberta.

Walker, Iain S., & Sherman, M. H. (2006). Evaluation of Existing Technologies for Meeting Residential Ventilation Requirements (No. LBNL-59998). Berkeley, CA: Lawrence Berkeley National Lab. Retrieved from https://buildings.lbl.gov/sites/all/files/lbnl-59998.pdf

Walker, I.S., Forest, T. W., & Wilson, D. J. (2005). An attic-interior infiltration and interzone transport model of a house. Building and Environment, 40(5), 701–718. https://doi.org/10.1016/j.buildenv.2004.08.002

Wilson, D. J., & Walker, I. S. (1990). Combining Air Infiltration and Exhaust Ventilation. In Indoor Air 90′ (pp. 467–472). Toronto, Canada.

Appendix B-1

Simulation Data Tables

Table 14 Tabular summary of HVAC energy end-uses, air exchange rate, Whole house fan airflow and relative exposure for all cases.

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	0.6	T24_2008	B	1	64	166	7237	0	230	7633	9243	0.179	1.521
Large	0.6	T24_2008	B	3	64	282	3300	1110	230	4921	5704	0.176	1.550
Large	0.6	T24_2008	B	10	64	577	1491	2973	230	5271	5839	0.171	1.599
Large	0.6	T24_2008	B	12	64	583	4477	2603	230	7892	8865	0.175	1.555
Large	0.6	T24_2008	B	13	64	746	4519	3489	230	8984	10099	0.171	1.592
Large	0.6	T24_2008	B	16	64	523	10053	1515	230	12320	14246	0.180	1.522
Large	0.6	T24_2008	E	1	64	154	6700	0	115	6968	8991	0.148	1.833
Large	0.6	T24_2008	E	3	64	286	3084	1157	115	4642	5597	0.148	1.834
Large	0.6	T24_2008	E	10	64	577	1321	2988	115	5001	5566	0.148	1.832
Large	0.6	T24_2008	E	12	64	576	4109	2608	115	7408	8466	0.148	1.833
Large	0.6	T24_2008	E	13	64	737	4161	3480	115	8492	9652	0.148	1.834
Large	0.6	T24_2008	E	16	64	505	9146	1534	115	11300	13526	0.148	1.834
Large	0.6	T24_2013	B	1	107	207	9023	0	385	9615	9451	0.281	0.968
Large	0.6	T24_2013	B	3	107	280	4229	990	386	5886	5833	0.279	0.978
Large	0.6	T24_2013	B	10	109	575	2070	2916	394	5955	5923	0.278	0.980
Large	0.6	T24_2013	B	12	108	594	5507	2551	388	9041	8969	0.279	0.975
Large	0.6	T24_2013	B	13	109	765	5480	3494	392	10131	10076	0.277	0.982
Large	0.6	T24_2013	B	16	109	552	12059	1427	393	14432	14137	0.287	0.949
Large	0.6	T24_2013	E	1	107	191	8345	0	193	8729	9120	0.249	1.094
Large	0.6	T24_2013	E	3	107	285	3950	1051	193	5480	5658	0.250	1.090
Large	0.6	T24_2013	E	10	109	572	1827	2927	197	5523	5605	0.255	1.068
Large	0.6	T24_2013	E	12	108	583	5037	2549	194	8364	8552	0.251	1.084
Large	0.6	T24_2013	E	13	109	751	5047	3471	196	9465	9640	0.253	1.074
Large	0.6	T24_2013	E	16	109	530	10948	1441	196	13116	13439	0.254	1.072
Large	0.6	Qtotal	B	1	117	216	9439	0	421	10076	9482	0.305	0.893
Large	0.6	Qtotal	B	3	117	281	4467	965	421	6134	5880	0.301	0.904

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year): Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	0.6	Qtotal	B	10	117	576	2187	2907	421	6090	5952	0.296	0.922
Large	0.6	Qtotal	B	12	117	596	5714	2539	421	9271	8975	0.301	0.906
Large	0.6	Qtotal	B	13	117	768	5668	3493	421	10351	10088	0.296	0.919
Large	0.6	Qtotal	B	16	117	559	12434	1414	421	14827	14153	0.306	0.891
Large	0.6	Qtotal	E	1	117	201	8748	0	211	9159	9159	0.272	1.000
Large	0.6	Qtotal	E	3	117	286	4152	1029	211	5677	5677	0.272	1.000
Large	0.6	Qtotal	E	10	117	571	1912	2916	211	5611	5611	0.272	1.000
Large	0.6	Qtotal	E	12	117	585	5224	2537	211	8557	8557	0.272	1.000
Large	0.6	Qtotal	E	13	117	754	5193	3470	211	9627	9627	0.272	1.000
Large	0.6	Qtotal	E	16	117	535	11287	1427	211	13459	13459	0.272	1.000
Large	0.6	ASH62.2_2016	B	1	107	207	9023	0	385	9615	9451	0.281	0.968
Large	0.6	ASH62.2_2016	B	3	107	280	4229	990	386	5886	5833	0.279	0.978
Large	0.6	ASH62.2_2016	B	10	109	575	2070	2916	394	5955	5923	0.278	0.980
Large	0.6	ASH62.2_2016	B	12	108	594	5507	2551	388	9041	8969	0.279	0.975
Large	0.6	ASH62.2_2016	B	13	109	765	5480	3494	392	10131	10076	0.277	0.982
Large	0.6	ASH62.2_2016	B	16	109	552	12059	1427	393	14432	14137	0.287	0.949
Large	0.6	ASH62.2_2016	E	1	116	200	8716	0	209	9125	9159	0.270	1.007
Large	0.6	ASH62.2_2016	E	3	116	286	4137	1031	209	5663	5678	0.270	1.007
Large	0.6	ASH62.2_2016	E	10	116	572	1908	2918	210	5607	5612	0.271	1.004
Large	0.6	ASH62.2_2016	E	12	116	585	5212	2537	209	8544	8559	0.271	1.006
Large	0.6	ASH62.2_2016	E	13	116	753	5183	3470	210	9615	9627	0.271	1.005
Large	0.6	ASH62.2_2016	E	16	116	534	11264	1428	210	13437	13458	0.271	1.005
Large	0.6	T24_2019	B	1	107	207	9023	0	385	9615	9451	0.281	0.968
Large	0.6	T24_2019	B	3	107	280	4229	990	386	5886	5833	0.279	0.978
Large	0.6	T24_2019	B	10	109	575	2070	2916	394	5955	5923	0.278	0.980
Large	0.6	T24_2019	B	12	108	594	5507	2551	388	9041	8969	0.279	0.975
Large	0.6	T24_2019	B	13	109	765	5480	3494	392	10131	10076	0.277	0.982
Large	0.6	T24_2019	B	16	109	552	12059	1427	393	14432	14137	0.287	0.949
Large	0.6	T24_2019	E	1	116	200	8716	0	209	9125	9159	0.270	1.007
Large	0.6	T24_2019	E	3	116	286	4137	1031	209	5663	5678	0.270	1.007
Large	0.6	T24_2019	E	10	116	572	1908	2918	210	5607	5612	0.271	1.004

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	0.6	T24_2019	E	12	116	585	5212	2537	209	8544	8559	0.271	1.006
Large	0.6	T24_2019	E	13	116	753	5183	3470	210	9615	9627	0.271	1.005
Large	0.6	T24_2019	E	16	116	534	11264	1428	210	13437	13458	0.271	1.005
Large	0.6	BuilderPractice	B	1	89	190	8277	0	321	8789	9372	0.239	1.137
Large	0.6	BuilderPractice	B	3	89	280	3830	1039	321	5471	5776	0.236	1.154
Large	0.6	BuilderPractice	B	10	89	576	1821	2942	321	5660	5904	0.231	1.182
Large	0.6	BuilderPractice	B	12	89	589	5073	2573	321	8556	8937	0.236	1.157
Large	0.6	BuilderPractice	B	13	89	756	5055	3492	321	9625	10076	0.231	1.179
Large	0.6	BuilderPractice	B	16	89	538	11120	1464	321	13442	14098	0.240	1.136
Large	0.6	BuilderPractice	E	1	89	175	7643	0	161	7979	9046	0.208	1.310
Large	0.6	BuilderPractice	E	3	89	285	3577	1094	161	5117	5620	0.208	1.310
Large	0.6	BuilderPractice	E	10	89	574	1590	2955	161	5279	5576	0.208	1.310
Large	0.6	BuilderPractice	E	12	89	580	4647	2575	161	7963	8529	0.208	1.310
Large	0.6	BuilderPractice	E	13	89	745	4671	3474	161	9051	9656	0.208	1.311
Large	0.6	BuilderPractice	E	16	89	518	10115	1480	161	12273	13404	0.208	1.310
Large	0.6	None	B	1	0	111	4848	0	0	4959	8638	0.028	9.815
Large	0.6	None	B	3	0	290	2071	1296	0	3657	5259	0.025	10.922
Large	0.6	None	B	10	0	572	827	2977	0	4376	5097	0.021	14.317
Large	0.6	None	B	12	0	561	3177	2613	0	6351	8539	0.025	11.348
Large	0.6	None	B	13	0	705	3202	3389	0	7296	9792	0.021	13.895
Large	0.6	None	B	16	0	483	7093	1682	0	9259	15546	0.028	10.998
Large	0.6	None	E	1	0	111	4848	0	0	4959	8638	0.028	9.815
Large	0.6	None	E	3	0	290	2071	1296	0	3657	5259	0.025	10.922
Large	0.6	None	E	10	0	572	827	2977	0	4376	5097	0.021	14.317
Large	0.6	None	E	12	0	561	3177	2613	0	6351	8539	0.025	11.348
Large	0.6	None	E	13	0	705	3202	3389	0	7296	9792	0.021	13.895
Large	0.6	None	E	16	0	483	7093	1682	0	9259	15546	0.028	10.998
Large	1	T24_2008	B	1	64	173	7527	0	230	7930	9229	0.197	1.384
Large	1	T24_2008	B	3	64	282	3451	1092	230	5054	5709	0.192	1.421
Large	1	T24_2008	B	10	64	576	1584	2961	230	5351	5853	0.184	1.487
Large	1	T24_2008	B	12	64	584	4660	2591	230	8065	8886	0.192	1.426

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	1	T24_2008	B	13	64	748	4666	3483	230	9127	10092	0.185	1.477
Large	1	T24_2008	B	16	64	531	10503	1503	230	12766	14371	0.198	1.388
Large	1	T24_2008	E	1	64	154	6727	0	115	6996	9026	0.149	1.827
Large	1	T24_2008	E	3	64	285	3091	1154	115	4645	5599	0.149	1.830
Large	1	T24_2008	E	10	64	576	1334	2985	115	5010	5579	0.149	1.827
Large	1	T24_2008	E	12	64	576	4135	2605	115	7431	8498	0.149	1.826
Large	1	T24_2008	E	13	64	737	4182	3477	115	8511	9684	0.148	1.833
Large	1	T24_2008	E	16	64	507	9218	1533	115	11372	13652	0.149	1.831
Large	1	T24_2013	B	1	100	208	9059	0	361	9627	9431	0.284	0.961
Large	1	T24_2013	B	3	101	281	4246	990	363	5880	5821	0.279	0.975
Large	1	T24_2013	B	10	104	575	2099	2909	376	5959	5921	0.279	0.977
Large	1	T24_2013	B	12	102	594	5543	2546	366	9049	8963	0.281	0.970
Large	1	T24_2013	B	13	103	765	5519	3488	373	10144	10082	0.279	0.979
Large	1	T24_2013	B	16	104	557	12260	1427	374	14618	14219	0.293	0.933
Large	1	T24_2013	E	1	100	186	8111	0	181	8477	9129	0.234	1.165
Large	1	T24_2013	E	3	101	285	3817	1064	182	5348	5642	0.235	1.159
Large	1	T24_2013	E	10	104	572	1783	2930	188	5473	5609	0.243	1.118
Large	1	T24_2013	E	12	102	583	4936	2555	183	8257	8571	0.237	1.148
Large	1	T24_2013	E	13	103	750	4962	3470	186	9368	9661	0.241	1.129
Large	1	T24_2013	E	16	104	527	10776	1451	187	12941	13483	0.242	1.126
Large	1	Qtotal	B	1	117	224	9758	0	421	10403	9489	0.323	0.844
Large	1	Qtotal	B	3	117	281	4624	948	421	6275	5882	0.317	0.859
Large	1	Qtotal	B	10	117	576	2278	2898	421	6173	5957	0.309	0.884
Large	1	Qtotal	B	12	117	598	5891	2528	421	9438	8978	0.317	0.861
Large	1	Qtotal	B	13	117	771	5830	3489	421	10511	10101	0.310	0.880
Large	1	Qtotal	B	16	117	567	12885	1405	421	15278	14236	0.324	0.843
Large	1	Qtotal	E	1	117	201	8767	0	211	9179	9177	0.272	1.000
Large	1	Qtotal	E	3	117	285	4157	1027	211	5680	5679	0.272	1.000
Large	1	Qtotal	E	10	117	571	1923	2914	211	5619	5618	0.272	0.999
Large	1	Qtotal	E	12	117	585	5245	2535	211	8575	8575	0.272	1.000
Large	1	Qtotal	E	13	117	754	5222	3468	211	9654	9654	0.272	1.000

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	1	Qtotal	E	16	117	536	11333	1427	211	13506	13505	0.272	1.000
Large	1	ASH62.2_2016	B	1	100	208	9059	0	361	9627	9431	0.284	0.961
Large	1	ASH62.2_2016	B	3	101	281	4246	990	363	5880	5821	0.279	0.975
Large	1	ASH62.2_2016	B	10	104	575	2099	2909	376	5959	5921	0.279	0.977
Large	1	ASH62.2_2016	B	12	102	594	5543	2546	366	9049	8963	0.281	0.970
Large	1	ASH62.2_2016	B	13	103	765	5519	3488	373	10144	10082	0.279	0.979
Large	1	ASH62.2_2016	B	16	104	557	12260	1427	374	14618	14219	0.293	0.933
Large	1	ASH62.2_2016	E	1	114	199	8678	0	206	9083	9176	0.267	1.020
Large	1	ASH62.2_2016	E	3	115	285	4110	1032	207	5634	5674	0.267	1.019
Large	1	ASH62.2_2016	E	10	115	571	1911	2916	208	5606	5620	0.269	1.011
Large	1	ASH62.2_2016	E	12	115	585	5204	2537	207	8533	8573	0.268	1.017
Large	1	ASH62.2_2016	E	13	115	753	5180	3468	208	9609	9642	0.269	1.013
Large	1	ASH62.2_2016	E	16	115	535	11270	1429	208	13442	13502	0.269	1.013
Large	1	T24_2019	B	1	100	208	9059	0	361	9627	9431	0.284	0.961
Large	1	T24_2019	B	3	101	281	4246	990	363	5880	5821	0.279	0.975
Large	1	T24_2019	B	10	104	575	2099	2909	376	5959	5921	0.279	0.977
Large	1	T24_2019	B	12	102	594	5543	2546	366	9049	8963	0.281	0.970
Large	1	T24_2019	B	13	103	765	5519	3488	373	10144	10082	0.279	0.979
Large	1	T24_2019	B	16	104	557	12260	1427	374	14618	14219	0.293	0.933
Large	1	T24_2019	E	1	114	199	8678	0	206	9083	9176	0.267	1.020
Large	1	T24_2019	E	3	115	285	4110	1032	207	5634	5674	0.267	1.019
Large	1	T24_2019	E	10	115	571	1911	2916	208	5606	5620	0.269	1.011
Large	1	T24_2019	E	12	115	585	5204	2537	207	8533	8573	0.268	1.017
Large	1	T24_2019	E	13	115	753	5180	3468	208	9609	9642	0.269	1.013
Large	1	T24_2019	E	16	115	535	11270	1429	208	13442	13502	0.269	1.013
Large	1	BuilderPractice	B	1	89	197	8580	0	321	9099	9368	0.257	1.059
Large	1	BuilderPractice	B	3	89	280	3971	1022	321	5595	5766	0.252	1.082
Large	1	BuilderPractice	B	10	89	575	1910	2928	321	5735	5905	0.244	1.120
Large	1	BuilderPractice	B	12	89	591	5252	2561	321	8726	8944	0.252	1.085
Large	1	BuilderPractice	B	13	89	758	5200	3488	321	9768	10073	0.245	1.114
Large	1	BuilderPractice	B	16	89	546	11572	1454	321	13893	14207	0.258	1.060

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	1	BuilderPractice	E	1	89	176	7671	0	161	8008	9079	0.208	1.309
Large	1	BuilderPractice	E	3	89	285	3582	1091	161	5118	5620	0.208	1.309
Large	1	BuilderPractice	E	10	89	573	1601	2952	161	5286	5583	0.208	1.308
Large	1	BuilderPractice	E	12	89	580	4669	2572	161	7983	8552	0.208	1.309
Large	1	BuilderPractice	E	13	89	745	4691	3472	161	9068	9679	0.208	1.310
Large	1	BuilderPractice	E	16	89	519	10172	1479	161	12331	13477	0.208	1.310
Large	1	None	B	1	0	117	5121	0	0	5238	8683	0.047	5.945
Large	1	None	B	3	0	288	2211	1273	0	3772	5324	0.042	6.610
Large	1	None	B	10	0	570	901	2956	0	4426	5224	0.035	8.677
Large	1	None	B	12	0	561	3340	2598	0	6499	8620	0.042	6.895
Large	1	None	B	13	0	706	3370	3377	0	7453	10057	0.035	8.408
Large	1	None	B	16	0	490	7530	1658	0	9678	15645	0.047	6.695
Large	1	None	E	1	0	117	5121	0	0	5238	8683	0.047	5.945
Large	1	None	E	3	0	288	2211	1273	0	3772	5324	0.042	6.610
Large	1	None	E	10	0	570	901	2956	0	4426	5224	0.035	8.677
Large	1	None	E	12	0	561	3340	2598	0	6499	8620	0.042	6.895
Large	1	None	E	13	0	706	3370	3377	0	7453	10057	0.035	8.408
Large	1	None	E	16	0	490	7530	1658	0	9678	15645	0.047	6.695
Large	2	T24_2008	B	1	64	191	8333	0	230	8754	9308	0.242	1.132
Large	2	T24_2008	B	3	64	282	3834	1046	230	5391	5730	0.232	1.179
Large	2	T24_2008	B	10	64	575	1820	2928	230	5552	5886	0.217	1.272
Large	2	T24_2008	B	12	64	588	5108	2562	230	8488	8925	0.232	1.186
Large	2	T24_2008	B	13	64	753	5048	3471	230	9502	10111	0.220	1.254
Large	2	T24_2008	B	16	64	551	11600	1476	230	13857	14607	0.243	1.144
Large	2	T24_2008	E	1	64	158	6906	0	115	7179	9174	0.156	1.757
Large	2	T24_2008	E	3	64	284	3137	1141	115	4678	5622	0.152	1.799
Large	2	T24_2008	E	10	64	575	1405	2967	115	5061	5646	0.153	1.791
Large	2	T24_2008	E	12	64	577	4288	2592	115	7572	8649	0.156	1.752
Large	2	T24_2008	E	13	64	738	4311	3470	115	8634	9843	0.152	1.790
Large	2	T24_2008	E	16	64	522	9906	1528	115	12070	14470	0.162	1.698
Large	2	T24_2013	B	1	83	210	9169	0	301	9680	9409	0.289	0.947

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	2	T24_2013	B	3	85	282	4296	990	305	5873	5805	0.281	0.971
Large	2	T24_2013	B	10	92	575	2180	2896	331	5982	5934	0.283	0.971
Large	2	T24_2013	B	12	86	594	5641	2535	312	9083	8967	0.286	0.961
Large	2	T24_2013	B	13	90	765	5628	3475	325	10192	10115	0.281	0.975
Large	2	T24_2013	B	16	91	569	12774	1427	327	15096	14444	0.307	0.899
Large	2	T24_2013	E	1	83	173	7547	0	151	7870	9141	0.197	1.382
Large	2	T24_2013	E	3	85	284	3521	1093	153	5051	5625	0.199	1.369
Large	2	T24_2013	E	10	92	572	1689	2936	166	5362	5636	0.216	1.263
Large	2	T24_2013	E	12	86	580	4705	2566	156	8007	8627	0.205	1.332
Large	2	T24_2013	E	13	90	746	4774	3466	162	9148	9744	0.211	1.291
Large	2	T24_2013	E	16	91	526	10511	1473	163	12673	13789	0.214	1.276
Large	2	Qtotal	B	1	117	243	10588	0	421	11252	9534	0.367	0.744
Large	2	Qtotal	B	3	117	283	5013	908	421	6624	5890	0.357	0.765
Large	2	Qtotal	B	10	117	575	2504	2867	421	6367	5965	0.341	0.803
Large	2	Qtotal	B	12	117	602	6332	2498	421	9854	8988	0.357	0.767
Large	2	Qtotal	B	13	117	777	6236	3476	421	10910	10132	0.344	0.796
Large	2	Qtotal	B	16	117	590	14034	1384	421	16428	14443	0.369	0.745
Large	2	Qtotal	E	1	117	203	8847	0	211	9261	9237	0.274	0.995
Large	2	Qtotal	E	3	117	285	4187	1019	211	5701	5695	0.273	0.997
Large	2	Qtotal	E	10	117	570	1963	2903	211	5646	5640	0.274	0.996
Large	2	Qtotal	E	12	117	585	5318	2526	211	8640	8626	0.274	0.994
Large	2	Qtotal	E	13	117	754	5279	3462	211	9706	9703	0.273	0.999
Large	2	Qtotal	E	16	117	539	11509	1424	211	13683	13671	0.273	0.998
Large	2	ASH62.2_2016	B	1	83	210	9169	0	301	9680	9409	0.289	0.947
Large	2	ASH62.2_2016	B	3	85	282	4296	990	305	5873	5805	0.281	0.971
Large	2	ASH62.2_2016	B	10	92	575	2180	2896	331	5982	5934	0.283	0.971
Large	2	ASH62.2_2016	B	12	86	594	5641	2535	312	9083	8967	0.286	0.961
Large	2	ASH62.2_2016	B	13	90	765	5628	3475	325	10192	10115	0.281	0.975
Large	2	ASH62.2_2016	B	16	91	569	12774	1427	327	15096	14444	0.307	0.899
Large	2	ASH62.2_2016	E	1	107	194	8459	0	193	8846	9197	0.252	1.082
Large	2	ASH62.2_2016	E	3	108	284	3994	1039	195	5511	5669	0.253	1.078

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	2	ASH62.2_2016	E	10	111	571	1907	2910	201	5589	5643	0.261	1.043
Large	2	ASH62.2_2016	E	12	109	584	5162	2537	196	8479	8630	0.256	1.065
Large	2	ASH62.2_2016	E	13	111	752	5156	3463	200	9571	9703	0.258	1.054
Large	2	ASH62.2_2016	E	16	111	536	11271	1435	200	13442	13681	0.259	1.050
Large	2	T24_2019	B	1	83	210	9169	0	301	9680	9409	0.289	0.947
Large	2	T24_2019	B	3	85	282	4296	990	305	5873	5805	0.281	0.971
Large	2	T24_2019	B	10	92	575	2180	2896	331	5982	5934	0.283	0.971
Large	2	T24_2019	B	12	86	594	5641	2535	312	9083	8967	0.286	0.961
Large	2	T24_2019	B	13	90	765	5628	3475	325	10192	10115	0.281	0.975
Large	2	T24_2019	B	16	91	569	12774	1427	327	15096	14444	0.307	0.899
Large	2	T24_2019	E	1	107	194	8459	0	193	8846	9197	0.252	1.082
Large	2	T24_2019	E	3	108	284	3994	1039	195	5511	5669	0.253	1.078
Large	2	T24_2019	E	10	111	571	1907	2910	201	5589	5643	0.261	1.043
Large	2	T24_2019	E	12	109	584	5162	2537	196	8479	8630	0.256	1.065
Large	2	T24_2019	E	13	111	752	5156	3463	200	9571	9703	0.258	1.054
Large	2	T24_2019	E	16	111	536	11271	1435	200	13442	13681	0.259	1.050
Large	2	BuilderPractice	B	1	89	216	9399	0	321	9935	9426	0.302	0.906
Large	2	BuilderPractice	B	3	89	282	4404	978	321	5986	5828	0.292	0.936
Large	2	BuilderPractice	B	10	89	575	2147	2899	321	5943	5933	0.277	0.994
Large	2	BuilderPractice	B	12	89	595	5702	2532	321	9151	8970	0.292	0.940
Large	2	BuilderPractice	B	13	89	764	5606	3475	321	10166	10113	0.279	0.983
Large	2	BuilderPractice	B	16	89	568	12702	1429	321	15021	14446	0.304	0.910
Large	2	BuilderPractice	E	1	89	178	7765	0	161	8104	9163	0.210	1.297
Large	2	BuilderPractice	E	3	89	283	3607	1082	161	5134	5629	0.209	1.303
Large	2	BuilderPractice	E	10	89	572	1663	2939	161	5335	5639	0.210	1.300
Large	2	BuilderPractice	E	12	89	580	4755	2563	161	8059	8623	0.211	1.294
Large	2	BuilderPractice	E	13	89	745	4759	3466	161	9132	9750	0.209	1.305
Large	2	BuilderPractice	E	16	89	525	10460	1476	161	12621	13803	0.210	1.296
Large	2	None	B	1	0	134	5826	0	0	5959	8824	0.093	3.021
Large	2	None	B	3	0	287	2564	1223	0	4075	5439	0.083	3.356
Large	2	None	B	10	0	578	1062	2984	0	4624	5653	0.069	4.399

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	2	None	B	12	0	563	3749	2566	0	6878	8738	0.083	3.519
Large	2	None	B	13	0	727	3695	3448	0	7871	10332	0.071	4.200
Large	2	None	B	16	0	509	8653	1615	0	10777	15966	0.093	3.416
Large	2	None	E	1	0	134	5826	0	0	5959	8824	0.093	3.021
Large	2	None	E	3	0	287	2564	1223	0	4075	5439	0.083	3.356
Large	2	None	E	10	0	578	1062	2984	0	4624	5653	0.069	4.399
Large	2	None	E	12	0	563	3749	2566	0	6878	8738	0.083	3.519
Large	2	None	E	13	0	727	3695	3448	0	7871	10332	0.071	4.200
Large	2	None	E	16	0	509	8653	1615	0	10777	15966	0.093	3.416
Large	3	T24_2008	B	1	64	210	9150	0	230	9590	9387	0.287	0.960
Large	3	T24_2008	B	3	64	283	4216	1004	230	5732	5755	0.272	1.010
Large	3	T24_2008	B	10	64	573	2036	2899	230	5737	5902	0.250	1.116
Large	3	T24_2008	B	12	64	593	5563	2533	230	8918	8972	0.273	1.019
Large	3	T24_2008	B	13	64	759	5443	3459	230	9891	10151	0.254	1.094
Large	3	T24_2008	B	16	64	571	12678	1451	230	14929	14785	0.288	0.977
Large	3	T24_2008	E	1	64	174	7568	0	115	7857	9319	0.193	1.441
Large	3	T24_2008	E	3	64	284	3427	1107	115	4933	5713	0.179	1.543
Large	3	T24_2008	E	10	64	573	1601	2935	115	5224	5774	0.173	1.610
Large	3	T24_2008	E	12	64	581	4726	2565	115	7986	8882	0.187	1.485
Large	3	T24_2008	E	13	64	744	4685	3454	115	8997	10075	0.175	1.569
Large	3	T24_2008	E	16	64	545	11043	1511	115	13214	15136	0.201	1.419
Large	3	T24_2013	B	1	67	213	9286	0	241	9740	9403	0.294	0.935
Large	3	T24_2013	B	3	69	283	4336	991	247	5857	5783	0.283	0.969
Large	3	T24_2013	B	10	79	575	2249	2883	286	5993	5941	0.287	0.969
Large	3	T24_2013	B	12	71	595	5739	2524	257	9116	8980	0.291	0.954
Large	3	T24_2013	B	13	77	765	5746	3461	276	10248	10165	0.284	0.973
Large	3	T24_2013	B	16	78	580	13284	1426	280	15570	14679	0.321	0.872
Large	3	T24_2013	E	1	67	175	7626	0	121	7921	9342	0.195	1.420
Large	3	T24_2013	E	3	69	284	3462	1102	124	4972	5711	0.183	1.501
Large	3	T24_2013	E	10	79	572	1697	2928	143	5341	5741	0.198	1.393
Large	3	T24_2013	E	12	71	582	4795	2559	129	8065	8853	0.196	1.409

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	3	T24_2013	E	13	77	745	4798	3457	138	9139	9973	0.194	1.409
Large	3	T24_2013	E	16	78	545	11205	1490	140	13380	14736	0.218	1.286
Large	3	Qtotal	B	1	117	262	11442	0	421	12125	9593	0.411	0.666
Large	3	Qtotal	B	3	117	285	5422	868	421	6995	5915	0.396	0.691
Large	3	Qtotal	B	10	117	576	2770	2842	421	6609	6010	0.374	0.738
Large	3	Qtotal	B	12	117	607	6775	2471	421	10274	9006	0.397	0.693
Large	3	Qtotal	B	13	117	783	6648	3465	421	11317	10169	0.378	0.728
Large	3	Qtotal	B	16	117	612	15152	1363	421	17547	14603	0.414	0.670
Large	3	Qtotal	E	1	117	206	8980	0	211	9397	9324	0.277	0.985
Large	3	Qtotal	E	3	117	284	4241	1009	211	5745	5725	0.275	0.991
Large	3	Qtotal	E	10	117	570	2029	2890	211	5700	5686	0.276	0.990
Large	3	Qtotal	E	12	117	586	5435	2516	211	8747	8698	0.278	0.981
Large	3	Qtotal	E	13	117	755	5376	3456	211	9798	9777	0.274	0.992
Large	3	Qtotal	E	16	117	551	12043	1421	211	14226	14077	0.281	0.973
Large	3	ASH62.2_2016	B	1	67	213	9286	0	241	9740	9403	0.294	0.935
Large	3	ASH62.2_2016	B	3	69	283	4336	991	247	5857	5783	0.283	0.969
Large	3	ASH62.2_2016	B	10	79	575	2249	2883	286	5993	5941	0.287	0.969
Large	3	ASH62.2_2016	B	12	71	595	5739	2524	257	9116	8980	0.291	0.954
Large	3	ASH62.2_2016	B	13	77	765	5746	3461	276	10248	10165	0.284	0.973
Large	3	ASH62.2_2016	B	16	78	580	13284	1426	280	15570	14679	0.321	0.872
Large	3	ASH62.2_2016	E	1	95	189	8244	0	172	8605	9317	0.233	1.175
Large	3	ASH62.2_2016	E	3	97	283	3846	1052	175	5356	5698	0.231	1.184
Large	3	ASH62.2_2016	E	10	105	570	1907	2904	189	5570	5693	0.249	1.099
Large	3	ASH62.2_2016	E	12	99	584	5132	2537	179	8432	8744	0.241	1.136
Large	3	ASH62.2_2016	E	13	103	751	5128	3458	186	9524	9807	0.244	1.117
Large	3	ASH62.2_2016	E	16	104	548	11709	1445	187	13888	14261	0.257	1.071
Large	3	T24_2019	B	1	83	229	9968	0	301	10497	9451	0.333	0.824
Large	3	T24_2019	B	3	85	283	4699	948	305	6235	5836	0.321	0.854
Large	3	T24_2019	B	10	92	575	2416	2868	331	6190	5961	0.316	0.877
Large	3	T24_2019	B	12	86	599	6088	2506	312	9504	8992	0.326	0.848
Large	3	T24_2019	B	13	90	771	6048	3462	325	10606	10167	0.315	0.875

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	3	T24_2019	B	16	91	591	13921	1404	327	16243	14658	0.352	0.792
Large	3	T24_2019	E	1	107	198	8618	0	193	9010	9301	0.256	1.065
Large	3	T24_2019	E	3	108	283	4049	1028	195	5555	5698	0.255	1.070
Large	3	T24_2019	E	10	111	570	1970	2895	201	5636	5683	0.264	1.036
Large	3	T24_2019	E	12	109	585	5291	2526	196	8598	8712	0.261	1.046
Large	3	T24_2019	E	13	111	753	5266	3457	200	9676	9792	0.261	1.045
Large	3	T24_2019	E	16	111	549	11890	1431	200	14071	14156	0.270	1.016
Large	3	BuilderPractice	B	1	89	234	10206	0	321	10761	9472	0.346	0.793
Large	3	BuilderPractice	B	3	89	283	4795	937	321	6337	5847	0.331	0.827
Large	3	BuilderPractice	B	10	89	575	2385	2874	321	6155	5964	0.309	0.896
Large	3	BuilderPractice	B	12	89	599	6151	2503	321	9574	8996	0.332	0.832
Large	3	BuilderPractice	B	13	89	771	6024	3462	321	10578	10164	0.313	0.881
Large	3	BuilderPractice	B	16	89	590	13850	1407	321	16168	14663	0.349	0.800
Large	3	BuilderPractice	E	1	89	185	8076	0	161	8422	9335	0.222	1.235
Large	3	BuilderPractice	E	3	89	283	3702	1068	161	5214	5687	0.214	1.276
Large	3	BuilderPractice	E	10	89	571	1765	2921	161	5418	5714	0.216	1.270
Large	3	BuilderPractice	E	12	89	583	4996	2547	161	8287	8787	0.222	1.233
Large	3	BuilderPractice	E	13	89	748	4937	3459	161	9305	9888	0.216	1.265
Large	3	BuilderPractice	E	16	89	546	11417	1470	161	13593	14518	0.234	1.186
Large	3	None	B	1	0	151	6578	0	0	6729	9003	0.138	2.039
Large	3	None	B	3	0	286	2914	1178	0	4378	5493	0.124	2.264
Large	3	None	B	10	0	576	1279	2954	0	4809	5770	0.102	2.973
Large	3	None	B	12	0	577	4101	2603	0	7282	8854	0.124	2.377
Large	3	None	B	13	0	732	4064	3438	0	8234	10308	0.105	2.833
Large	3	None	B	16	0	528	9756	1581	0	11866	16089	0.139	2.305
Large	3	None	E	1	0	151	6578	0	0	6729	9003	0.138	2.039
Large	3	None	E	3	0	286	2914	1178	0	4378	5493	0.124	2.264
Large	3	None	E	10	0	576	1279	2954	0	4809	5770	0.102	2.973
Large	3	None	E	12	0	577	4101	2603	0	7282	8854	0.124	2.377
Large	3	None	E	13	0	732	4064	3438	0	8234	10308	0.105	2.833
Large	3	None	E	16	0	528	9756	1581	0	11866	16089	0.139	2.305

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	5	T24_2008	B	1	64	246	10746	0	230	11222	9489	0.375	0.741
Large	5	T24_2008	B	3	64	286	5040	920	230	6475	5848	0.350	0.790
Large	5	T24_2008	B	10	64	574	2525	2846	230	6175	5995	0.315	0.903
Large	5	T24_2008	B	12	64	602	6454	2477	230	9763	9040	0.353	0.801
Large	5	T24_2008	B	13	64	772	6277	3436	230	10715	10267	0.322	0.876
Large	5	T24_2008	B	16	64	613	14898	1404	230	17145	15115	0.378	0.762
Large	5	T24_2008	E	1	64	211	9216	0	115	9542	9480	0.283	0.988
Large	5	T24_2008	E	3	64	285	4210	1015	115	5624	5777	0.260	1.072
Large	5	T24_2008	E	10	64	571	2058	2873	115	5617	5910	0.233	1.226
Large	5	T24_2008	E	12	64	590	5640	2505	115	8850	9049	0.265	1.073
Large	5	T24_2008	E	13	64	755	5474	3427	115	9770	10249	0.240	1.180
Large	5	T24_2008	E	16	64	585	13209	1463	115	15373	15609	0.288	1.035
Large	5	T24_2013	B	1	34	218	9501	0	121	9839	9397	0.305	0.917
Large	5	T24_2013	B	3	37	285	4429	991	132	5836	5759	0.287	0.967
Large	5	T24_2013	B	10	54	574	2390	2857	196	6016	5973	0.293	0.975
Large	5	T24_2013	B	12	41	595	5935	2502	148	9180	9034	0.300	0.952
Large	5	T24_2013	B	13	50	766	5966	3433	180	10345	10278	0.290	0.979
Large	5	T24_2013	B	16	51	604	14316	1425	185	16529	15203	0.350	0.832
Large	5	T24_2013	E	1	34	199	8673	0	60	8933	9345	0.257	1.094
Large	5	T24_2013	E	3	37	284	3965	1044	66	5360	5703	0.236	1.184
Large	5	T24_2013	E	10	54	571	2013	2877	98	5560	5921	0.223	1.291
Large	5	T24_2013	E	12	41	588	5408	2519	74	8590	9050	0.243	1.188
Large	5	T24_2013	E	13	50	752	5346	3423	90	9612	10293	0.225	1.272
Large	5	T24_2013	E	16	51	582	12962	1474	93	15110	15697	0.277	1.091
Large	5	Qtotal	B	1	117	298	12989	0	421	13708	9605	0.499	0.552
Large	5	Qtotal	B	3	117	289	6210	793	421	7713	5948	0.473	0.581
Large	5	Qtotal	B	10	117	577	3289	2788	421	7075	6078	0.438	0.638
Large	5	Qtotal	B	12	117	617	7706	2415	421	11160	9071	0.476	0.584
Large	5	Qtotal	B	13	117	796	7462	3440	421	12119	10232	0.445	0.624
Large	5	Qtotal	B	16	117	655	17365	1321	421	19762	14861	0.503	0.560
Large	5	Qtotal	E	1	117	228	9950	0	211	10389	9510	0.327	0.850

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	5	Qtotal	E	3	117	285	4675	964	211	6135	5880	0.305	0.903
Large	5	Qtotal	E	10	117	570	2360	2851	211	5992	5857	0.301	0.919
Large	5	Qtotal	E	12	117	594	6150	2471	211	9426	8964	0.323	0.860
Large	5	Qtotal	E	13	117	765	5981	3435	211	10391	10059	0.306	0.899
Large	5	Qtotal	E	16	117	599	14256	1406	211	16472	15057	0.345	0.820
Large	5	ASH62.2_2016	B	1	34	218	9501	0	121	9839	9397	0.305	0.917
Large	5	ASH62.2_2016	B	3	37	285	4429	991	132	5836	5759	0.287	0.967
Large	5	ASH62.2_2016	B	10	54	574	2390	2857	196	6016	5973	0.293	0.975
Large	5	ASH62.2_2016	B	12	41	595	5935	2502	148	9180	9034	0.300	0.952
Large	5	ASH62.2_2016	B	13	50	766	5966	3433	180	10345	10278	0.290	0.979
Large	5	ASH62.2_2016	B	16	51	604	14316	1425	185	16529	15203	0.350	0.832
Large	5	ASH62.2_2016	E	1	57	209	9101	0	104	9413	9449	0.278	1.007
Large	5	ASH62.2_2016	E	3	62	285	4193	1017	111	5605	5773	0.258	1.080
Large	5	ASH62.2_2016	E	10	83	571	2157	2867	150	5745	5890	0.256	1.102
Large	5	ASH62.2_2016	E	12	68	590	5678	2503	122	8893	9045	0.269	1.055
Large	5	ASH62.2_2016	E	13	78	758	5609	3430	141	9938	10198	0.256	1.092
Large	5	ASH62.2_2016	E	16	80	590	13535	1448	145	15718	15462	0.304	0.964
Large	5	T24_2019	B	1	83	267	11631	0	301	12199	9573	0.421	0.657
Large	5	T24_2019	B	3	85	286	5503	869	305	6963	5894	0.398	0.692
Large	5	T24_2019	B	10	92	576	2930	2815	331	6652	6045	0.380	0.740
Large	5	T24_2019	B	12	86	608	6987	2451	312	10358	9052	0.406	0.690
Large	5	T24_2019	B	13	90	784	6864	3439	325	11412	10246	0.383	0.729
Large	5	T24_2019	B	16	91	634	16139	1361	327	18462	14955	0.441	0.643
Large	5	T24_2019	E	1	107	228	9930	0	193	10351	9625	0.318	0.875
Large	5	T24_2019	E	3	108	285	4599	973	195	6052	5881	0.296	0.933
Large	5	T24_2019	E	10	111	570	2325	2854	201	5950	5865	0.293	0.947
Large	5	T24_2019	E	12	109	593	6075	2477	196	9341	8984	0.313	0.889
Large	5	T24_2019	E	13	111	763	5921	3435	200	10319	10084	0.297	0.927
Large	5	T24_2019	E	16	111	598	14148	1413	200	16359	15129	0.338	0.841
Large	5	BuilderPractice	B	1	89	273	11883	0	321	12477	9594	0.434	0.637
Large	5	BuilderPractice	B	3	89	286	5595	857	321	7060	5898	0.409	0.674

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	5	BuilderPractice	B	10	89	576	2896	2819	321	6612	6046	0.374	0.753
Large	5	BuilderPractice	B	12	89	609	7048	2448	321	10427	9053	0.412	0.680
Large	5	BuilderPractice	B	13	89	784	6844	3439	321	11388	10246	0.381	0.734
Large	5	BuilderPractice	B	16	89	633	16070	1364	321	18388	14963	0.438	0.649
Large	5	BuilderPractice	E	1	89	221	9645	0	161	10027	9577	0.304	0.918
Large	5	BuilderPractice	E	3	89	285	4434	991	161	5871	5846	0.280	0.989
Large	5	BuilderPractice	E	10	89	571	2191	2864	161	5786	5887	0.263	1.069
Large	5	BuilderPractice	E	12	89	592	5883	2489	161	9124	9017	0.291	0.964
Large	5	BuilderPractice	E	13	89	760	5718	3432	161	10070	10170	0.269	1.034
Large	5	BuilderPractice	E	16	89	593	13715	1439	161	15907	15373	0.313	0.927
Large	5	None	B	1	0	186	8103	0	0	8289	9220	0.227	1.248
Large	5	None	B	3	0	286	3655	1087	0	5028	5619	0.203	1.386
Large	5	None	B	10	0	572	1708	2901	0	5181	5894	0.168	1.830
Large	5	None	B	12	0	585	4992	2547	0	8124	9032	0.205	1.458
Large	5	None	B	13	0	743	4874	3416	0	9033	10449	0.174	1.733
Large	5	None	B	16	0	567	11959	1520	0	14046	16243	0.230	1.406
Large	5	None	E	1	0	186	8103	0	0	8289	9220	0.227	1.248
Large	5	None	E	3	0	286	3655	1087	0	5028	5619	0.203	1.386
Large	5	None	E	10	0	572	1708	2901	0	5181	5894	0.168	1.830
Large	5	None	E	12	0	585	4992	2547	0	8124	9032	0.205	1.458
Large	5	None	E	13	0	743	4874	3416	0	9033	10449	0.174	1.733
Large	5	None	E	16	0	567	11959	1520	0	14046	16243	0.230	1.406
Med	0.6	T24_2008	B	1	50	170	7434	0	181	7786	9223	0.182	1.600
Med	0.6	T24_2008	B	3	50	246	3565	884	181	4876	5549	0.180	1.618
Med	0.6	T24_2008	B	10	50	480	1533	2424	181	4619	5086	0.176	1.655
Med	0.6	T24_2008	B	12	50	501	4585	2135	181	7402	8241	0.180	1.620
Med	0.6	T24_2008	B	13	50	639	4599	2886	181	8305	9241	0.177	1.650
Med	0.6	T24_2008	B	16	50	457	9128	1281	181	11047	12775	0.182	1.599
Med	0.6	T24_2008	E	1	50	163	7096	0	91	7349	8956	0.160	1.821
Med	0.6	T24_2008	E	3	50	250	3435	920	91	4695	5440	0.160	1.820
Med	0.6	T24_2008	E	10	50	480	1425	2435	91	4431	4863	0.160	1.820

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	0.6	T24_2008	E	12	50	497	4361	2140	91	7088	7941	0.160	1.821
Med	0.6	T24_2008	E	13	50	632	4368	2878	91	7968	8874	0.160	1.821
Med	0.6	T24_2008	E	16	50	446	8572	1293	91	10401	12239	0.160	1.821
Med	0.6	T24_2013	B	1	86	206	8973	0	310	9488	9403	0.297	0.979
Med	0.6	T24_2013	B	3	86	242	4359	768	311	5680	5651	0.296	0.985
Med	0.6	T24_2013	B	10	87	477	2039	2363	315	5194	5176	0.295	0.987
Med	0.6	T24_2013	B	12	87	508	5459	2080	312	8359	8319	0.296	0.983
Med	0.6	T24_2013	B	13	87	654	5422	2882	314	9272	9243	0.295	0.988
Med	0.6	T24_2013	B	16	87	485	10995	1202	314	12997	12825	0.302	0.964
Med	0.6	T24_2013	E	1	86	196	8557	0	155	8908	9140	0.273	1.066
Med	0.6	T24_2013	E	3	86	248	4200	818	155	5422	5525	0.274	1.063
Med	0.6	T24_2013	E	10	87	476	1889	2374	158	4896	4945	0.278	1.049
Med	0.6	T24_2013	E	12	87	502	5152	2081	156	7890	8000	0.275	1.060
Med	0.6	T24_2013	E	13	87	645	5132	2867	157	8800	8901	0.277	1.052
Med	0.6	T24_2013	E	16	87	470	10266	1213	157	12106	12308	0.277	1.051
Med	0.6	Qtotal	B	1	92	212	9236	0	331	9778	9436	0.316	0.922
Med	0.6	Qtotal	B	3	92	242	4500	749	331	5822	5678	0.313	0.929
Med	0.6	Qtotal	B	10	92	482	2075	2386	331	5274	5196	0.309	0.943
Med	0.6	Qtotal	B	12	92	509	5593	2069	331	8502	8332	0.313	0.930
Med	0.6	Qtotal	B	13	92	656	5522	2882	331	9391	9243	0.309	0.941
Med	0.6	Qtotal	B	16	92	488	11221	1193	331	13233	12829	0.317	0.920
Med	0.6	Qtotal	E	1	92	202	8794	0	165	9161	9161	0.291	1.000
Med	0.6	Qtotal	E	3	92	248	4324	803	165	5540	5540	0.291	1.000
Med	0.6	Qtotal	E	10	92	480	1916	2396	165	4957	4957	0.291	1.000
Med	0.6	Qtotal	E	12	92	502	5259	2072	165	7999	7999	0.291	1.000
Med	0.6	Qtotal	E	13	92	646	5222	2863	165	8897	8897	0.291	1.000
Med	0.6	Qtotal	E	16	92	473	10466	1204	165	12308	12308	0.291	1.000
Med	0.6	ASH62.2_2016	B	1	86	206	8973	0	310	9488	9403	0.297	0.979
Med	0.6	ASH62.2_2016	B	3	86	242	4359	768	311	5680	5651	0.296	0.985
Med	0.6	ASH62.2_2016	B	10	87	477	2039	2363	315	5194	5176	0.295	0.987
Med	0.6	ASH62.2_2016	B	12	87	508	5459	2080	312	8359	8319	0.296	0.983

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	0.6	ASH62.2_2016	B	13	87	654	5422	2882	314	9272	9243	0.295	0.988
Med	0.6	ASH62.2_2016	B	16	87	485	10995	1202	314	12997	12825	0.302	0.964
Med	0.6	ASH62.2_2016	E	1	91	201	8779	0	165	9145	9160	0.290	1.004
Med	0.6	ASH62.2_2016	E	3	91	248	4317	804	165	5534	5540	0.290	1.004
Med	0.6	ASH62.2_2016	E	10	91	480	1914	2396	165	4955	4958	0.290	1.002
Med	0.6	ASH62.2_2016	E	12	91	502	5251	2072	165	7990	7996	0.290	1.003
Med	0.6	ASH62.2_2016	E	13	91	646	5217	2863	165	8891	8896	0.290	1.002
Med	0.6	ASH62.2_2016	E	16	91	473	10457	1204	165	12299	12309	0.290	1.002
Med	0.6	T24_2019	B	1	86	206	8973	0	310	9488	9403	0.297	0.979
Med	0.6	T24_2019	B	3	86	242	4359	768	311	5680	5651	0.296	0.985
Med	0.6	T24_2019	B	10	87	477	2039	2363	315	5194	5176	0.295	0.987
Med	0.6	T24_2019	B	12	87	508	5459	2080	312	8359	8319	0.296	0.983
Med	0.6	T24_2019	B	13	87	654	5422	2882	314	9272	9243	0.295	0.988
Med	0.6	T24_2019	B	16	87	485	10995	1202	314	12997	12825	0.302	0.964
Med	0.6	T24_2019	E	1	91	201	8779	0	165	9145	9160	0.290	1.004
Med	0.6	T24_2019	E	3	91	248	4317	804	165	5534	5540	0.290	1.004
Med	0.6	T24_2019	E	10	91	480	1914	2396	165	4955	4958	0.290	1.002
Med	0.6	T24_2019	E	12	91	502	5251	2072	165	7990	7996	0.290	1.003
Med	0.6	T24_2019	E	13	91	646	5217	2863	165	8891	8896	0.290	1.002
Med	0.6	T24_2019	E	16	91	473	10457	1204	165	12299	12309	0.290	1.002
Med	0.6	BuilderPractice	B	1	70	190	8295	0	254	8740	9336	0.247	1.178
Med	0.6	BuilderPractice	B	3	70	244	4004	819	254	5320	5610	0.245	1.189
Med	0.6	BuilderPractice	B	10	70	478	1807	2393	254	4932	5147	0.241	1.210
Med	0.6	BuilderPractice	B	12	70	505	5071	2104	254	7934	8293	0.245	1.190
Med	0.6	BuilderPractice	B	13	70	647	5046	2885	254	8833	9241	0.241	1.207
Med	0.6	BuilderPractice	B	16	70	472	10163	1236	254	12126	12825	0.248	1.176
Med	0.6	BuilderPractice	E	1	70	181	7897	0	127	8206	9052	0.224	1.301
Med	0.6	BuilderPractice	E	3	70	249	3855	865	127	5096	5489	0.224	1.301
Med	0.6	BuilderPractice	E	10	70	477	1655	2402	127	4661	4889	0.224	1.301
Med	0.6	BuilderPractice	E	12	70	499	4799	2107	127	7532	7979	0.224	1.301
Med	0.6	BuilderPractice	E	13	70	639	4800	2872	127	8439	8913	0.224	1.301

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	0.6	BuilderPractice	E	16	70	459	9491	1247	127	11324	12275	0.224	1.301
Med	0.6	None	B	1	0	126	5486	0	0	5612	8833	0.019	15.573
Med	0.6	None	B	3	0	257	2576	1064	0	3896	5630	0.017	16.896
Med	0.6	None	B	10	0	489	927	2515	0	3932	4494	0.014	21.515
Med	0.6	None	B	12	0	493	3455	2215	0	6163	8002	0.018	16.992
Med	0.6	None	B	13	0	620	3475	2892	0	6987	9370	0.015	20.496
Med	0.6	None	B	16	0	421	6647	1419	0	8487	13729	0.019	17.118
Med	0.6	None	E	1	0	126	5486	0	0	5612	8833	0.019	15.573
Med	0.6	None	E	3	0	257	2576	1064	0	3896	5630	0.017	16.896
Med	0.6	None	E	10	0	489	927	2515	0	3932	4494	0.014	21.515
Med	0.6	None	E	12	0	493	3455	2215	0	6163	8002	0.018	16.992
Med	0.6	None	E	13	0	620	3475	2892	0	6987	9370	0.015	20.496
Med	0.6	None	E	16	0	421	6647	1419	0	8487	13729	0.019	17.118
Med	1	T24_2008	B	1	50	174	7584	0	181	7940	9212	0.194	1.499
Med	1	T24_2008	B	3	50	245	3635	873	181	4934	5534	0.191	1.523
Med	1	T24_2008	B	10	50	479	1574	2416	181	4652	5080	0.185	1.574
Med	1	T24_2008	B	12	50	501	4682	2128	181	7492	8248	0.191	1.524
Med	1	T24_2008	B	13	50	640	4677	2882	181	8381	9238	0.186	1.565
Med	1	T24_2008	B	16	50	461	9366	1274	181	11282	12846	0.195	1.501
Med	1	T24_2008	E	1	50	163	7107	0	91	7360	8971	0.160	1.818
Med	1	T24_2008	E	3	50	249	3438	918	91	4697	5441	0.160	1.819
Med	1	T24_2008	E	10	50	480	1431	2433	91	4434	4866	0.160	1.816
Med	1	T24_2008	E	12	50	496	4373	2138	91	7098	7955	0.160	1.817
Med	1	T24_2008	E	13	50	632	4378	2876	91	7977	8890	0.160	1.820
Med	1	T24_2008	E	16	50	447	8599	1292	91	10429	12286	0.160	1.819
Med	1	T24_2013	B	1	82	206	8975	0	296	9477	9392	0.297	0.979
Med	1	T24_2013	B	3	83	242	4360	768	298	5668	5643	0.295	0.987
Med	1	T24_2013	B	10	85	477	2049	2360	305	5190	5174	0.295	0.987
Med	1	T24_2013	B	12	83	508	5470	2078	300	8355	8314	0.297	0.982
Med	1	T24_2013	B	13	84	654	5433	2879	303	9269	9243	0.295	0.989
Med	1	T24_2013	B	16	84	487	11081	1202	304	13074	12864	0.305	0.957

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	1	T24_2013	E	1	82	193	8401	0	148	8742	9127	0.261	1.115
Med	1	T24_2013	E	3	83	248	4123	829	149	5350	5522	0.262	1.110
Med	1	T24_2013	E	10	85	476	1863	2377	152	4868	4948	0.269	1.083
Med	1	T24_2013	E	12	83	501	5087	2085	150	7822	8006	0.264	1.104
Med	1	T24_2013	E	13	84	644	5080	2867	152	8742	8912	0.267	1.090
Med	1	T24_2013	E	16	84	469	10156	1218	152	11995	12332	0.267	1.088
Med	1	Qtotal	B	1	92	216	9408	0	331	9955	9443	0.328	0.888
Med	1	Qtotal	B	3	92	242	4589	739	331	5901	5684	0.324	0.897
Med	1	Qtotal	B	10	92	481	2118	2379	331	5309	5191	0.318	0.916
Med	1	Qtotal	B	12	92	510	5685	2062	331	8587	8328	0.325	0.898
Med	1	Qtotal	B	13	92	657	5602	2879	331	9469	9243	0.319	0.913
Med	1	Qtotal	B	16	92	493	11455	1188	331	13466	12866	0.329	0.887
Med	1	Qtotal	E	1	92	202	8801	0	165	9168	9168	0.291	1.000
Med	1	Qtotal	E	3	92	248	4327	802	165	5542	5542	0.291	1.000
Med	1	Qtotal	E	10	92	480	1921	2395	165	4960	4960	0.291	1.000
Med	1	Qtotal	E	12	92	502	5265	2070	165	8003	8003	0.291	1.000
Med	1	Qtotal	E	13	92	646	5228	2862	165	8901	8901	0.291	1.000
Med	1	Qtotal	E	16	92	474	10483	1203	165	12325	12325	0.291	1.000
Med	1	ASH62.2_2016	B	1	82	206	8975	0	296	9477	9392	0.297	0.979
Med	1	ASH62.2_2016	B	3	83	242	4360	768	298	5668	5643	0.295	0.987
Med	1	ASH62.2_2016	B	10	85	477	2049	2360	305	5190	5174	0.295	0.987
Med	1	ASH62.2_2016	B	12	83	508	5470	2078	300	8355	8314	0.297	0.982
Med	1	ASH62.2_2016	B	13	84	654	5433	2879	303	9269	9243	0.295	0.989
Med	1	ASH62.2_2016	B	16	84	487	11081	1202	304	13074	12864	0.305	0.957
Med	1	ASH62.2_2016	E	1	91	201	8761	0	164	9126	9166	0.288	1.011
Med	1	ASH62.2_2016	E	3	91	248	4307	804	164	5523	5540	0.288	1.010
Med	1	ASH62.2_2016	E	10	91	480	1915	2395	164	4954	4960	0.289	1.006
Med	1	ASH62.2_2016	E	12	91	502	5250	2072	164	7988	8005	0.288	1.009
Med	1	ASH62.2_2016	E	13	91	646	5215	2862	164	8887	8901	0.289	1.007
Med	1	ASH62.2_2016	E	16	91	473	10458	1205	164	12300	12328	0.289	1.007
Med	1	T24_2019	B	1	82	206	8975	0	296	9477	9392	0.297	0.979

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	1	T24_2019	B	3	83	242	4360	768	298	5668	5643	0.295	0.987
Med	1	T24_2019	B	10	85	477	2049	2360	305	5190	5174	0.295	0.987
Med	1	T24_2019	B	12	83	508	5470	2078	300	8355	8314	0.297	0.982
Med	1	T24_2019	B	13	84	654	5433	2879	303	9269	9243	0.295	0.989
Med	1	T24_2019	B	16	84	487	11081	1202	304	13074	12864	0.305	0.957
Med	1	T24_2019	E	1	91	201	8761	0	164	9126	9166	0.288	1.011
Med	1	T24_2019	E	3	91	248	4307	804	164	5523	5540	0.288	1.010
Med	1	T24_2019	E	10	91	480	1915	2395	164	4954	4960	0.289	1.006
Med	1	T24_2019	E	12	91	502	5250	2072	164	7988	8005	0.288	1.009
Med	1	T24_2019	E	13	91	646	5215	2862	164	8887	8901	0.289	1.007
Med	1	T24_2019	E	16	91	473	10458	1205	164	12300	12328	0.289	1.007
Med	1	BuilderPractice	B	1	70	194	8456	0	254	8904	9336	0.259	1.123
Med	1	BuilderPractice	B	3	70	243	4092	807	254	5397	5617	0.256	1.137
Med	1	BuilderPractice	B	10	70	479	1874	2385	254	4992	5173	0.250	1.166
Med	1	BuilderPractice	B	12	70	505	5168	2097	254	8025	8297	0.256	1.138
Med	1	BuilderPractice	B	13	70	648	5124	2882	254	8908	9238	0.251	1.162
Med	1	BuilderPractice	B	16	70	477	10405	1231	254	12367	12881	0.260	1.122
Med	1	BuilderPractice	E	1	70	181	7909	0	127	8218	9067	0.224	1.300
Med	1	BuilderPractice	E	3	70	249	3857	863	127	5096	5489	0.224	1.300
Med	1	BuilderPractice	E	10	70	477	1666	2401	127	4671	4900	0.224	1.300
Med	1	BuilderPractice	E	12	70	499	4807	2106	127	7539	7986	0.224	1.300
Med	1	BuilderPractice	E	13	70	639	4809	2871	127	8446	8922	0.224	1.301
Med	1	BuilderPractice	E	16	70	459	9513	1247	127	11347	12304	0.224	1.301
Med	1	None	B	1	0	129	5617	0	0	5745	8733	0.032	9.427
Med	1	None	B	3	0	256	2649	1051	0	3956	5508	0.029	10.215
Med	1	None	B	10	0	488	981	2502	0	3972	4780	0.024	13.034
Med	1	None	B	12	0	494	3538	2207	0	6239	8019	0.029	10.310
Med	1	None	B	13	0	620	3548	2887	0	7055	9217	0.025	12.388
Med	1	None	B	16	0	425	6885	1405	0	8715	13910	0.032	10.402
Med	1	None	E	1	0	129	5617	0	0	5745	8733	0.032	9.427
Med	1	None	E	3	0	256	2649	1051	0	3956	5508	0.029	10.215

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	1	None	E	10	0	488	981	2502	0	3972	4780	0.024	13.034
Med	1	None	E	12	0	494	3538	2207	0	6239	8019	0.029	10.310
Med	1	None	E	13	0	620	3548	2887	0	7055	9217	0.025	12.388
Med	1	None	E	16	0	425	6885	1405	0	8715	13910	0.032	10.402
Med	2	T24_2008	B	1	50	183	7981	0	181	8346	9225	0.225	1.298
Med	2	T24_2008	B	3	50	245	3832	845	181	5104	5539	0.220	1.330
Med	2	T24_2008	B	10	50	478	1702	2396	181	4758	5104	0.209	1.405
Med	2	T24_2008	B	12	50	503	4922	2108	181	7714	8264	0.221	1.330
Med	2	T24_2008	B	13	50	642	4875	2874	181	8573	9238	0.211	1.390
Med	2	T24_2008	B	16	50	472	9979	1258	181	11891	13029	0.226	1.305
Med	2	T24_2008	E	1	50	164	7163	0	91	7418	9027	0.162	1.794
Med	2	T24_2008	E	3	50	249	3458	912	91	4710	5453	0.161	1.805
Med	2	T24_2008	E	10	50	479	1453	2424	91	4446	4882	0.162	1.803
Med	2	T24_2008	E	12	50	496	4422	2131	91	7139	8000	0.163	1.789
Med	2	T24_2008	E	13	50	632	4410	2872	91	8005	8927	0.161	1.809
Med	2	T24_2008	E	16	50	449	8712	1290	91	10541	12464	0.161	1.808
Med	2	T24_2013	B	1	73	206	8978	0	262	9446	9368	0.298	0.981
Med	2	T24_2013	B	3	73	243	4364	770	265	5641	5628	0.294	0.993
Med	2	T24_2013	B	10	77	476	2073	2352	279	5180	5166	0.296	0.989
Med	2	T24_2013	B	12	74	508	5499	2070	268	8345	8302	0.298	0.981
Med	2	T24_2013	B	13	76	653	5464	2871	276	9264	9245	0.294	0.992
Med	2	T24_2013	B	16	77	492	11298	1203	277	13271	12970	0.312	0.941
Med	2	T24_2013	E	1	73	184	8039	0	131	8355	9103	0.232	1.252
Med	2	T24_2013	E	3	73	248	3938	850	132	5169	5506	0.234	1.244
Med	2	T24_2013	E	10	77	476	1771	2383	140	4769	4922	0.247	1.178
Med	2	T24_2013	E	12	74	500	4932	2093	134	7659	8020	0.238	1.224
Med	2	T24_2013	E	13	76	641	4957	2866	138	8602	8946	0.243	1.198
Med	2	T24_2013	E	16	77	465	9895	1233	138	11731	12413	0.244	1.191
Med	2	Qtotal	B	1	92	226	9839	0	331	10395	9461	0.359	0.813
Med	2	Qtotal	B	3	92	242	4822	713	331	6107	5706	0.352	0.827
Med	2	Qtotal	B	10	92	481	2261	2360	331	5432	5212	0.341	0.856

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	*Annual HVAC Energy Use (kWh/year)* Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	2	Qtotal	B	12	92	512	5927	2043	331	8812	8333	0.353	0.827
Med	2	Qtotal	B	13	92	660	5833	2869	331	9693	9270	0.343	0.851
Med	2	Qtotal	B	16	92	503	12039	1173	331	14046	12952	0.360	0.814
Med	2	Qtotal	E	1	92	203	8830	0	165	9198	9188	0.292	0.997
Med	2	Qtotal	E	3	92	247	4336	798	165	5547	5544	0.292	0.998
Med	2	Qtotal	E	10	92	479	1936	2389	165	4969	4966	0.292	0.997
Med	2	Qtotal	E	12	92	502	5295	2066	165	8029	8023	0.292	0.997
Med	2	Qtotal	E	13	92	646	5255	2859	165	8925	8925	0.291	1.000
Med	2	Qtotal	E	16	92	475	10558	1202	165	12400	12396	0.291	0.999
Med	2	ASH62.2_2016	B	1	73	206	8978	0	262	9446	9368	0.298	0.981
Med	2	ASH62.2_2016	B	3	73	243	4364	770	265	5641	5628	0.294	0.993
Med	2	ASH62.2_2016	B	10	77	476	2073	2352	279	5180	5166	0.296	0.989
Med	2	ASH62.2_2016	B	12	74	508	5499	2070	268	8345	8302	0.298	0.981
Med	2	ASH62.2_2016	B	13	76	653	5464	2871	276	9264	9245	0.294	0.992
Med	2	ASH62.2_2016	B	16	77	492	11298	1203	277	13271	12970	0.312	0.941
Med	2	ASH62.2_2016	E	1	88	199	8669	0	158	9026	9176	0.280	1.041
Med	2	ASH62.2_2016	E	3	88	247	4258	808	159	5471	5538	0.280	1.039
Med	2	ASH62.2_2016	E	10	89	479	1912	2392	161	4945	4967	0.285	1.021
Med	2	ASH62.2_2016	E	12	88	502	5231	2071	159	7963	8027	0.282	1.033
Med	2	ASH62.2_2016	E	13	89	645	5202	2859	161	8867	8923	0.283	1.028
Med	2	ASH62.2_2016	E	16	89	474	10452	1207	161	12294	12400	0.284	1.026
Med	2	T24_2019	B	1	73	206	8978	0	262	9446	9368	0.298	0.981
Med	2	T24_2019	B	3	73	243	4364	770	265	5641	5628	0.294	0.993
Med	2	T24_2019	B	10	77	476	2073	2352	279	5180	5166	0.296	0.989
Med	2	T24_2019	B	12	74	508	5499	2070	268	8345	8302	0.298	0.981
Med	2	T24_2019	B	13	76	653	5464	2871	276	9264	9245	0.294	0.992
Med	2	T24_2019	B	16	77	492	11298	1203	277	13271	12970	0.312	0.941
Med	2	T24_2019	E	1	88	199	8669	0	158	9026	9176	0.280	1.041
Med	2	T24_2019	E	3	88	247	4258	808	159	5471	5538	0.280	1.039
Med	2	T24_2019	E	10	89	479	1912	2392	161	4945	4967	0.285	1.021
Med	2	T24_2019	E	12	88	502	5231	2071	159	7963	8027	0.282	1.033

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	2	T24_2019	E	13	89	645	5202	2859	161	8867	8923	0.283	1.028
Med	2	T24_2019	E	16	89	474	10452	1207	161	12294	12400	0.284	1.026
Med	2	BuilderPractice	B	1	70	204	8877	0	254	9335	9358	0.290	1.006
Med	2	BuilderPractice	B	3	70	243	4295	779	254	5570	5617	0.284	1.026
Med	2	BuilderPractice	B	10	70	477	1978	2366	254	5075	5157	0.273	1.070
Med	2	BuilderPractice	B	12	70	507	5399	2078	254	8238	8294	0.285	1.026
Med	2	BuilderPractice	B	13	70	650	5330	2871	254	9106	9244	0.275	1.062
Med	2	BuilderPractice	B	16	70	487	10989	1216	254	12947	12987	0.291	1.008
Med	2	BuilderPractice	E	1	70	182	7947	0	127	8256	9094	0.225	1.292
Med	2	BuilderPractice	E	3	70	248	3871	858	127	5104	5494	0.225	1.296
Med	2	BuilderPractice	E	10	70	476	1683	2392	127	4678	4906	0.225	1.294
Med	2	BuilderPractice	E	12	70	499	4851	2099	127	7577	8023	0.225	1.292
Med	2	BuilderPractice	E	13	70	639	4835	2867	127	8469	8949	0.224	1.299
Med	2	BuilderPractice	E	16	70	461	9608	1245	127	11442	12418	0.224	1.298
Med	2	None	B	1	0	137	5967	0	0	6104	8798	0.063	4.776
Med	2	None	B	3	0	254	2832	1015	0	4101	5407	0.058	5.168
Med	2	None	B	10	0	484	1082	2471	0	4037	4780	0.048	6.608
Med	2	None	B	12	0	494	3757	2183	0	6434	8073	0.059	5.245
Med	2	None	B	13	0	621	3755	2870	0	7247	9257	0.049	6.264
Med	2	None	B	16	0	434	7481	1374	0	9288	14122	0.063	5.294
Med	2	None	E	1	0	137	5967	0	0	6104	8798	0.063	4.776
Med	2	None	E	3	0	254	2832	1015	0	4101	5407	0.058	5.168
Med	2	None	E	10	0	484	1082	2471	0	4037	4780	0.048	6.608
Med	2	None	E	12	0	494	3757	2183	0	6434	8073	0.059	5.245
Med	2	None	E	13	0	621	3755	2870	0	7247	9257	0.049	6.264
Med	2	None	E	16	0	434	7481	1374	0	9288	14122	0.063	5.294
Med	3	T24_2008	B	1	50	193	8422	0	181	8797	9292	0.256	1.145
Med	3	T24_2008	B	3	50	244	4049	817	181	5291	5565	0.248	1.182
Med	3	T24_2008	B	10	50	477	1839	2377	181	4875	5138	0.232	1.271
Med	3	T24_2008	B	12	50	504	5152	2089	181	7927	8269	0.250	1.182
Med	3	T24_2008	B	13	50	645	5080	2866	181	8773	9253	0.235	1.252

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	3	T24_2008	B	16	50	483	10579	1243	181	12486	13167	0.257	1.157
Med	3	T24_2008	E	1	50	167	7264	0	91	7521	9119	0.167	1.750
Med	3	T24_2008	E	3	50	248	3492	903	91	4734	5472	0.164	1.780
Med	3	T24_2008	E	10	50	478	1494	2413	91	4475	4917	0.165	1.774
Med	3	T24_2008	E	12	50	496	4509	2121	91	7217	8069	0.169	1.729
Med	3	T24_2008	E	13	50	633	4480	2867	91	8071	9000	0.165	1.770
Med	3	T24_2008	E	16	50	457	9113	1286	91	10947	12924	0.172	1.710
Med	3	T24_2013	B	1	63	206	8983	0	228	9418	9351	0.298	0.983
Med	3	T24_2013	B	3	64	243	4364	770	232	5609	5608	0.293	1.000
Med	3	T24_2013	B	10	70	475	2097	2345	254	5171	5160	0.296	0.992
Med	3	T24_2013	B	12	66	507	5528	2064	237	8337	8296	0.299	0.982
Med	3	T24_2013	B	13	69	653	5496	2864	248	9261	9252	0.294	0.996
Med	3	T24_2013	B	16	69	497	11526	1203	250	13477	13091	0.319	0.927
Med	3	T24_2013	E	1	63	177	7728	0	114	8019	9118	0.206	1.418
Med	3	T24_2013	E	3	64	247	3755	867	116	4985	5473	0.207	1.408
Med	3	T24_2013	E	10	70	475	1712	2383	127	4697	4926	0.226	1.288
Med	3	T24_2013	E	12	66	498	4812	2099	119	7528	8059	0.215	1.359
Med	3	T24_2013	E	13	69	639	4844	2863	124	8470	8982	0.221	1.319
Med	3	T24_2013	E	16	69	464	9716	1246	125	11551	12591	0.223	1.307
Med	3	Qtotal	B	1	92	236	10269	0	331	10835	9479	0.389	0.751
Med	3	Qtotal	B	3	92	242	5021	687	331	6280	5701	0.380	0.768
Med	3	Qtotal	B	10	92	481	2395	2344	331	5551	5229	0.365	0.804
Med	3	Qtotal	B	12	92	513	6162	2025	331	9031	8335	0.382	0.767
Med	3	Qtotal	B	13	92	663	6054	2861	331	9909	9289	0.367	0.796
Med	3	Qtotal	B	16	92	514	12617	1160	331	14621	13027	0.390	0.753
Med	3	Qtotal	E	1	92	204	8890	0	165	9259	9223	0.294	0.991
Med	3	Qtotal	E	3	92	247	4354	792	165	5558	5549	0.293	0.995
Med	3	Qtotal	E	10	92	478	1956	2380	165	4980	4973	0.293	0.993
Med	3	Qtotal	E	12	92	502	5346	2059	165	8072	8051	0.294	0.990
Med	3	Qtotal	E	13	92	646	5292	2855	165	8959	8953	0.292	0.997
Med	3	Qtotal	E	16	92	477	10661	1201	165	12505	12489	0.292	0.996

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	3	ASH62.2_2016	B	1	63	206	8983	0	228	9418	9351	0.298	0.983
Med	3	ASH62.2_2016	B	3	64	243	4364	770	232	5609	5608	0.293	1.000
Med	3	ASH62.2_2016	B	10	70	475	2097	2345	254	5171	5160	0.296	0.992
Med	3	ASH62.2_2016	B	12	66	507	5528	2064	237	8337	8296	0.299	0.982
Med	3	ASH62.2_2016	B	13	69	653	5496	2864	248	9261	9252	0.294	0.996
Med	3	ASH62.2_2016	B	16	69	497	11526	1203	250	13477	13091	0.319	0.927
Med	3	ASH62.2_2016	E	1	83	196	8525	0	149	8870	9193	0.267	1.093
Med	3	ASH62.2_2016	E	3	84	247	4182	813	151	5393	5538	0.267	1.091
Med	3	ASH62.2_2016	E	10	87	474	1926	2360	156	4916	4966	0.278	1.049
Med	3	ASH62.2_2016	E	12	84	501	5194	2071	152	7918	8053	0.272	1.072
Med	3	ASH62.2_2016	E	13	86	644	5176	2858	155	8833	8955	0.274	1.062
Med	3	ASH62.2_2016	E	16	86	474	10430	1211	156	12270	12510	0.275	1.058
Med	3	T24_2019	B	1	73	216	9426	0	262	9905	9414	0.329	0.891
Med	3	T24_2019	B	3	73	242	4584	742	265	5834	5646	0.322	0.908
Med	3	T24_2019	B	10	77	476	2210	2335	279	5301	5189	0.319	0.920
Med	3	T24_2019	B	12	74	509	5747	2050	268	8575	8317	0.327	0.898
Med	3	T24_2019	B	13	76	656	5671	2864	276	9467	9258	0.319	0.919
Med	3	T24_2019	B	16	77	503	11895	1189	277	13864	13072	0.342	0.861
Med	3	T24_2019	E	1	88	200	8729	0	158	9088	9212	0.282	1.034
Med	3	T24_2019	E	3	88	247	4275	802	159	5482	5542	0.281	1.035
Med	3	T24_2019	E	10	89	478	1934	2384	161	4958	4976	0.286	1.017
Med	3	T24_2019	E	12	88	501	5274	2064	159	7999	8047	0.284	1.025
Med	3	T24_2019	E	13	89	645	5238	2855	161	8899	8949	0.284	1.025
Med	3	T24_2019	E	16	89	476	10558	1205	161	12400	12497	0.285	1.023
Med	3	BuilderPractice	B	1	70	214	9319	0	254	9787	9400	0.321	0.912
Med	3	BuilderPractice	B	3	70	242	4504	751	254	5751	5626	0.312	0.936
Med	3	BuilderPractice	B	10	70	475	2098	2345	254	5172	5160	0.297	0.991
Med	3	BuilderPractice	B	12	70	508	5643	2056	254	8462	8305	0.314	0.935
Med	3	BuilderPractice	B	13	70	653	5532	2864	254	9303	9252	0.299	0.979
Med	3	BuilderPractice	B	16	70	498	11580	1201	254	13533	13088	0.322	0.917
Med	3	BuilderPractice	E	1	70	184	8014	0	127	8325	9144	0.228	1.279

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	3	BuilderPractice	E	3	70	247	3891	851	127	5117	5500	0.226	1.288
Med	3	BuilderPractice	E	10	70	475	1714	2384	127	4700	4927	0.227	1.287
Med	3	BuilderPractice	E	12	70	499	4903	2092	127	7621	8052	0.229	1.274
Med	3	BuilderPractice	E	13	70	639	4874	2863	127	8503	8979	0.226	1.290
Med	3	BuilderPractice	E	16	70	464	9758	1243	127	11592	12581	0.226	1.288
Med	3	None	B	1	0	145	6316	0	0	6461	8818	0.095	3.203
Med	3	None	B	3	0	252	3031	983	0	4266	5451	0.086	3.471
Med	3	None	B	10	0	482	1195	2446	0	4123	4875	0.072	4.446
Med	3	None	B	12	0	495	3984	2163	0	6642	8148	0.088	3.536
Med	3	None	B	13	0	623	3958	2859	0	7440	9287	0.074	4.211
Med	3	None	B	16	0	443	8072	1347	0	9863	14223	0.095	3.564
Med	3	None	E	1	0	145	6316	0	0	6461	8818	0.095	3.203
Med	3	None	E	3	0	252	3031	983	0	4266	5451	0.086	3.471
Med	3	None	E	10	0	482	1195	2446	0	4123	4875	0.072	4.446
Med	3	None	E	12	0	495	3984	2163	0	6642	8148	0.088	3.536
Med	3	None	E	13	0	623	3958	2859	0	7440	9287	0.074	4.211
Med	3	None	E	16	0	443	8072	1347	0	9863	14223	0.095	3.564
Med	5	T24_2008	B	1	50	213	9285	0	181	9679	9381	0.318	0.930
Med	5	T24_2008	B	3	50	243	4456	760	181	5639	5583	0.304	0.969
Med	5	T24_2008	B	10	50	475	2077	2338	181	5072	5156	0.279	1.072
Med	5	T24_2008	B	12	50	507	5646	2049	181	8384	8314	0.308	0.970
Med	5	T24_2008	B	13	50	650	5491	2849	181	9172	9281	0.284	1.047
Med	5	T24_2008	B	16	50	505	11766	1213	181	13665	13377	0.319	0.948
Med	5	T24_2008	E	1	50	182	7949	0	91	8222	9324	0.215	1.389
Med	5	T24_2008	E	3	50	246	3777	859	91	4972	5528	0.202	1.469
Med	5	T24_2008	E	10	50	475	1723	2375	91	4664	5066	0.195	1.530
Med	5	T24_2008	E	12	50	499	4957	2083	91	7630	8252	0.215	1.393
Med	5	T24_2008	E	13	50	637	4867	2847	91	8442	9215	0.198	1.490
Med	5	T24_2008	E	16	50	482	10359	1267	91	12199	13694	0.224	1.370
Med	5	T24_2013	B	1	44	207	9008	0	160	9375	9341	0.299	0.991
Med	5	T24_2013	B	3	46	243	4351	773	166	5533	5561	0.290	1.016

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	5	T24_2013	B	10	56	475	2165	2331	203	5174	5176	0.298	1.002
Med	5	T24_2013	B	12	49	507	5606	2052	175	8340	8314	0.302	0.989
Med	5	T24_2013	B	13	54	652	5567	2849	194	9261	9280	0.294	1.008
Med	5	T24_2013	B	16	55	508	11975	1205	197	13884	13350	0.333	0.907
Med	5	T24_2013	E	1	44	180	7837	0	80	8097	9271	0.209	1.434
Med	5	T24_2013	E	3	46	246	3741	863	83	4933	5513	0.197	1.506
Med	5	T24_2013	E	10	56	475	1754	2369	101	4699	5048	0.206	1.440
Med	5	T24_2013	E	12	49	499	4940	2085	88	7611	8255	0.212	1.412
Med	5	T24_2013	E	13	54	638	4898	2849	97	8482	9197	0.204	1.443
Med	5	T24_2013	E	16	55	483	10441	1261	98	12284	13606	0.230	1.321
Med	5	Qtotal	B	1	92	257	11187	0	331	11774	9553	0.451	0.652
Med	5	Qtotal	B	3	92	242	5448	635	331	6656	5716	0.436	0.672
Med	5	Qtotal	B	10	92	480	2639	2310	331	5760	5240	0.411	0.720
Med	5	Qtotal	B	12	92	517	6646	1987	331	9480	8351	0.440	0.671
Med	5	Qtotal	B	13	92	669	6486	2845	331	10331	9318	0.416	0.708
Med	5	Qtotal	B	16	92	536	13791	1133	331	15790	13174	0.452	0.657
Med	5	Qtotal	E	1	92	208	9057	0	165	9430	9317	0.301	0.972
Med	5	Qtotal	E	3	92	245	4424	777	165	5612	5580	0.297	0.983
Med	5	Qtotal	E	10	92	476	2027	2359	165	5027	5007	0.298	0.982
Med	5	Qtotal	E	12	92	502	5493	2041	165	8201	8122	0.304	0.963
Med	5	Qtotal	E	13	92	646	5396	2847	165	9054	9014	0.297	0.982
Med	5	Qtotal	E	16	92	489	11236	1196	165	13086	12888	0.305	0.960
Med	5	ASH62.2_2016	B	1	44	207	9008	0	160	9375	9341	0.299	0.991
Med	5	ASH62.2_2016	B	3	46	243	4351	773	166	5533	5561	0.290	1.016
Med	5	ASH62.2_2016	B	10	56	475	2165	2331	203	5174	5176	0.298	1.002
Med	5	ASH62.2_2016	B	12	49	507	5606	2052	175	8340	8314	0.302	0.989
Med	5	ASH62.2_2016	B	13	54	652	5567	2849	194	9261	9280	0.294	1.008
Med	5	ASH62.2_2016	B	16	55	508	11975	1205	197	13884	13350	0.333	0.907
Med	5	ASH62.2_2016	E	1	67	190	8281	0	121	8593	9347	0.239	1.236
Med	5	ASH62.2_2016	E	3	69	246	4006	832	124	5209	5587	0.232	1.266
Med	5	ASH62.2_2016	E	10	78	473	1922	2351	141	4887	5022	0.258	1.137

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	5	ASH62.2_2016	E	12	71	500	5179	2067	129	7875	8184	0.252	1.169
Med	5	ASH62.2_2016	E	13	76	642	5146	2850	137	8775	9072	0.253	1.155
Med	5	ASH62.2_2016	E	16	77	487	10893	1223	138	12741	13168	0.271	1.093
Med	5	T24_2019	B	1	73	236	10285	0	262	10783	9465	0.390	0.755
Med	5	T24_2019	B	3	73	243	5019	690	265	6215	5675	0.378	0.777
Med	5	T24_2019	B	10	77	476	2482	2303	279	5540	5231	0.365	0.811
Med	5	T24_2019	B	12	74	513	6232	2014	268	9027	8341	0.385	0.770
Med	5	T24_2019	B	13	76	662	6126	2846	276	9911	9312	0.367	0.803
Med	5	T24_2019	B	16	77	525	13063	1161	277	15026	13228	0.404	0.738
Med	5	T24_2019	E	1	88	204	8908	0	158	9271	9314	0.289	1.011
Med	5	T24_2019	E	3	88	245	4345	786	159	5535	5572	0.286	1.021
Med	5	T24_2019	E	10	89	476	1988	2362	161	4987	4992	0.291	1.005
Med	5	T24_2019	E	12	88	502	5429	2047	159	8137	8125	0.295	0.994
Med	5	T24_2019	E	13	89	646	5352	2847	161	9006	9020	0.289	1.007
Med	5	T24_2019	E	16	89	489	11173	1200	161	13022	12926	0.300	0.980
Med	5	BuilderPractice	B	1	70	234	10188	0	254	10676	9462	0.383	0.770
Med	5	BuilderPractice	B	3	70	242	4947	698	254	6142	5665	0.368	0.798
Med	5	BuilderPractice	B	10	70	475	2373	2311	254	5414	5210	0.343	0.865
Med	5	BuilderPractice	B	12	70	512	6125	2020	254	8911	8329	0.372	0.797
Med	5	BuilderPractice	B	13	70	660	5987	2847	254	9748	9312	0.348	0.849
Med	5	BuilderPractice	B	16	70	520	12754	1173	254	14700	13257	0.384	0.779
Med	5	BuilderPractice	E	1	70	192	8356	0	127	8675	9335	0.246	1.201
Med	5	BuilderPractice	E	3	70	246	4027	829	127	5229	5584	0.235	1.246
Med	5	BuilderPractice	E	10	70	474	1860	2360	127	4821	5036	0.239	1.235
Med	5	BuilderPractice	E	12	70	500	5169	2068	127	7864	8189	0.250	1.179
Med	5	BuilderPractice	E	13	70	641	5076	2851	127	8695	9103	0.239	1.223
Med	5	BuilderPractice	E	16	70	486	10760	1235	127	12607	13283	0.259	1.152
Med	5	None	B	1	0	163	7100	0	0	7263	9036	0.157	1.948
Med	5	None	B	3	0	250	3407	924	0	4581	5461	0.143	2.108
Med	5	None	B	10	0	478	1416	2406	0	4299	4973	0.119	2.708
Med	5	None	B	12	0	497	4432	2125	0	7054	8216	0.147	2.156

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	5	None	B	13	0	628	4350	2843	0	7821	9315	0.123	2.562
Med	5	None	B	16	0	463	9255	1307	0	11025	14355	0.158	2.163
Med	5	None	E	1	0	163	7100	0	0	7263	9036	0.157	1.948
Med	5	None	E	3	0	250	3407	924	0	4581	5461	0.143	2.108
Med	5	None	E	10	0	478	1416	2406	0	4299	4973	0.119	2.708
Med	5	None	E	12	0	497	4432	2125	0	7054	8216	0.147	2.156
Med	5	None	E	13	0	628	4350	2843	0	7821	9315	0.123	2.562
Med	**5**	**None**	**E**	**16**	**0**	**463**	**9255**	**1307**	**0**	**11025**	**14355**	**0.158**	**2.163**

Table 15 Raw and normalized HVAC energy savings by sealing from 5 ACH_{50}.

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				Normalized Savings			
				3	2	1	0.6	3	2	1	0.6
Large	T24_2008	B	1	1632	2468	3292	3589	102	181	260	246
Large	T24_2008	B	3	743	1084	1421	1554	93	118	139	144
Large	T24_2008	B	10	437	623	824	904	94	109	143	157
Large	T24_2008	B	12	844	1275	1698	1870	68	115	154	175
Large	T24_2008	B	13	824	1213	1588	1731	116	156	175	168
Large	T24_2008	B	16	2216	3288	4379	4826	330	507	744	869
Large	T24_2008	E	1	1685	2363	2546	2574	161	306	455	489
Large	T24_2008	E	3	691	946	979	982	64	156	178	180
Large	T24_2008	E	10	393	556	607	616	135	264	331	344
Large	T24_2008	E	12	864	1278	1419	1442	166	400	551	583
Large	T24_2008	E	13	773	1136	1259	1278	175	406	565	598
Large	T24_2008	E	16	2158	3303	4000	4073	473	1139	1958	2084
Large	T24_2013	B	1	100	159	212	225	-5	-12	-34	-54
Large	T24_2013	B	3	-21	-37	-44	-50	-24	-46	-63	-74
Large	T24_2013	B	10	23	34	57	61	32	39	52	50
Large	T24_2013	B	12	65	97	131	139	55	68	71	65
Large	T24_2013	B	13	96	153	200	214	113	163	196	201

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Large	T24_2013	B	16	959	1433	1912	2098	524	758	984	1066
Large	T24_2013	E	1	1012	1062	455	204	3	204	216	224
Large	T24_2013	E	3	388	309	12	-120	-9	77	61	44
Large	T24_2013	E	10	220	198	87	37	180	285	312	316
Large	T24_2013	E	12	525	583	333	226	198	424	479	499
Large	T24_2013	E	13	473	464	243	146	320	549	632	653
Large	T24_2013	E	16	1730	2437	2169	1994	960	1908	2214	2258
Large	Qtotal	B	1	1583	2456	3305	3632	12	71	116	123
Large	Qtotal	B	3	718	1089	1438	1579	33	58	65	68
Large	Qtotal	B	10	466	708	902	985	68	113	121	126
Large	Qtotal	B	12	886	1306	1722	1889	66	83	93	96
Large	Qtotal	B	13	802	1209	1609	1769	63	101	131	144
Large	Qtotal	B	16	2215	3334	4484	4935	258	418	625	709
Large	Qtotal	E	1	992	1128	1210	1230	187	274	333	351
Large	Qtotal	E	3	390	434	455	458	155	185	201	203
Large	Qtotal	E	10	292	346	373	381	171	216	239	246
Large	Qtotal	E	12	678	785	850	869	266	338	390	408
Large	Qtotal	E	13	593	685	737	764	281	356	404	432
Large	Qtotal	E	16	2246	2789	2966	3012	980	1385	1552	1597
Large	ASH62.2_2016	B	1	100	159	212	225	-5	-12	-34	-54
Large	ASH62.2_2016	B	3	-21	-37	-44	-50	-24	-46	-63	-74
Large	ASH62.2_2016	B	10	23	34	57	61	32	39	52	50
Large	ASH62.2_2016	B	12	65	97	131	139	55	68	71	65
Large	ASH62.2_2016	B	13	96	153	200	214	113	163	196	201
Large	ASH62.2_2016	B	16	959	1433	1912	2098	524	758	984	1066
Large	ASH62.2_2016	E	1	808	567	330	288	132	252	273	290
Large	ASH62.2_2016	E	3	250	94	-28	-58	75	105	99	95
Large	ASH62.2_2016	E	10	175	156	139	139	197	247	270	278
Large	ASH62.2_2016	E	12	461	414	360	349	301	414	472	486
Large	ASH62.2_2016	E	13	415	367	330	323	391	495	556	571
Large	ASH62.2_2016	E	16	1830	2276	2276	2281	1201	1781	1959	2003
Large	T24_2019	B	1	1702	2518	2571	2584	122	164	142	122
Large	T24_2019	B	3	728	1090	1083	1077	58	89	73	61

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Large	T24_2019	B	10	462	670	692	697	84	111	124	123
Large	T24_2019	B	12	854	1275	1308	1317	60	86	89	83
Large	T24_2019	B	13	805	1220	1268	1281	78	131	164	169
Large	T24_2019	B	16	2218	3365	3844	4030	297	511	736	818
Large	T24_2019	E	1	1341	1505	1268	1226	324	428	449	466
Large	T24_2019	E	3	497	540	418	389	183	213	207	204
Large	T24_2019	E	10	314	362	344	344	181	221	244	252
Large	T24_2019	E	12	743	862	808	797	273	354	411	426
Large	T24_2019	E	13	642	748	710	703	292	381	443	457
Large	T24_2019	E	16	2289	2918	2917	2923	973	1448	1626	1671
Large	BuilderPractice	B	1	1715	2541	3378	3688	122	168	226	222
Large	BuilderPractice	B	3	723	1074	1466	1589	52	71	132	122
Large	BuilderPractice	B	10	457	669	877	952	81	113	141	142
Large	BuilderPractice	B	12	852	1276	1701	1870	58	83	109	117
Large	BuilderPractice	B	13	810	1221	1620	1763	83	133	174	170
Large	BuilderPractice	B	16	2220	3368	4496	4946	300	517	756	865
Large	BuilderPractice	E	1	1605	1922	2019	2048	243	414	498	532
Large	BuilderPractice	E	3	657	737	753	754	158	217	226	226
Large	BuilderPractice	E	10	368	451	500	507	173	248	303	311
Large	BuilderPractice	E	12	837	1065	1141	1161	230	394	465	488
Large	BuilderPractice	E	13	766	938	1002	1019	282	420	491	514
Large	BuilderPractice	E	16	2314	3286	3577	3635	854	1570	1896	1969
Large	None	B	1	1560	2330	3051	3330	217	396	537	582
Large	None	B	3	650	953	1256	1371	126	180	295	360
Large	None	B	10	372	557	755	805	124	241	670	797
Large	None	B	12	842	1246	1625	1773	177	294	412	492
Large	None	B	13	800	1162	1580	1738	141	117	393	657
Large	None	B	16	2180	3269	4368	4787	154	277	598	697
Large	None	E	1	1560	2330	3051	3330	217	396	537	582
Large	None	E	3	650	953	1256	1371	126	180	295	360
Large	None	E	10	372	557	755	805	124	241	670	797
Large	None	E	12	842	1246	1625	1773	177	294	412	492
Large	None	E	13	800	1162	1580	1738	141	117	393	657

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Large	None	E	16	2180	3269	4368	4787	154	277	598	697
Med	T24_2008	B	1	882	1333	1740	1893	88	155	168	158
Med	T24_2008	B	3	348	535	705	763	18	44	48	33
Med	T24_2008	B	10	197	314	420	453	18	52	76	70
Med	T24_2008	B	12	456	670	892	982	45	50	66	73
Med	T24_2008	B	13	399	599	791	867	28	43	43	40
Med	T24_2008	B	16	1178	1774	2383	2618	210	348	530	601
Med	T24_2008	E	1	701	805	862	873	205	297	353	368
Med	T24_2008	E	3	239	262	276	277	56	75	87	89
Med	T24_2008	E	10	189	217	230	233	150	185	200	204
Med	T24_2008	E	12	414	491	533	542	184	252	297	311
Med	T24_2008	E	13	371	438	465	474	215	288	325	341
Med	T24_2008	E	16	1253	1658	1771	1798	770	1230	1408	1456
Med	T24_2013	B	1	-43	-71	-102	-113	-10	-27	-52	-62
Med	T24_2013	B	3	-75	-108	-135	-146	-47	-67	-82	-90
Med	T24_2013	B	10	3	-7	-17	-20	16	11	3	0
Med	T24_2013	B	12	3	-5	-15	-19	18	12	0	-5
Med	T24_2013	B	13	0	-3	-8	-11	28	35	37	37
Med	T24_2013	B	16	407	613	810	887	258	380	486	525
Med	T24_2013	E	1	78	-258	-645	-811	153	168	144	131
Med	T24_2013	E	3	-52	-235	-416	-488	40	7	-9	-12
Med	T24_2013	E	10	1	-70	-169	-198	123	126	100	104
Med	T24_2013	E	12	83	-48	-211	-279	196	235	249	255
Med	T24_2013	E	13	12	-121	-261	-318	215	252	285	296
Med	T24_2013	E	16	733	553	289	178	1015	1193	1274	1299
Med	Qtotal	B	1	939	1379	1819	1996	74	92	109	117
Med	Qtotal	B	3	375	548	754	833	15	10	32	38
Med	Qtotal	B	10	209	328	451	486	10	28	48	44
Med	Qtotal	B	12	449	668	893	978	16	18	23	19
Med	Qtotal	B	13	422	639	863	940	29	48	75	76
Med	Qtotal	B	16	1169	1745	2325	2557	146	222	307	344
Med	Qtotal	E	1	171	232	262	269	94	129	149	156
Med	Qtotal	E	3	54	65	70	71	31	36	39	40

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Med	Qtotal	E	10	47	58	67	70	34	40	46	50
Med	Qtotal	E	12	129	172	198	202	71	98	119	123
Med	Qtotal	E	13	96	129	153	157	61	89	113	117
Med	Qtotal	E	16	581	686	761	778	399	492	563	580
Med	ASH62.2_2016	B	1	-43	-71	-102	-113	-10	-27	-52	-62
Med	ASH62.2_2016	B	3	-75	-108	-135	-146	-47	-67	-82	-90
Med	ASH62.2_2016	B	10	3	-7	-17	-20	16	11	3	0
Med	ASH62.2_2016	B	12	3	-5	-15	-19	18	12	0	-5
Med	ASH62.2_2016	B	13	0	-3	-8	-11	28	35	37	37
Med	ASH62.2_2016	B	16	407	613	810	887	258	380	486	525
Med	ASH62.2_2016	E	1	-278	-434	-533	-553	153	170	181	187
Med	ASH62.2_2016	E	3	-184	-262	-314	-325	49	50	47	48
Med	ASH62.2_2016	E	10	-29	-58	-67	-68	56	55	61	64
Med	ASH62.2_2016	E	12	-42	-87	-113	-115	132	158	179	188
Med	ASH62.2_2016	E	13	-58	-92	-113	-117	117	149	170	175
Med	ASH62.2_2016	E	16	470	447	440	442	658	768	840	859
Med	T24_2019	B	1	878	1338	1306	1295	51	97	72	62
Med	T24_2019	B	3	382	574	547	536	29	47	32	24
Med	T24_2019	B	10	240	360	350	347	42	66	58	55
Med	T24_2019	B	12	452	682	672	668	24	39	27	21
Med	T24_2019	B	13	443	647	642	639	54	67	69	68
Med	T24_2019	B	16	1162	1755	1952	2029	156	258	364	403
Med	T24_2019	E	1	183	244	145	125	102	137	148	154
Med	T24_2019	E	3	53	63	11	1	30	34	32	32
Med	T24_2019	E	10	29	43	33	32	16	25	32	34
Med	T24_2019	E	12	139	175	149	147	78	98	119	129
Med	T24_2019	E	13	107	138	118	114	71	97	119	124
Med	T24_2019	E	16	623	729	722	724	428	526	598	617
Med	BuilderPractice	B	1	890	1341	1772	1936	62	104	126	126
Med	BuilderPractice	B	3	390	571	745	821	39	48	48	55
Med	BuilderPractice	B	10	242	339	421	482	50	53	38	63
Med	BuilderPractice	B	12	449	673	886	976	24	35	32	36
Med	BuilderPractice	B	13	444	642	840	915	59	67	73	71

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Med	BuilderPractice	B	16	1167	1754	2334	2575	169	270	376	432
Med	BuilderPractice	E	1	350	419	457	469	191	241	268	283
Med	BuilderPractice	E	3	112	125	134	134	84	90	96	95
Med	BuilderPractice	E	10	122	143	151	160	109	131	136	148
Med	BuilderPractice	E	12	243	287	325	331	137	167	203	211
Med	BuilderPractice	E	13	192	226	249	256	124	154	181	190
Med	BuilderPractice	E	16	1015	1166	1261	1283	703	866	980	1008
Med	None	B	1	802	1158	1517	1651	218	238	303	203
Med	None	B	3	315	481	626	685	11	54	-47	-168
Med	None	B	10	176	262	327	367	98	193	193	479
Med	None	B	12	412	619	814	891	68	143	197	214
Med	None	B	13	381	575	767	834	28	58	98	-55
Med	None	B	16	1162	1737	2310	2538	133	233	446	626
Med	None	E	1	802	1158	1517	1651	218	238	303	203
Med	None	E	3	315	481	626	685	11	54	-47	-168
Med	None	E	10	176	262	327	367	98	193	193	479
Med	None	E	12	412	619	814	891	68	143	197	214
Med	None	E	13	381	575	767	834	28	58	98	-55
Med	**None**	**E**	**16**	**1162**	**1737**	**2310**	**2538**	**133**	**233**	**446**	**626**

Relative Exposure Plots

Figure 15 Relative exposure in CZ1 (Arcata), by airtightness, prototype, fan type and fan sizing method.

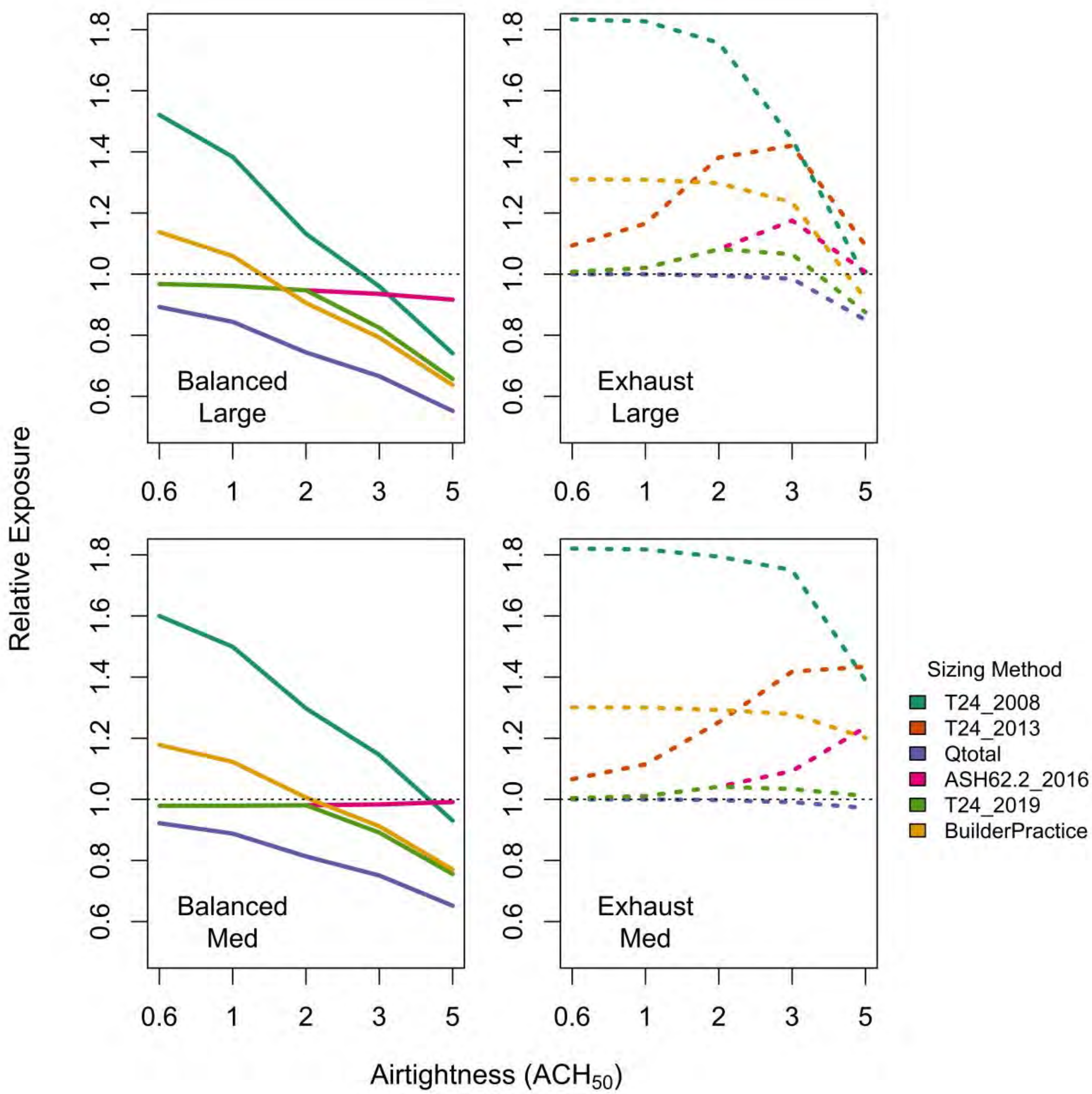


Figure 16 Relative exposure in CZ3 (Oakland), by airtightness, prototype, fan type and fan sizing method.

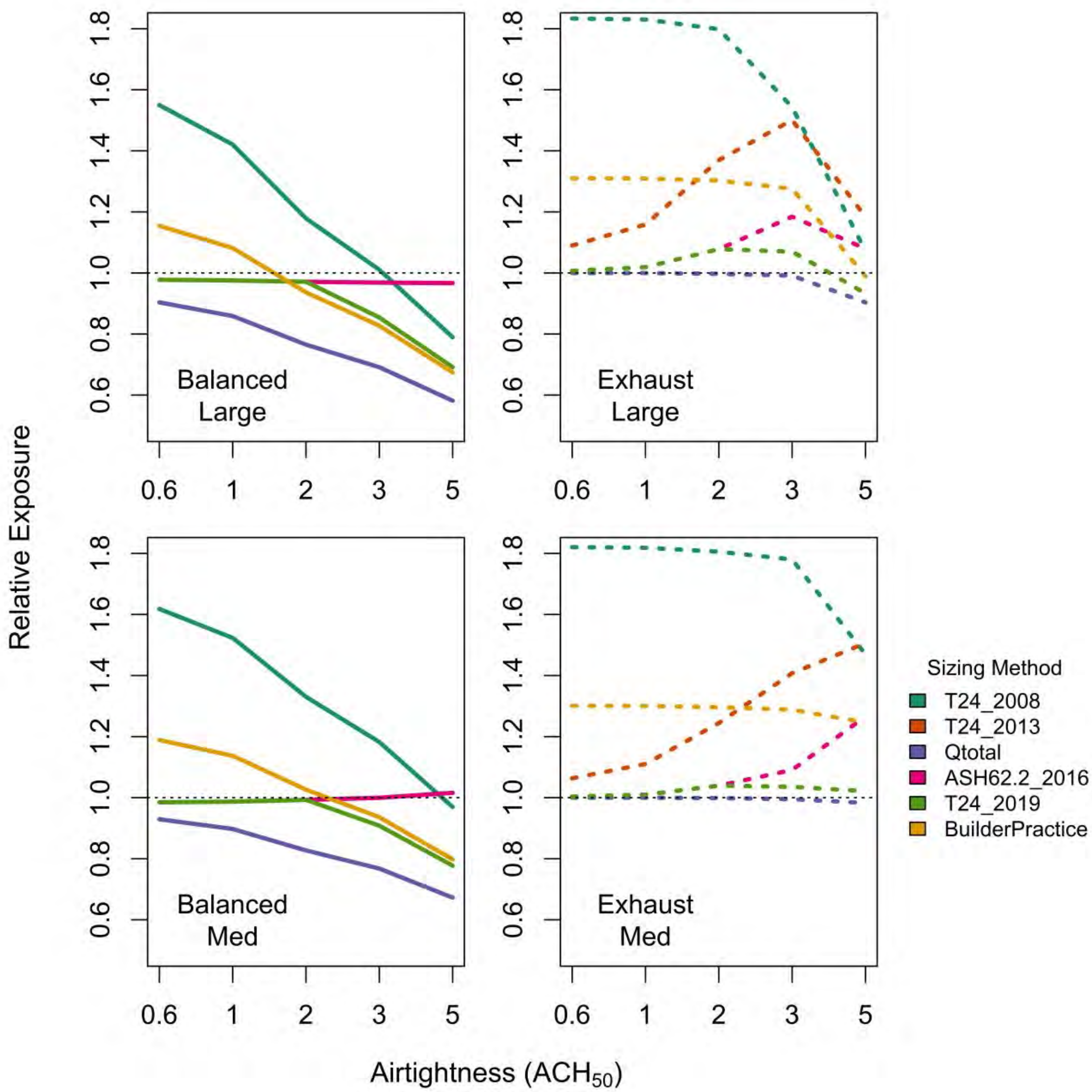


Figure 17 Relative exposure in CZ12 (Sacramento), by airtightness, prototype, fan type and fan sizing method.

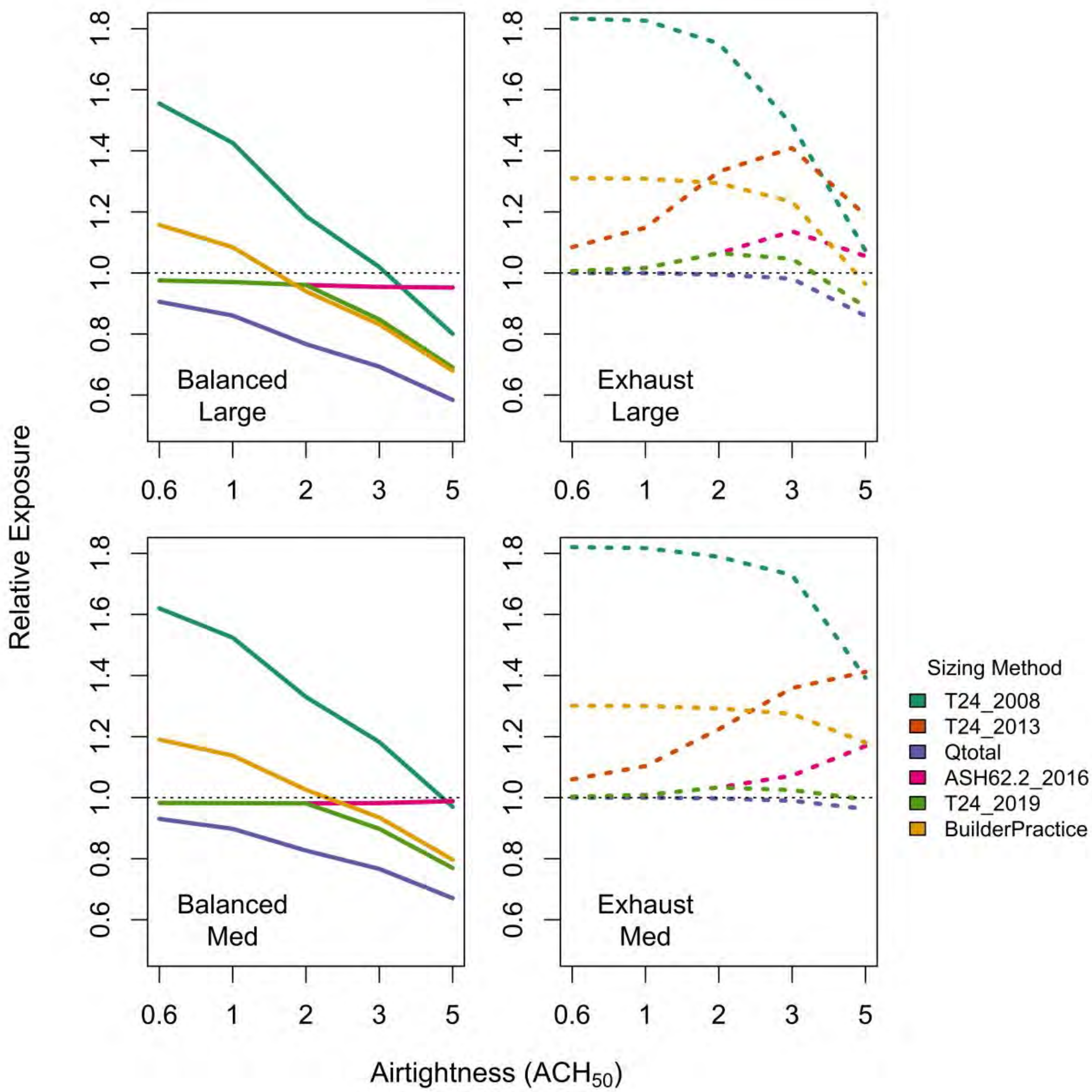


Figure 18 Relative exposure in CZ13 (Fresno), by airtightness, prototype, fan type and fan sizing method.

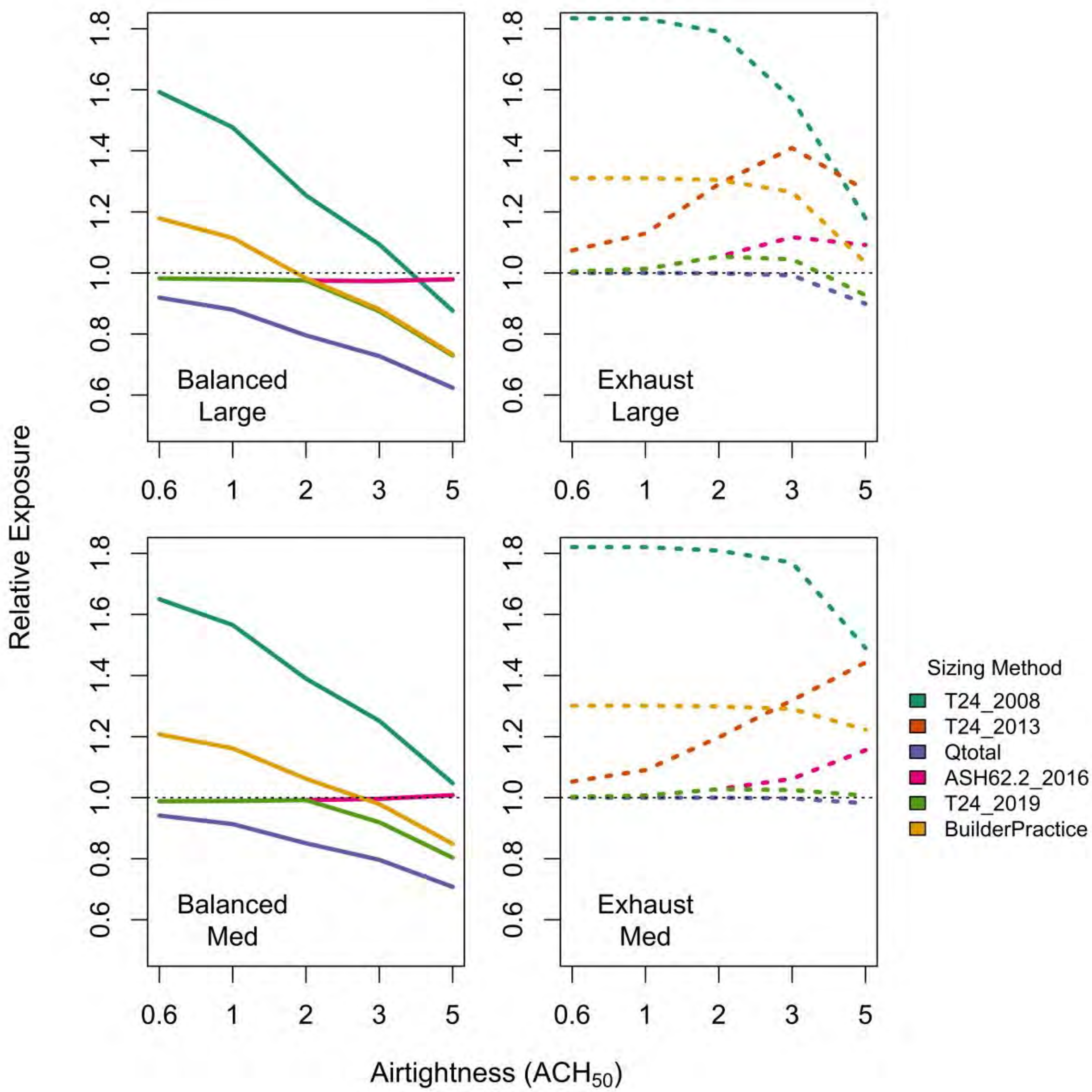
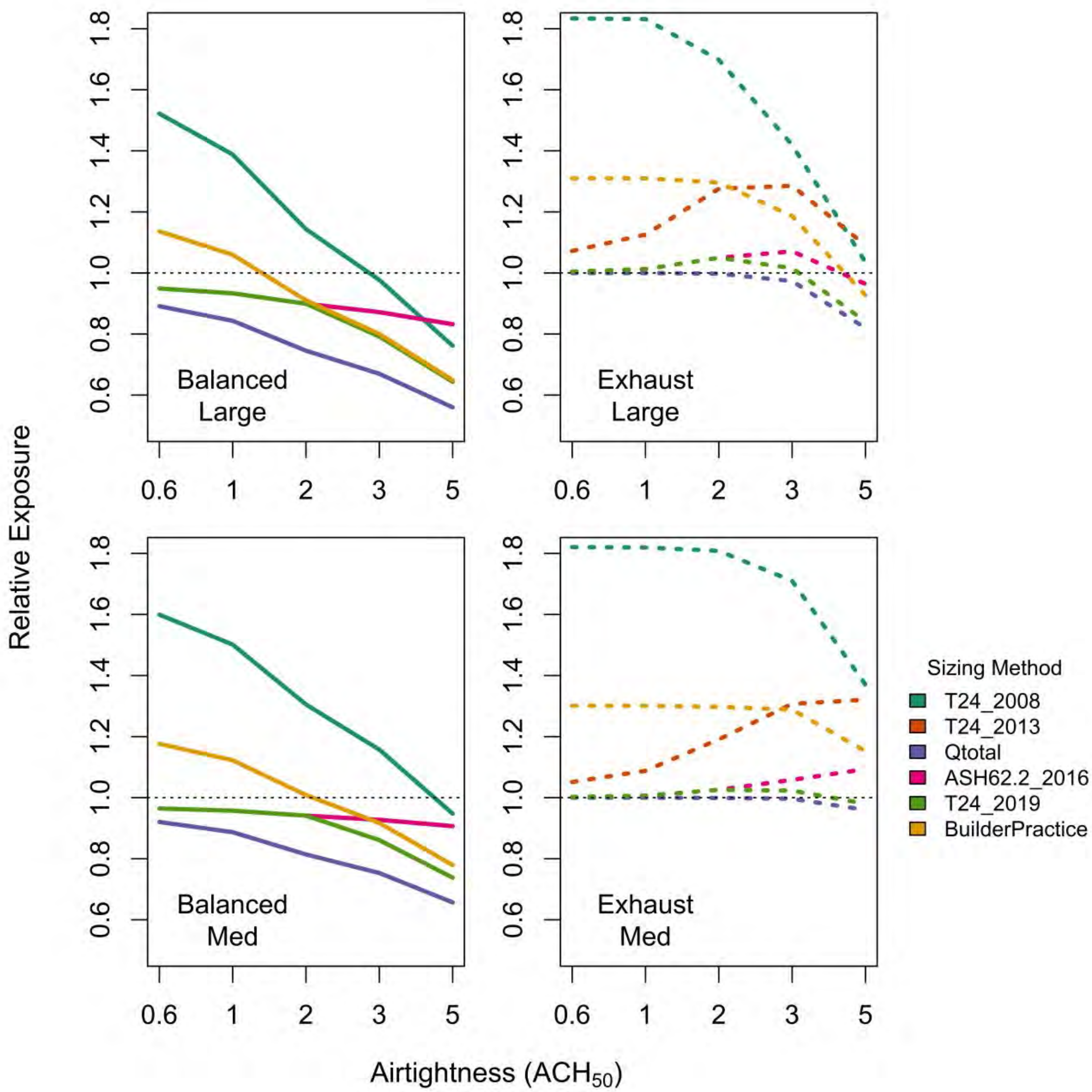


Figure 19 Relative exposure in CZ16 (Blue Canyon), by airtightness, prototype, fan type and fan sizing method.



HVAC Energy Savings from Airtightening Plots

Figure 20 T24_2008 (Fan Ventilation Rate Method) cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

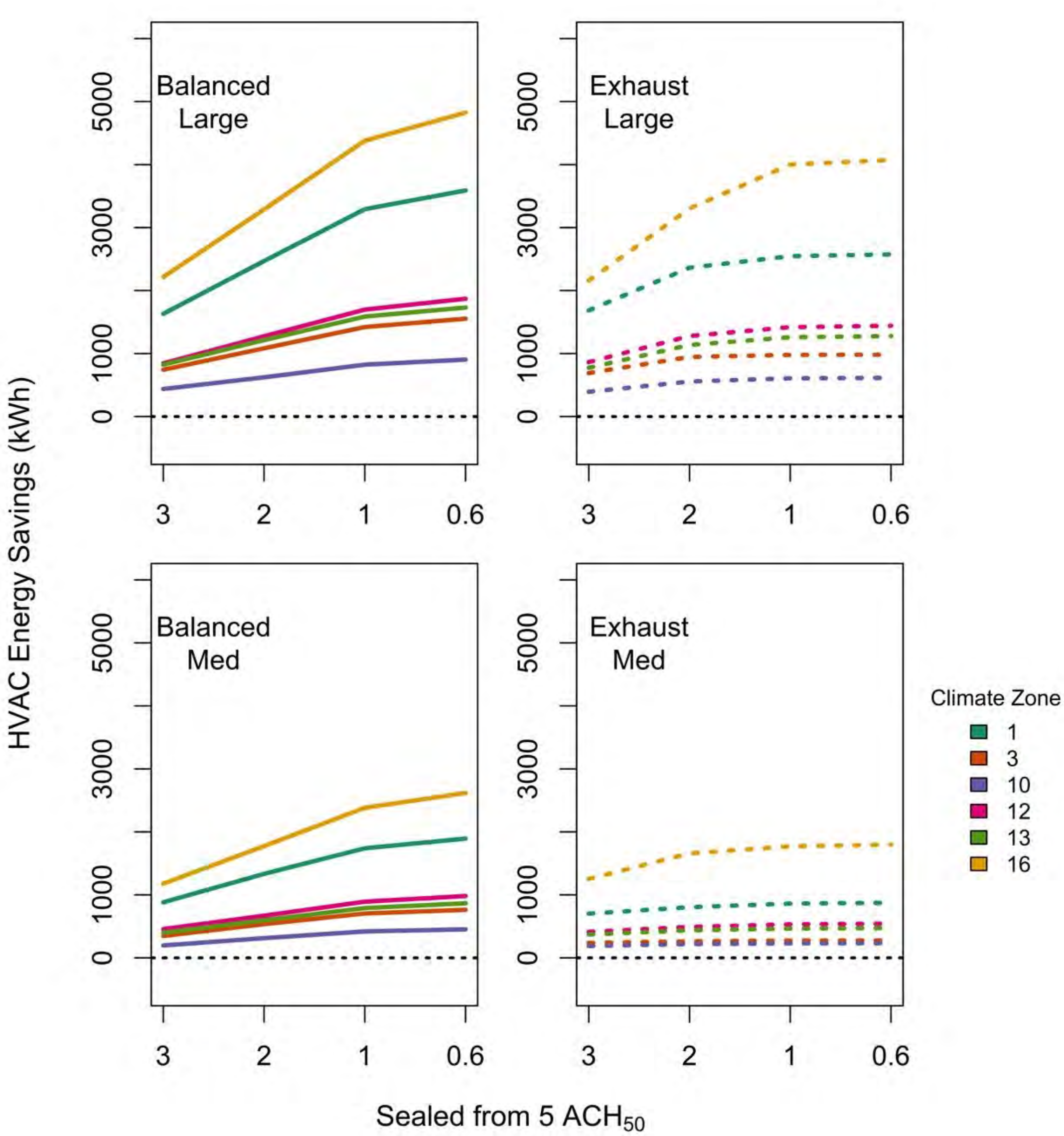


Figure 21 T24_2013 (Total Ventilation Rate Method) cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

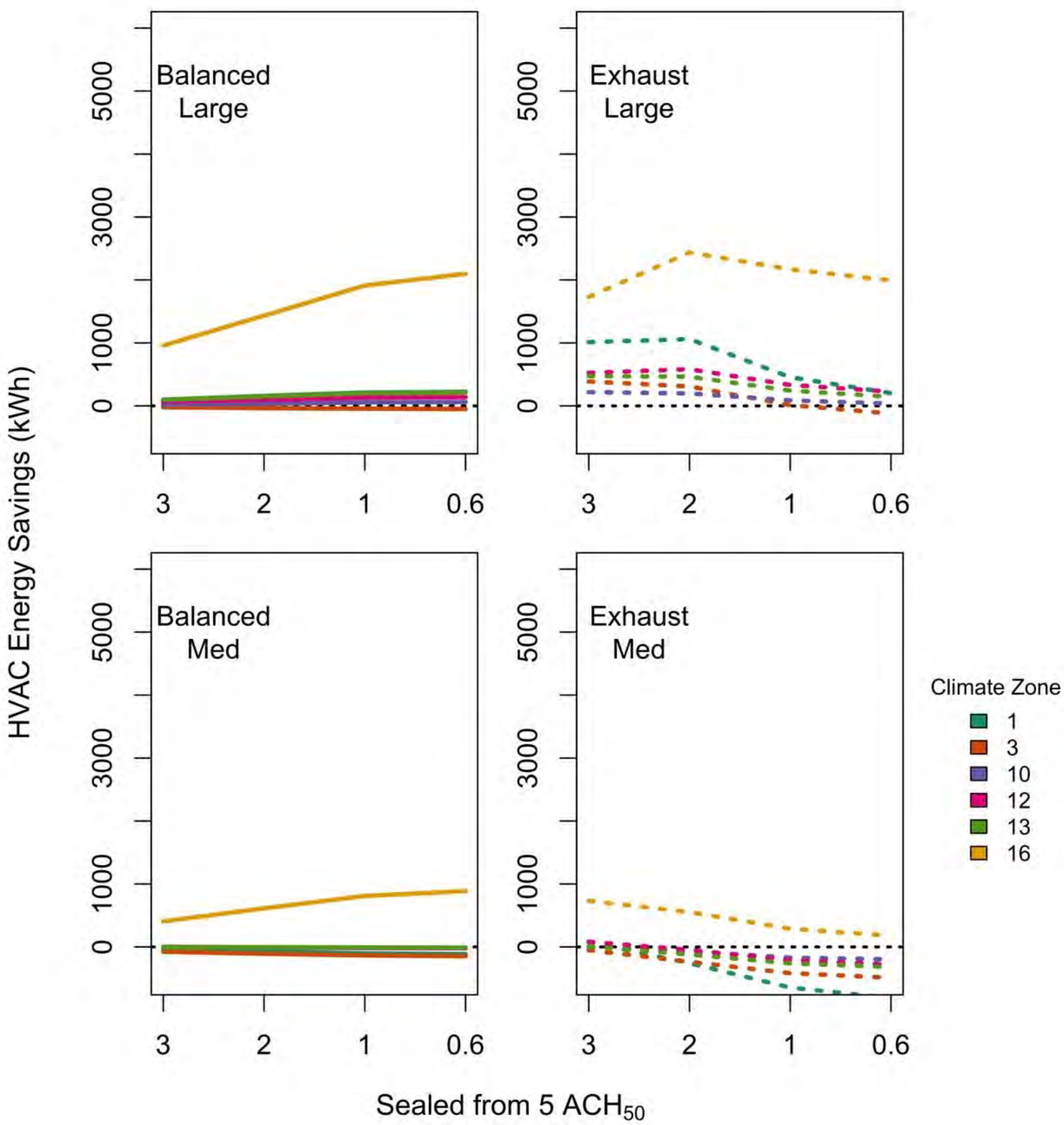


Figure 22 Qtotal cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

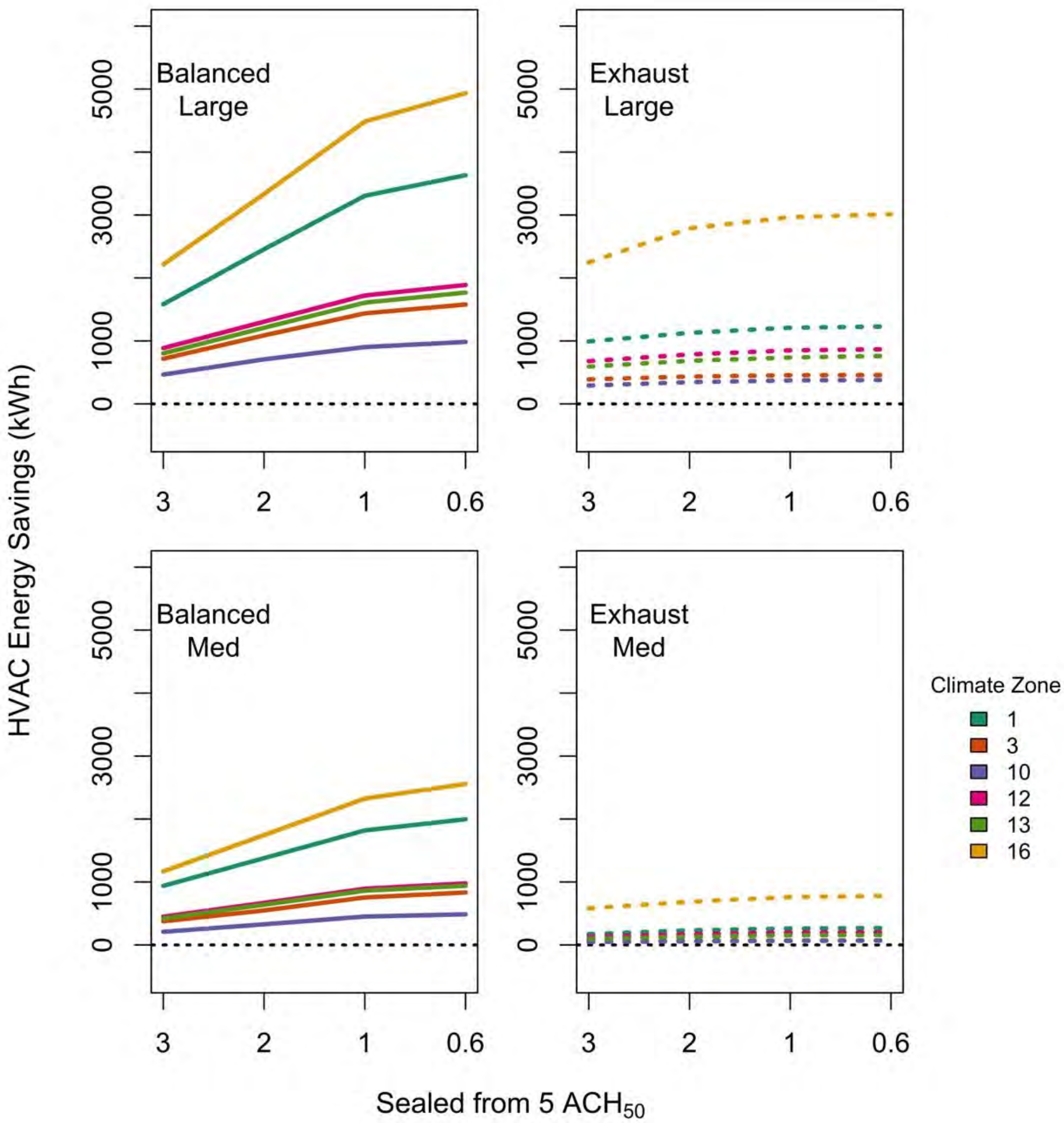
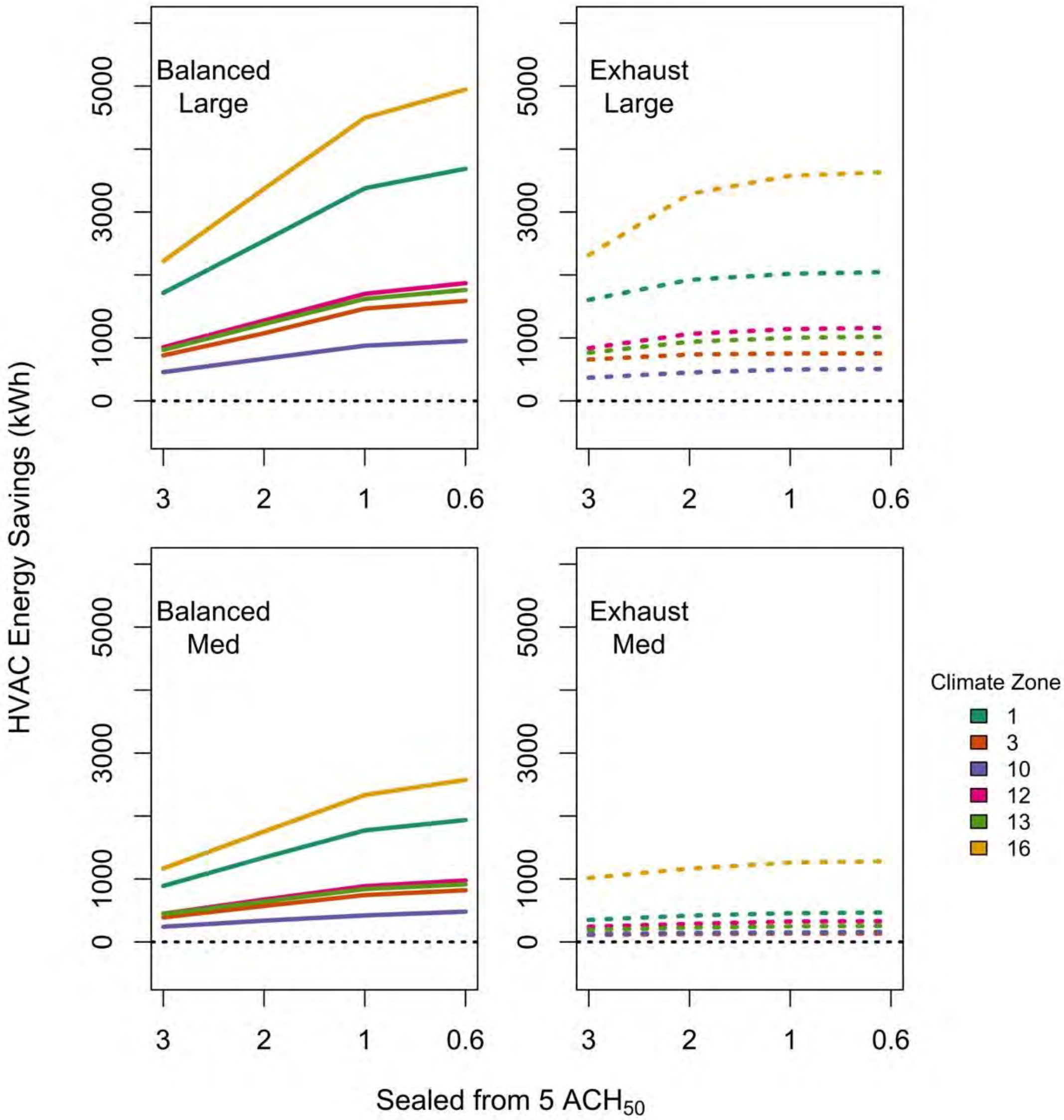


Figure 23 BuilderPractice (40% over-sizing relative to T24_2008) cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.



Normalized HVAC Energy Savings from Airtightening Plots

Figure 24 BuilderPractice. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

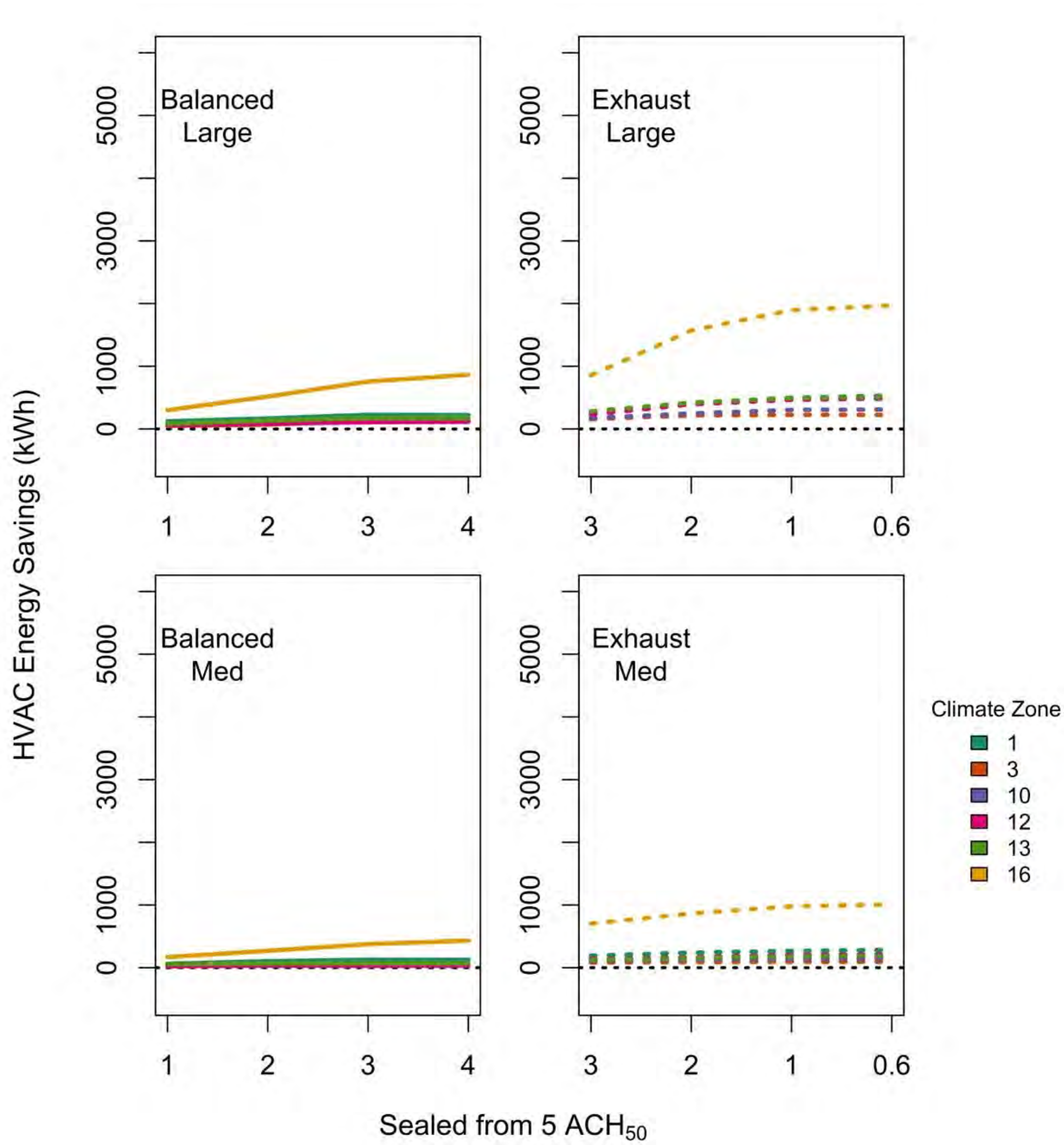


Figure 25 Qtotal. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

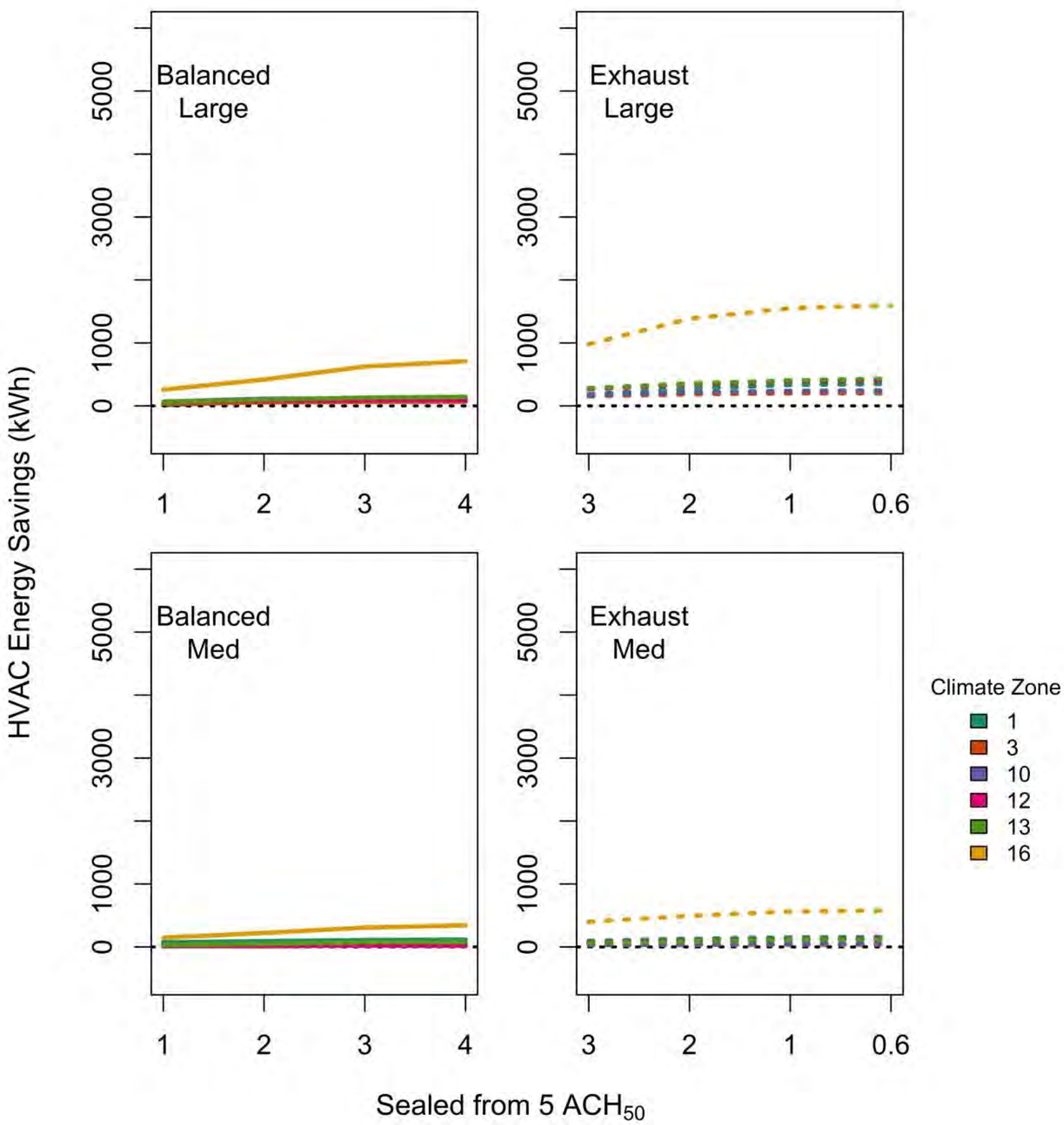


Figure 26 T24_2008. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

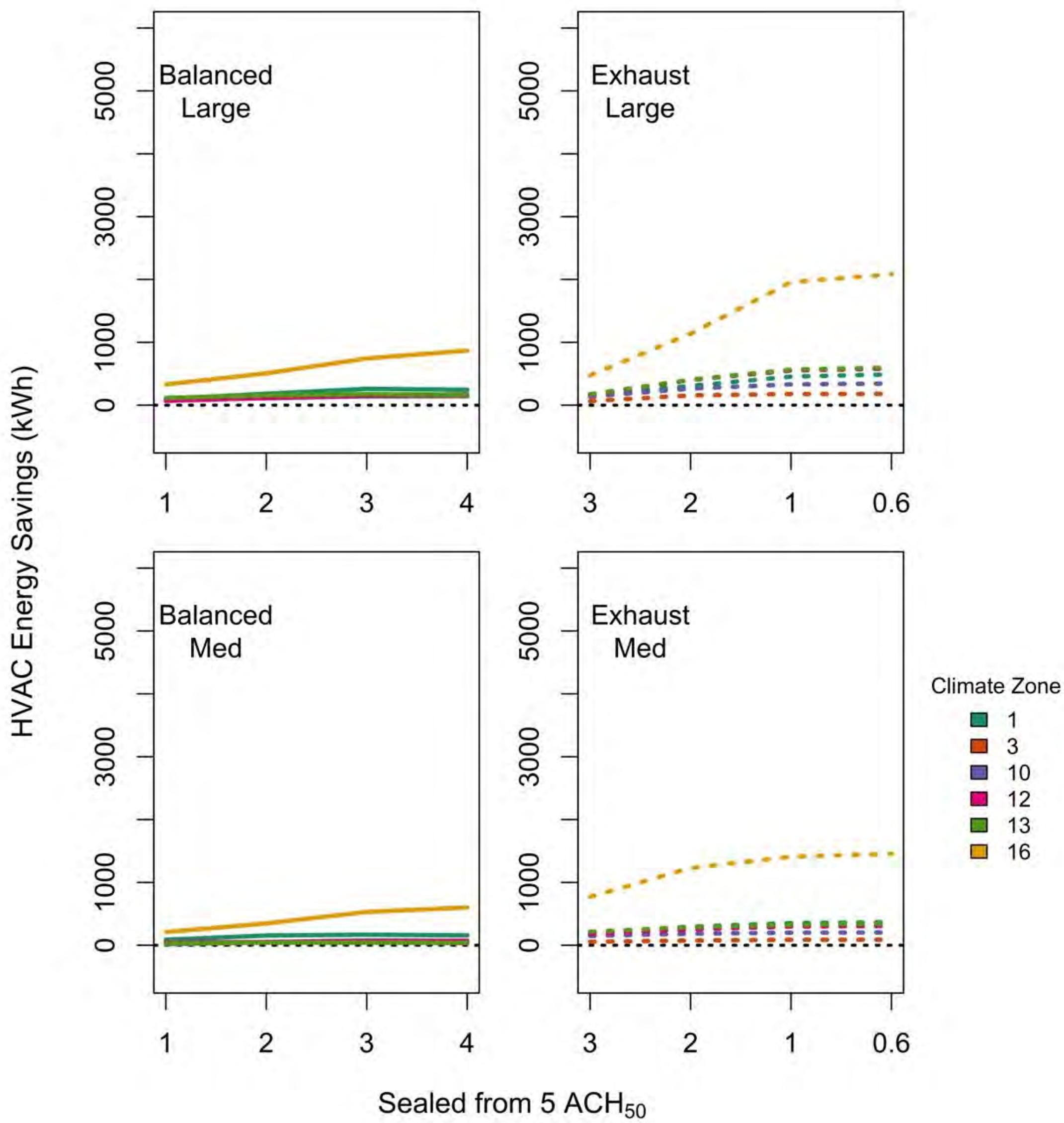
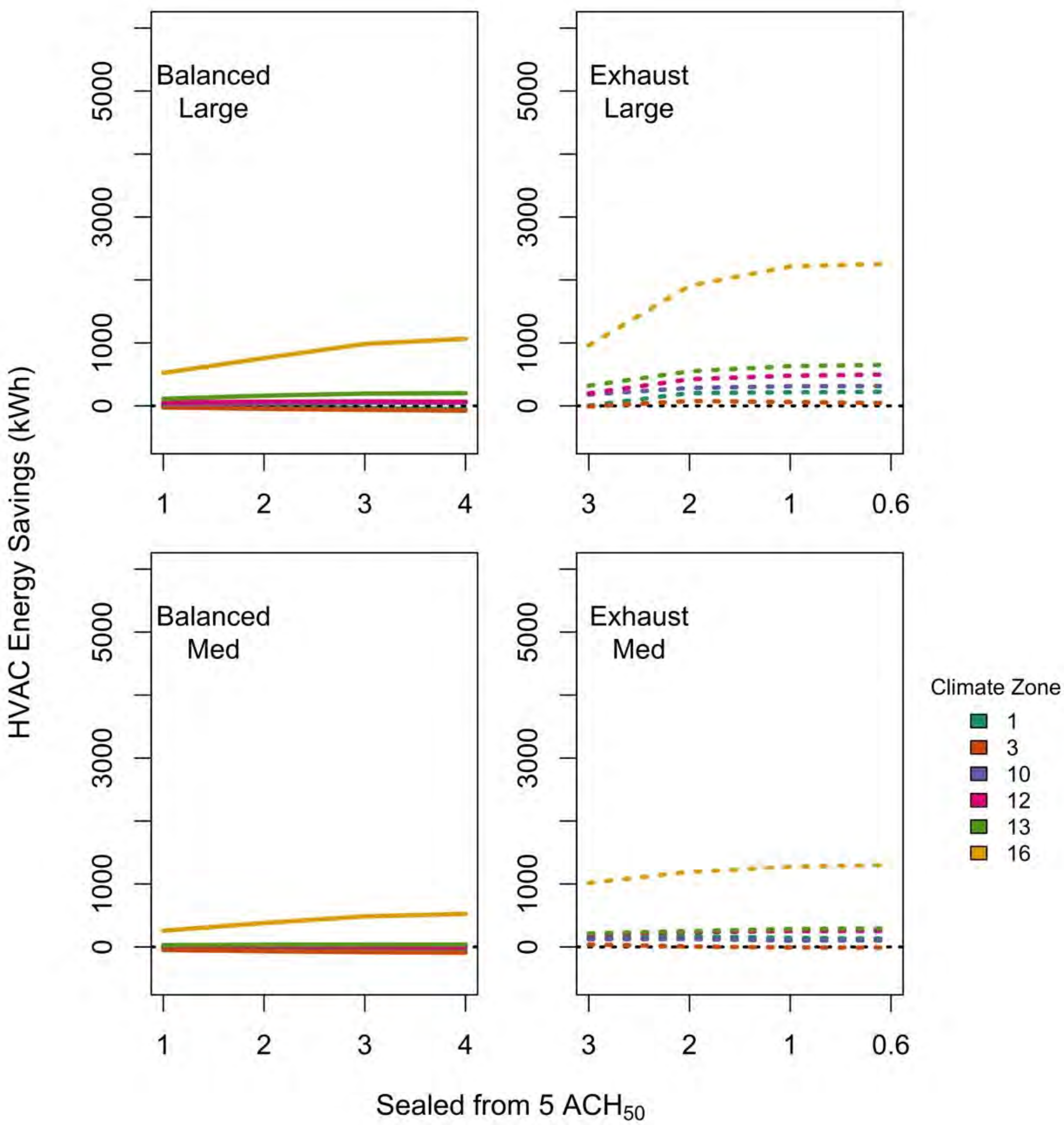


Figure 27 T24_2013. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

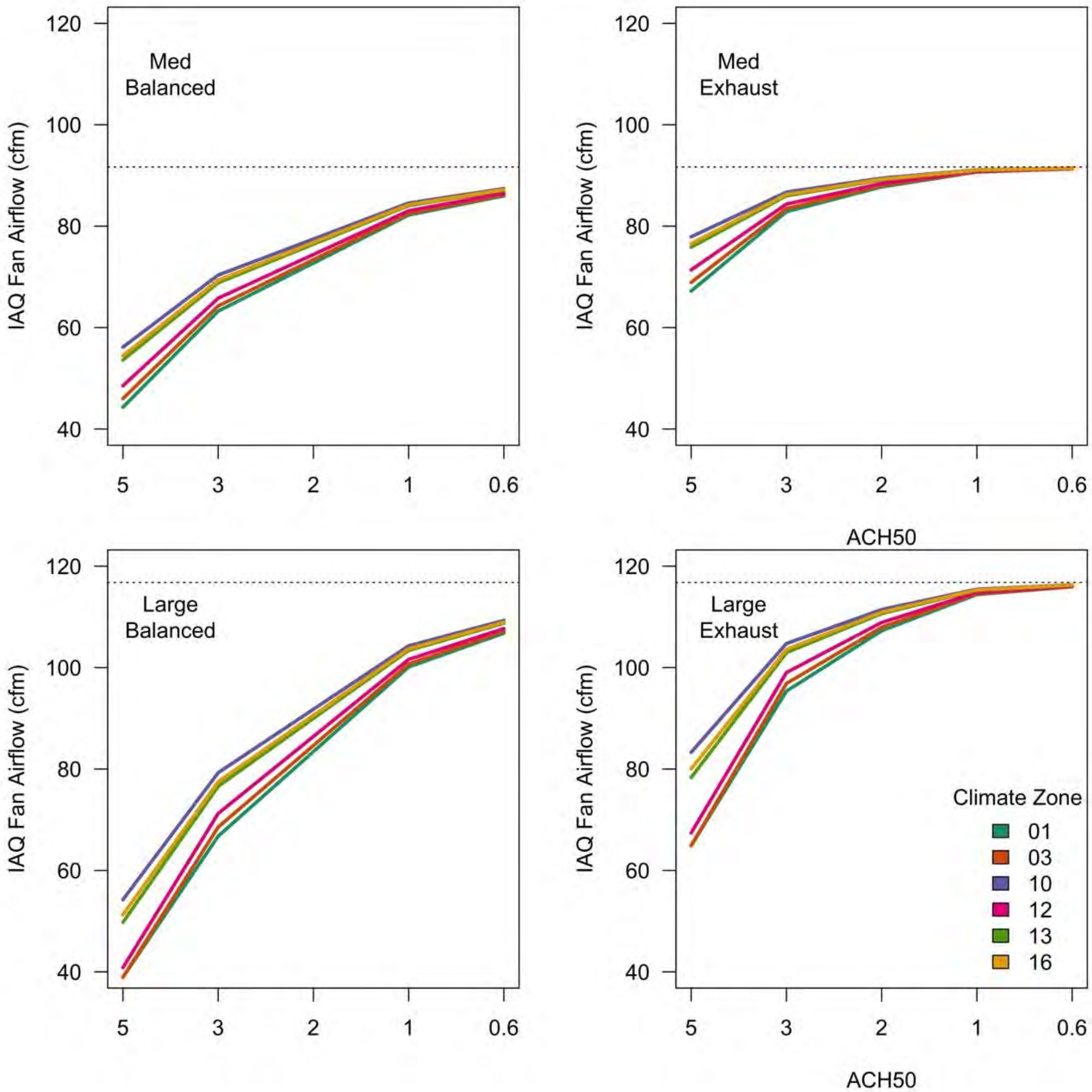


Whole house fan Airflows Illustration Plots

As outlined in Section 3.4, various methods have been or will be available to designers in complying with the IAQ requirements of Title 24. We simulated prototype homes with Whole house fans sized to each of the methods listed in Table 9 and described in Sections 3.4.1 and 3.4.2. We detail below how the ASH622_2016 (Figure 28), T24_2008 (Figure 29) and T24_2019 (Figure 30) sizing methods work in practice by discussing examples of calculated Whole house fan airflows for all prototypes, airtightness levels and climate zones. We selected these example methods, because they illustrate some of the key ways in which the methods differ, namely in how they treat infiltration, Whole house fan type and envelope airtightness. Where relevant, we highlight similarities between the plotted fan sizes and those for related sizing methods (e.g., T24_2008 and BuilderPractice). All other sizing methods not directly discussed are plotted for reference in Figure 31 through Figure 33.

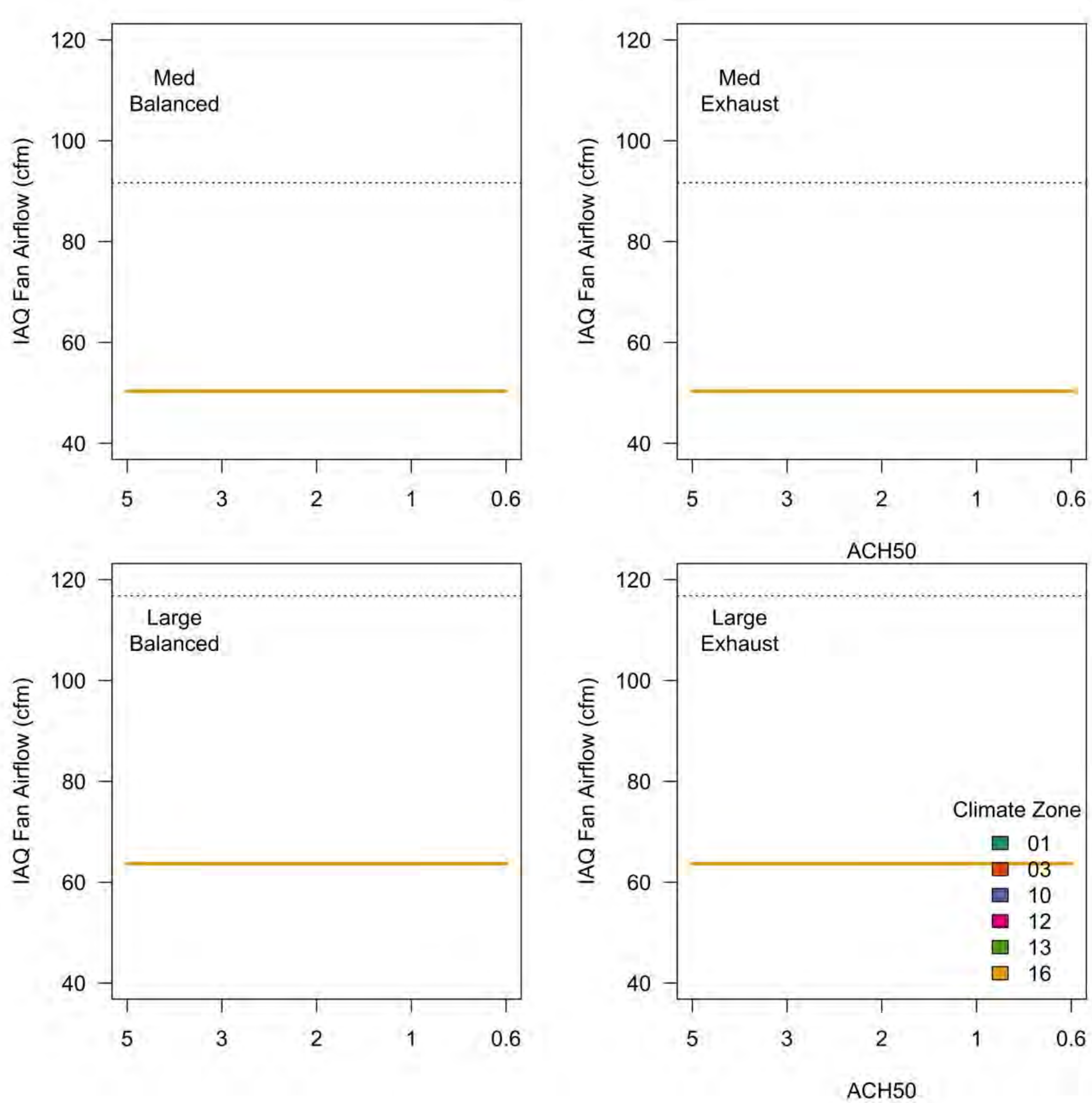
In Figure 28, we show the calculated Whole house fan airflows for each case used in the ASH622_2016 sizing method, which includes the most sophisticated infiltration estimates in fan sizing. The one-story prototypes ("Med") are in the two top panels, and the two-story prototypes ("Large") are in the lower two panels. The panels are separated left-to-right as Balanced or Exhaust fans. Each climate zone is represented by a colored line as indicated in the figure legend. For all cases, the required fan airflow increases as airtightness increase from 5 to 0.6 ACH_{50}. This compensates for reductions in natural infiltration. Differences in fan airflow are greatest between climate zones for the most leaky homes, and all climate zones get the same sized fan as airtightness increases to 0.6 ACH_{50}. Balanced fans change their airflow requirements more rapidly than exhaust fans do, because this sizing method also includes a superposition adjustment, which reduces the airflow credit for infiltration when using an unbalanced fan.

Figure 28 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to ASHRAE 62.2-2016. Grey dotted line shows target ventilation rate (Q_{total}).



In Figure 29, we show the fixed airflow approach of the T24_2008 sizing method, which does not account for natural infiltration in fan sizing. This method only distinguishes between the prototype homes, based on their size. The prescribed airflows are otherwise fixed across fan types, climate zone and airtightness. The BuilderPractice plot would look similar, except the yellow lines would be 40% higher.

Figure 29 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to T24_2008. Grey dotted line shows target ventilation rate (Q_{total}).



In Figure 30, we show the required fan airflows when using the T24_2019 sizing method, which includes a fixed infiltration adjustment based on a 2 ACH_{50} envelope and a sub-additivity adjustment for unbalanced fans. The infiltration credit varies by climate zone and house prototype, but not by airtightness, hence the scattered horizontal lines across the airtightness levels. Nevertheless, fan sizes are quite similar across climate zones, varying at most 10 cfm. The superposition adjustment for the unbalanced fans can be seen by comparing the Balanced and Exhaust airflows for the same prototype (i.e., top two panels or lower two panels). The sub-additivity adjustment is greater in the larger, two-story prototype, due to increased infiltration in 2-story homes.

Figure 30 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to T24_2019. Grey dotted line shows target ventilation rate (Q_{total}).

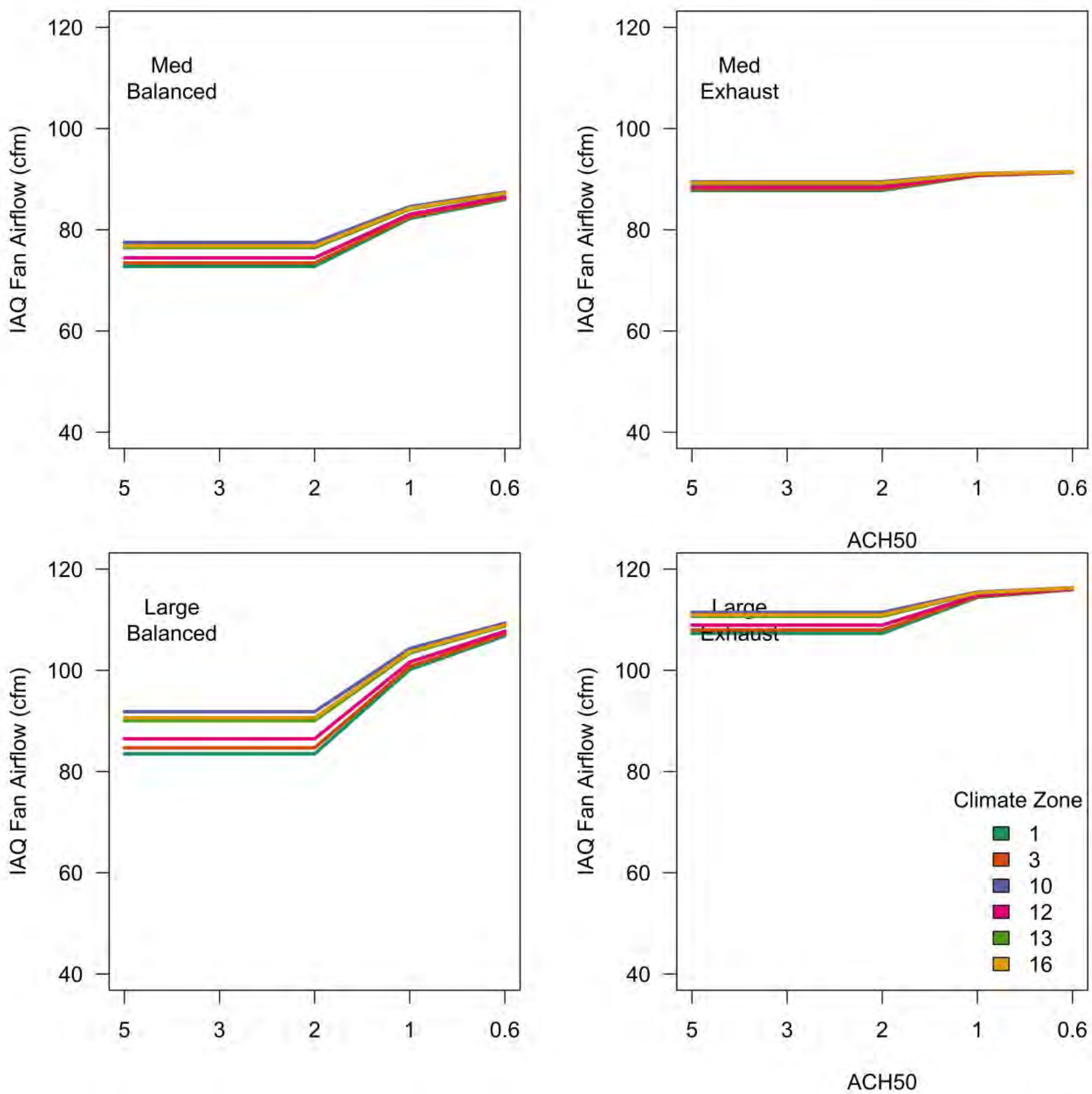


Figure 31 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to T24_2013 method. Grey dotted line shows target ventilation rate (Q_{total}).

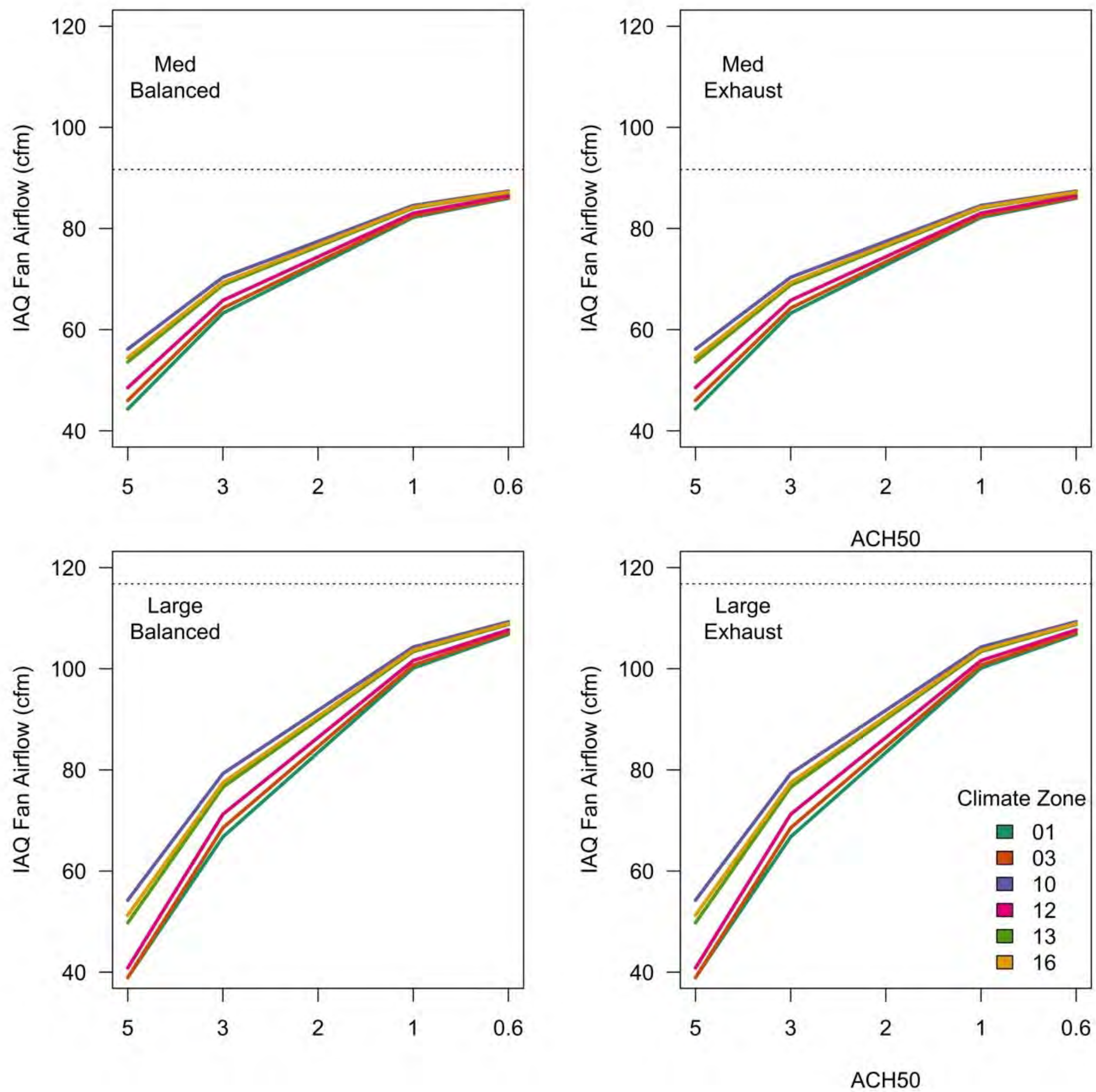


Figure 32 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to BuilderPractice method. Grey dotted line shows target ventilation rate (Q_{total}).

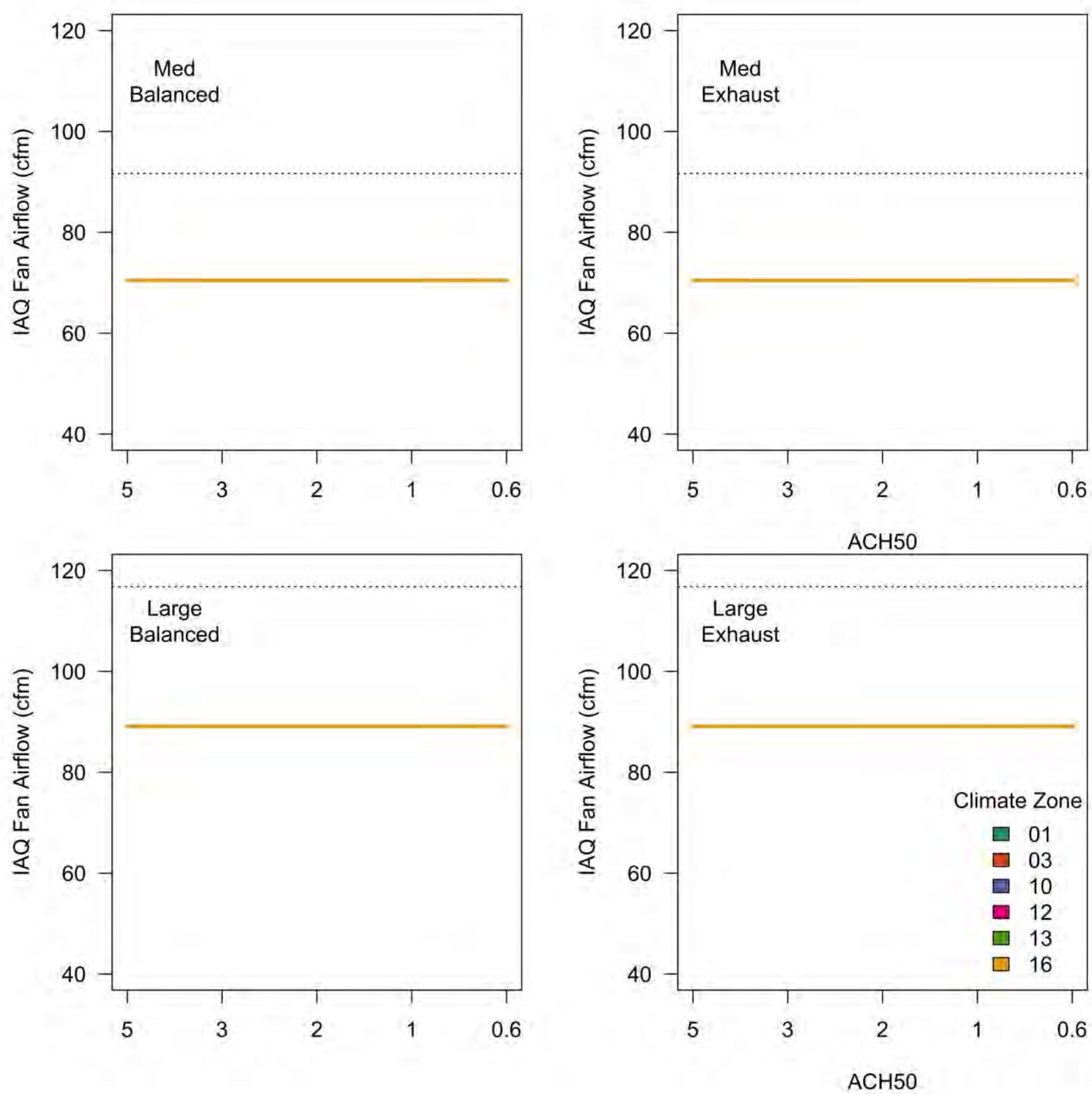
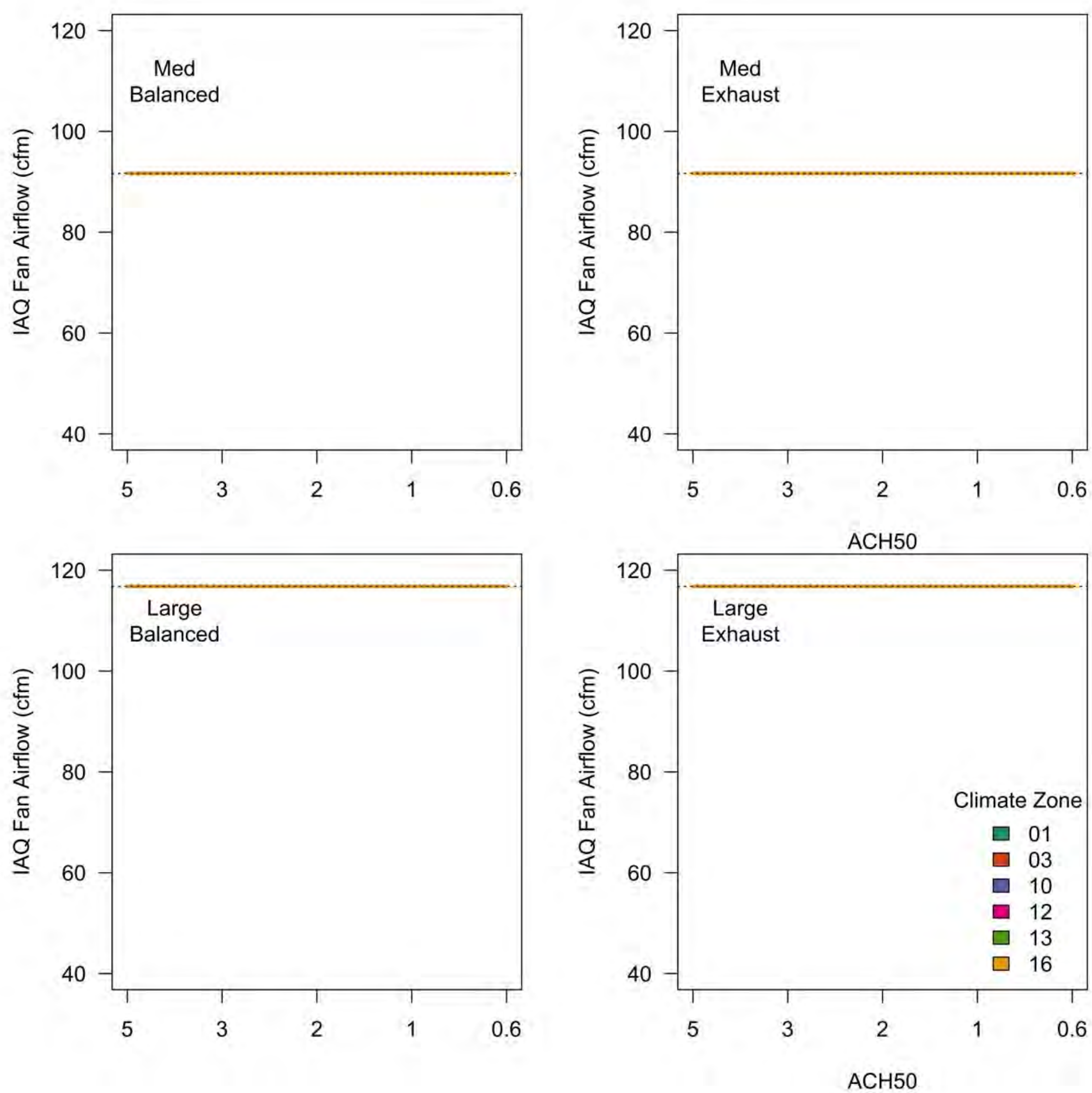


Figure 33 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to Qtotal method. Grey dotted line shows target ventilation rate (Q_{total}).



Discussion of Infiltration and Sub-Additivity in ASHRAE 62.2-2016 and REGCAP

As noted in the Methods sections of this report, the ASHRAE 62.2-2016 ventilation standard is carefully structured in an effort to help ensure that all compliant homes have similar whole house airflows that are consistent with the target airflow set by the standard (Q_{tot}). Consistent with this, our initial expectation was that the estimated annual average relative exposure for simulations using the ASH622_2016 sizing method would average very close to 1.0 and be tightly clustered around the mean. As shown in the weighted average and individual case sections of this work, while the ASH622_2016 method provided the least variable exposure of all the sizing methods, it still varied from roughly 0.8 to 1.2, with a weighted average of 1.1. This means that by design, some homes would be over- or under-vented by roughly 20%, and on average they would be under-vented by 10%, relative to the target ventilation rate in ASHRAE 62.2 and Title 24.

We hypothesized that the predictions of natural infiltration were higher in the fan sizing calculations than in the REGCAP simulations. This would lead to effectively under-sized Whole house fans, which result in overall higher exposure in the REGCAP model (e.g., mean of 1.1, rather than 1.0). For Whole house fan sizing, the house leakage area derived from blower door testing (i.e., ELA) is combined with the weather and shielding factor (wsf) to estimate the effective annual average infiltration airflow from weather effects. The wsf used in ASHRAE 62.2-2016 fan sizing were derived for each TMY3 location in the United States as described in Turner, Sherman, & Walker (2012). These wsf factors were calculated using certain assumptions about house leakage distributions (i.e., proportion of house leaks in floor, walls and ceiling), as well as TMY3 weather files. They used the AIM-2 advanced infiltration model to estimate infiltration airflows. These wsf are intended to be widely applicable and generic enough to function reasonably across the U.S. housing stock.

Assuming that these infiltration estimates were the cause of high exposure, we examined factors influencing infiltration predictions, each in isolation—weather data (page 107), house leakage distribution (page 109), weather and shielding factors (*wsf*) used in fan sizing (page 109), and superposition of unbalanced fans with infiltration (Section 4.3). We found that overall the simplified infiltration estimates from the ASHRAE standard align reasonably well with those in the REGCAP simulations when no Whole house fan is simulated, but the interaction of mechanical and natural airflows (i.e., superposition/sub-additivity) diverges sharply, leading to the increased weighted average exposure in this paper. This divergence is driven by known biases in the ASHRAE 62.2-2016 sub-additivity model, along with differences in leakage distribution, and to a much lesser extent by the marginal differences in weather data and natural infiltration predictions.

Weather Data

The weather files used in estimating infiltration and sizing the Whole house fan are not the same as those used for demonstrating Title 24 compliance. Weather data is factored into Whole house fan sizing using the weather and shielding factors (wsf), which are based on very geographically granular TMY3 weather data files. These are files commonly used in most building simulation tools and for many assessments of building performance. The California Title 24 uses different weather files entirely for demonstrating compliance based on a fixed energy budget for that geographic climate region. The sixteen CEC climate zones each represent much larger and more variable areas of land and weather than do TMY3 locations. Our understanding is that the outdoor dry-bulb data in the CEC files are adjusted such that the mean and extremes are in-line with reliable weather stations within the climate zone, and that non-dry-bulb data are matched to a single, representative location within the climate zone. Sometimes these generalized climate zone weather data files can differ substantially from TMY3 data used for wsf factors in ASHRAE 62.2-2016. As the determinants of weather induced infiltration in buildings, we examined outdoor dry-bulb temperature and wind speed.

In CEC weather files, the representative city for CZ16 is Blue Canyon, which is located in the Western foothills of the Sierra Nevada mountains at roughly 4,700 ft elevation. For Title 24 compliance, this weather is used to represent nearly the entire Sierra Nevada range in California, including some more harsh and cold locations, such as South Lake Tahoe at 6,200 ft. As such, the TMY3 location for Blue Canyon, CA (TMY3 ID 725845) differs substantially from the CEC CZ16 weather data. See Table 8 for our mapping of CEC climate zones to TMY3 locations. The annual distributions of outdoor dry-bulb temperature are plotted in Figure 34, and the distributions have very similar averages (vertical dashed lines), but the CEC weather data has many more hours in the 0-10°C temperature bin and many fewer hours in the 10 to 20°C bin. This shift affects infiltration due to stack effect based on indoor-outdoor temperature difference, and we expect more stack infiltration when using CEC weather data compared with TMY3 data. This is one of the worst discrepancies between the temperatures in the weather file types, while some others are a quite well-matched.

Wind speed is the other main determinant of weather-induced infiltration in homes, and we see similar differences between weather file types. An example of wind speed distributions is plotted for CZ5 in Figure 35 (Santa Maria, CA, TMY3 ID 723940). The CEC weather data has many more hours in the 0-1 m/s wind speed bin, while having many fewer hours in the roughly 2-4 m/s bin. We expect this to reduce wind-induced infiltration predictions when using CEC weather data, relative to TMY3 data.

Figure 34 Outdoor dry-bulb temperature distributions for Blue Canyon (CZ16), TMY3 versus CEC weather data.

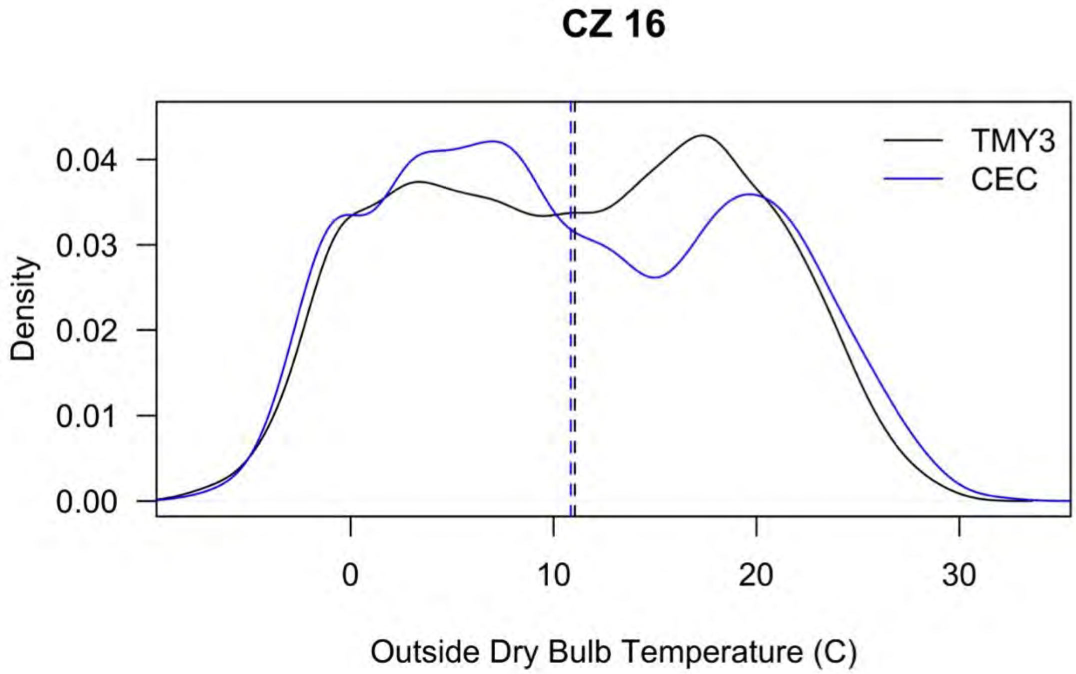
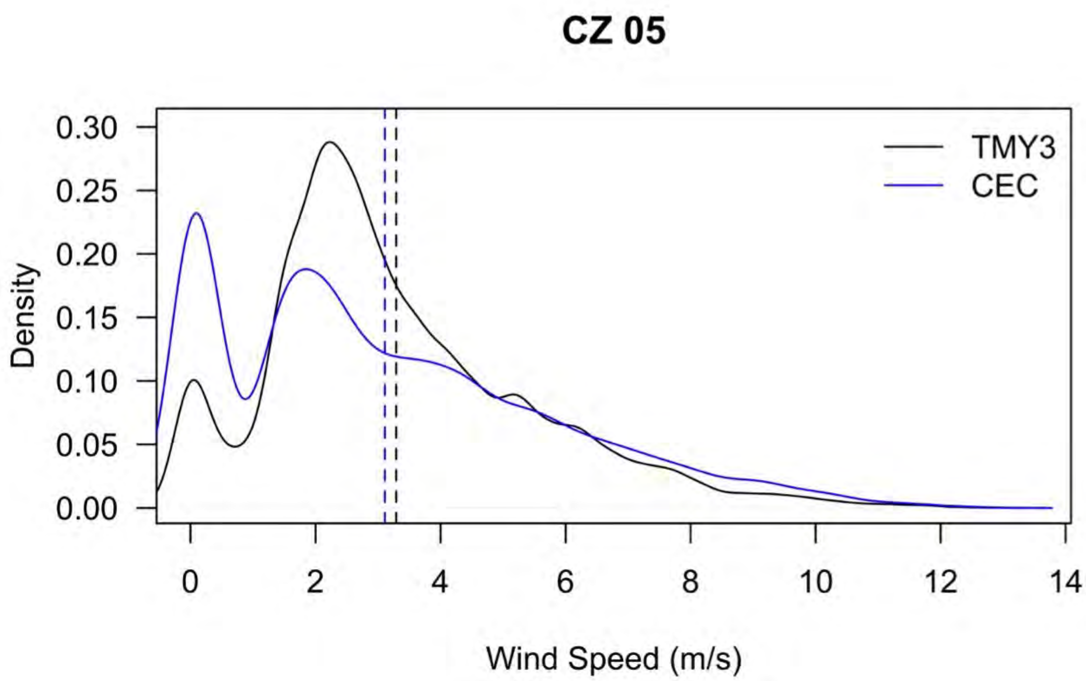


Figure 35 Wind speed distributions for Santa Maria (CZ5), TMY3 versus CEC weather data.



Building Leakage Distribution

The distribution of leakage area across the building envelope, by orientation and height, has a substantial impact on predicted infiltration rates. Per Table 3 in the 2016 Alternative Calculation Method (ACM), Title 24 assumes that 50% of building leaks at in the home's ceiling, between the house and attic volumes. The remaining leaks are distributed between the floor and walls (if crawlspace or basement foundations) or just the walls (slab on grade). This assumption places a lot of leakage area in the ceiling, which is the highest point in the home. The estimate that 50% of leakage is in the ceiling was derived from field measurements in new California homes (Proctor et al., 2011). If this leakage distribution is actually representative of new homes in California, it differs substantially from assumptions for the housing stock elsewhere, and it certainly differs substantially from the assumptions used to generate the 62.2 wsf factors (reproduced from Turner et al. in Table 16 alongside T24 ACM assumptions). The wsf factor analysis assigned between 17 and 25% of total leakage to the ceiling, which is at most half the Title 24 assumption. These differences in leakage distribution can substantially impact the weather-induced infiltration airflow for a residence.

Table 16 Reproduced leakage distribution assumptions used in wsf factor derivations, compared with T24 ACM assumptions.

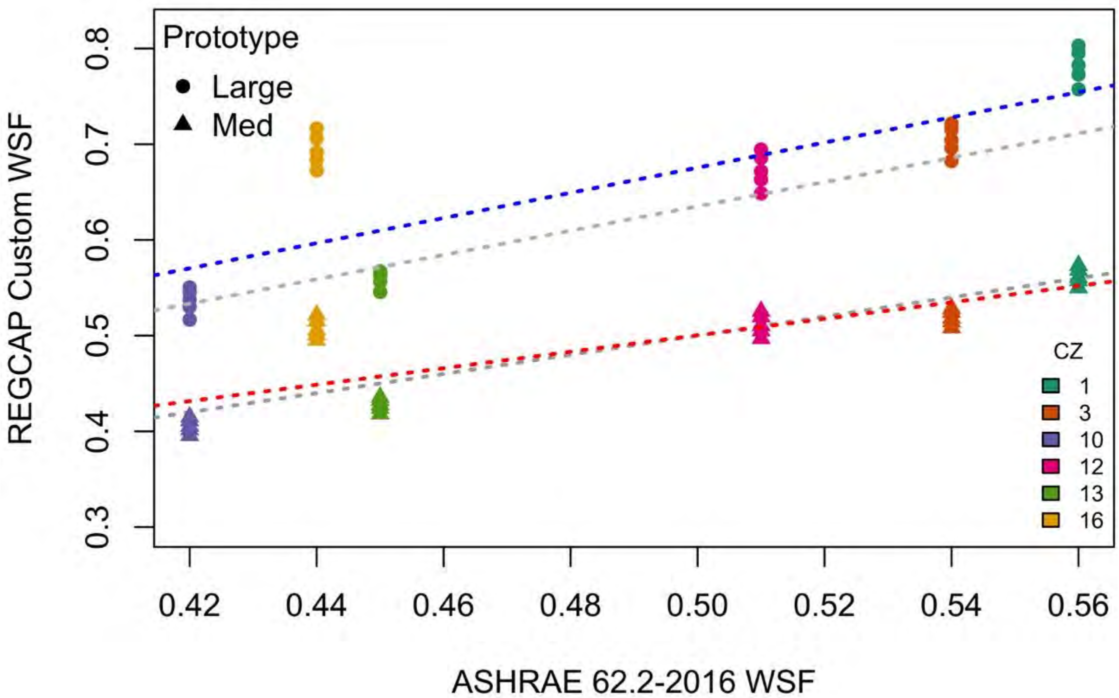
Building Element	Fraction of Total Leakage		
	Turner et al. WSF Analysis		T24 ACM
	1-story	2-story	1- and 2-story
Walls	0.5	0.66	0.25
Ceiling	0.25	0.165	0.5
Floor	0.25	0.165	0.25

Weather and Shielding Factors (wsf)

We have shown that the weather data files are different between fan sizing and HENGH simulations, and we have also highlighted the different leakage distributions assumed. The next step was to assess how these factors impacted the infiltration estimates used in fan sizing. So, we calculated custom WSF using the same calculation methods outlined in Turner et al. and applied them to the prototype homes that we simulated using REGCAP. We then used these custom wsf to predict infiltration airflows, all of which were compared to the assumptions used in fan sizing.

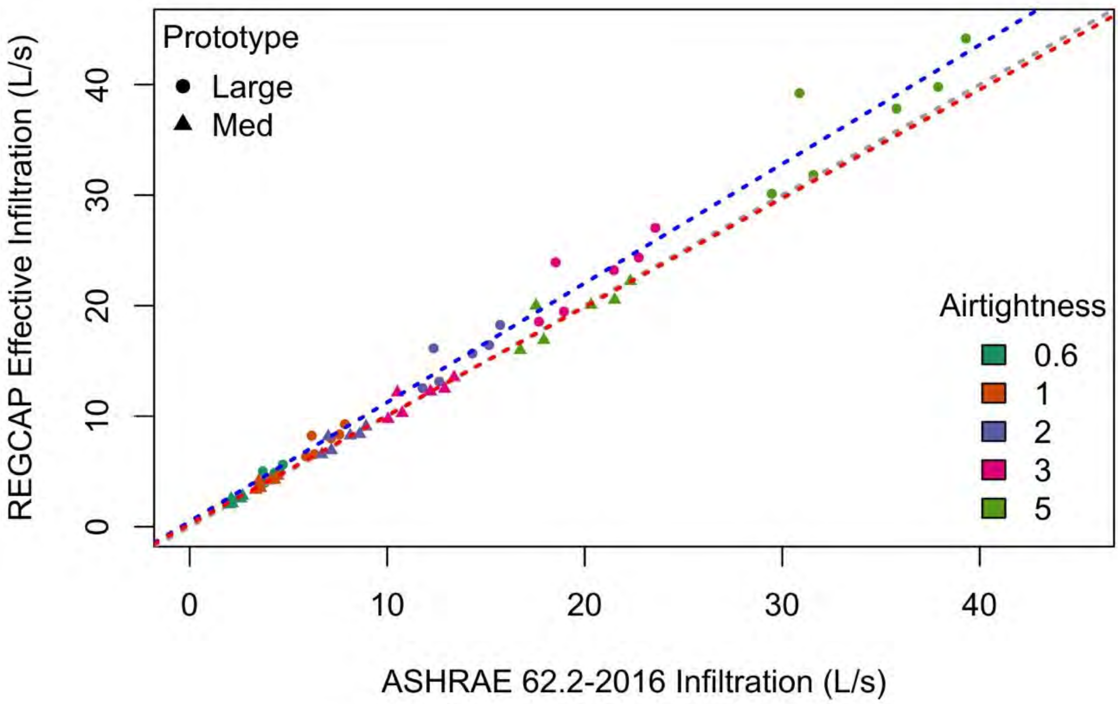
With the exception of CZ16 in Blue Canyon, we found very reasonable agreement between the wsf published in ASHRAE 62.2 and those generated directly from our simulation data. These values are plotted in Figure 36, with climate indicated by symbol color, and prototype by shape (Large, 2-story homes are circles; Med, 1-story homes are triangles). Within each prototype and climate zone there is some variability by airtightness. The grey dashed lines have a slope of 1 and intercept 0, representing exact agreement for the medium and large prototypes. The colored dashed lines represent linear model of custom wsf based on simulation outputs. The outlier nature of CZ16 is clear in this plot, with values roughly 0.1 higher than those used in the standard. The rest have some scatter high or low, but are generally well-aligned with the standard.

Figure 36 Comparison of ASHRAE 62.2-2016 wsf factors and those generated directly from our simulation outputs. CZ distinguished by color, prototype by shape.



The effects of this variation on predicted effective infiltration rates are shown in Figure 37. The 1-story medium prototypes (red dashed line) overlap nearly perfectly with the ASHRAE 62.2-2016 infiltration values (Qinf), while the 2-story large prototypes (blue line) are slightly higher on average, though we expect this is driven by the CZ16 behavior. Based on these results, we conclude that with the exception of CEC CZ16, the infiltration predictions from 62.2 are more than adequate for sizing ventilation fans.

Figure 37 Predicted effective infiltration airflows from ASHRAE 62.2-2016 versus effective average airflows from the REGCAP simulations. Dashed red line shows Medium, 1-story prototype linear model, and the blue line shows the Large, 2-story model.



APPENDIX C:
Healthy Efficient New Gas Homes (HENGH) Pilot Test Results

ABSTRACT

The Healthy Efficient New Gas Homes (HENGH) is a field study that will collect data on ventilation systems and indoor air quality (IAQ) in new California homes that were built to 2008 Title 24 standards. A pilot test was performed to help inform the most time and cost effective approaches to measuring IAQ in the 100 test homes that will be recruited for this study. Two occupied, single-family detached homes built to 2008 Title 24 participated in the pilot test. One of the test homes uses exhaust-only ventilation provided by a continuous exhaust fan in the laundry room. The other home uses supply air for ventilation. Measurements of IAQ were collected for two weeks. Time-resolved concentrations of particulate matter (PM), nitrogen dioxide (NO_2), carbon dioxide (CO_2), carbon monoxide (CO), and formaldehyde were measured. Measurements of IAQ also included time-integrated concentrations of volatile organic compounds (VOCs), volatile aldehydes, and NO_2. Three perfluorocarbon tracers (PFTs) were used to estimate the dilution rate of an indoor emitted air contaminant in the two pilot test homes. Diagnostic tests were performed to measure envelope air leakage, duct leakage, and airflow of range hood, exhaust fans, and clothes dryer vent when accessible. Occupant activities, such as cooking, use of range hood and exhaust fans, were monitored using various data loggers. This document describes results of the pilot test.

1 Introduction

The Healthy Efficient New Gas Homes (HENGH) field study will collect data on ventilation systems and indoor air quality (IAQ) in new California homes that were built to 2008 Title 24 standards (CEC, 2008). HENGH aims to collect IAQ data in 100 occupied California homes in different locations and seasons. Measurements will include mechanical ventilation system performance, indoor air contaminant concentrations, and other indoor environmental parameters. The collected data will be analyzed to evaluate IAQ in the sampled homes. It will also be used as input data for model simulations to determine how to provide adequate ventilation and acceptable IAQ while reducing air infiltration beyond the 2008 Title 24 standards.

2 Pilot Test Objectives

The main pilot test objective was to determine the most time and cost effective approaches to measuring IAQ in the test homes before testing all 100 homes. The pilot testing was also used to identify potential problems with field measurements. As a result, the field team performed more intensive air quality sampling and data collection than intended for the full-scale field study so that a subset could be selected that will best achieve the overall project objectives regarding IAQ assessment while being appropriate for a large-scale field study with limited home access.

3 Descriptions of Pilot Test Homes

Two occupied, single-family detached homes built to 2008 Title 24 were recruited. One of the pilot test homes uses exhaust-only ventilation provided by a continuous exhaust fan in the laundry room. The second pilot test home uses supply air for ventilation. Measurements of indoor air quality (IAQ) were collected for two weeks. Different approaches were used to collect data on usage of gas appliances and mechanical ventilation. This document summarizes field data collected from the two pilot test homes. Table 1 describes the basic house characteristics of these two homes. Floor plans are shown in Appendix C-1. The requirements for participation in the pilot test were that houses must be located in the Bay Area or Sacramento area, built in 2011 or later, have at least three occupants, have mechanical ventilation, and use natural gas for space heating, water heating, and cooking. Smoking must be prohibited. LBNL completed field testing in two homes between July and September 2015.

LBNL Institutional Review Board approved the human subject protocol that was followed in this study. Study participants were paid $560 for their time. Aside from making their homes available for this pilot test, study participants also filled out a daily log to record information about their indoor activities. They gave consent for LBNL to access Title 24 compliance documents from the CHEERS (ConSol Home Energy Efficiency Rating Services) data registry. However, the compliance documents on file did not contain information on mechanical ventilation. They contain other information (e.g., diagnostic test results, specifications on building components and appliances) that will be helpful for data analysis and interpretation.

Table 1 House characteristics of the two pilot test homes.

	House 1	House 2
Sampling Period: Week 1 Week 2	July 22–29 July 29–August 5	August 19–26 August 26–September 3
Location	Rancho Cordova, CA	Brentwood, CA
Year Built	2015	2013
Floor Area	1777 ft^2	2990 ft^2
Ceiling Height	10 ft	9 ft
Estimated House Volume*	17770 ft^3	26910 ft^3
Number of Stories	1 story	2 story
Number of Bedrooms	3 bedrooms	4 bedrooms
Number of Bathrooms	2 full	3 full
Number of Occupants	3 occupants	5 occupants
Garage	Attached, 3-car	Attached, 2-car

* House volume estimated by multiplying floor area and ceiling height.

4 Building Envelope and Duct Leakage Tests

A team of two researchers from LBNL conducted all sampling and data collection in the Pilot test homes. Building envelope air leakage and duct leakage was measured using the deltaQ test (ASTM, 2013). Table 3 shows the test results. Title 24 compliance documents showed the measured (tested at final, not rough-in) duct leakage at 25 Pa measured using duct pressurization. Note that deltaQ test measured duct leakage at operating conditions, so the results are not directly comparable to results from the duct pressurization test. However, deltaQ results are not very sensitive to the operating pressures of the system, as long as pressure are within a factor of two (Walker et al., 2001). In Table 2, envelope leakage measurements and HVAC airflow was available from the compliance documents for House 2 only.

Table 2 Measured building envelope and duct leakage in two pilot test homes.

		House 1	House 2
Building Envelope Leakage			
	Pressurization leakage	4.5 ACH50	3.2 ACH50
	Depressurization leakage	3.9 ACH50	3.1 ACH50
	Average leakage	4.2 ACH50	3.2 ACH50
	Title 24 Compliance Certificate	--	3.1 ACH50
Duct Leakage*			
	Supply leakage#	35 CFM (2%)	29 CFM (2%)
	Return leakage#	42 CFM (3%)	35 CFM (3%)
	Title 24 Compliance Certificate+	77 CFM (4%)	11 CFM (1%)
HVAC Airflow			
	Rated	1600 CFM	1500 CFM
	Title 24 Compliance Certificate	--	1268 CFM

* % duct leakage calculated using rated airflow for House 1, and measured airflow for House 2.
# Measured using deltaQ test at operating pressures.
+ Measured using duct pressurization test at 25 Pa.

5 Mechanical Ventilation Airflow Measurements

Table 3 shows the mechanical ventilation airflow measurements. Both houses have microwave-combined range hood. Range hood exhaust airflow rates were measured using a custom-made capture box that is fitted under the range hood. A fan and flow meter were connected to the capture box to measure the airflow at three fan speed settings. Airflow of the exhaust fan in bathrooms and laundry room were measured using a powered flow hood. Many of the exhaust fans found in the bathrooms were controlled by a humidistat. Clothes dryer vent airflow was measured only at House 2 at the exterior wall cap using a powered flow hood. The measured airflow was low compared to an expected 100 to 150 CFM for typical clothes dryers (Bendt, 2010). The clothes dryer vent at House 1 was not measured because the exterior vent was located on the roof and inaccessible to the field team.

Table 3 Measured mechanical ventilation airflow rates in two pilot test homes.

	House 1	House 2
Range Hood	158 CFM (High speed) 107 CFM (Mid) 98 CFM (Low)	132 CFM (High speed) 112 CFM (Mid) 104 CFM (Low)
Exhaust Fan – Master Bath	104 CFM (bath, humidistat) 54 CFM (toilet, manual)	98 CFM (bath, humidistat) 56 CFM (toilet, manual)
Full Bath 2	110 CFM	96 CFM (humidistat)
Full Bath 3	--	87 CFM (humidistat)
Laundry Room	86 CFM	86 CFM
Clothes Dryer Vent	Not measured because inaccessible located on roof	45 CFM

The laundry room exhaust fan provided most of the mechanical ventilation in House 1. Anemometer data showed that the fan was operating approximately two-thirds of the time. The required whole-building ventilation per Title 24 is calculated as follows:

$$Q_{cfm} = 0.01\ (A_{floor}) + 7.5\ (N_{br} + 1) = 48\ \text{CFM}$$

where the conditioned floor area (A_{floor}) = 1770 ft^2 and number of bedrooms (N_{br}) = 3. The laundry room exhaust fan would have provided sufficient whole-house ventilation if it were operating continuously. However, the fan was operating intermittently, though not as would be if it were cycled by a timer (see Appendix C-2). If the ventilation effectiveness of 0.75 were applied as specified in Title 24 for intermittent fans that operate between 60% to 80% of the time, the laundry room exhaust fan must have an airflow of at least 96 CFM to provide sufficient whole-building ventilation.

$$Q_f = 48\ \text{CFM} / (0.67 \times 0.75) = 96\ \text{CFM}$$

In House 2, mechanical ventilation was provided by an inline fan connected to the return plenum of the air handler. The required whole-house ventilation per Title 24 for House 2 is 68 CFM. The inline fan was observed to be continuously running during field visit. However, its airflow was not measured because it was buried in spray foam and was inaccessible.

In addition, Title 24 required exhaust fans installed to provide local ventilation in kitchen and each bathroom. The requirements for intermittent local ventilation are 100 CFM in kitchen and 50 CFM in bathroom. Both houses met Title 24 in terms of meeting the local ventilation airflow requirement.

6 Activity Monitoring

Table 4 shows the methods used to monitor usage of various appliances, including the cooktop and oven, bathroom exhaust fans, clothes dryer, central forced air system, water heater, and windows/door opening. Activity data were mostly logged on 1-minute time intervals. Figure 1 through Figure 6 show examples of the locations used for activity monitoring. Table 5 shows the daily average runtime of the devices used to compute the mechanical ventilation rates; see Appendix C-2 for the usage data collected over the two sampling weeks.

Table 4 Methods used to monitor appliance usage at the two pilot test homes.

Usage	House 1	House 2
Cooktop	Wire braid thermocouple	iButton temperature sensor
Oven	Thermocouple probe	Thermocouple probe
Bathroom Exhaust Fan	Motor on/off state logger Digital anemometer	Motor on/off state logger
Range Hood	Digital anemometer	Digital anemometer
Clothes Dryer	Power meter	T/RH at exterior vent
Central forced air system	Power meter T/RH at air register	Digital anemometer T/RH at air register Motor state logger
Water heater	--	Thermocouple probe at draft diverter
Windows/doors	Open/close state logger	Open/close state logger

Table 5 Daily average runtime in two pilot test homes.

	House 1	House 2
Range Hood	11 minutes	17 minutes
Exhaust Fan – Master Bath	24 minutes (bath) 26 minutes (toilet)	74 minutes (bath) 5 minutes (toilet)
Full Bath 2	46 minutes	16 minutes
Full Bath 3	--	44 minutes
Laundry Room	14.9 hours	51 minutes
Clothes Dryer Vent	32 minutes	38 minutes

Figure 1 Cooking activity monitoring

Wire braid thermocouple (five total: left-front, left-back, right-front, right-back, and center of the burner top) and thermocouple probe used to measure cooktop and oven use in House 1 (top left and right photo). The red arrow in bottom left photo shows where one of the four iButton temperature sensors were placed near the left-front burner top in House 2 (bottom left photo).

Figure 2 Fan use monitoring

Digital anemometer (upper photos) and motor state logger (lower photo) used to monitor bathroom exhaust fan use.

Figure 3 Digital anemometer used to monitor range hood use

Figure 4 Methods used to monitor central forced air system use.

Power meter on the air handler (upper left photo), temperature/relative humidity sensor at the supply grill closest to the air handler (upper right photo), digital anemometer at the return grill (lower photo)

Figure 5 Thermocouple probe used to monitor gas water heater usage.

Figure 6 State logger used to monitor opening and closing of windows and doors.

In House 1, four open/close state sensors were used to monitor the following doors: master bedroom door, master bathroom door, sliding door to back patio, and door from garage to house. Windows were not monitored in House 1. More doors and some windows were monitored in House 2, including 11 door sensors (master bedroom and three other bedroom doors, two other bathroom doors, laundry room door, sliding door to back patio, front door, door from garage to house, door from garage to outside) and 7 windows sensors (two master bedroom windows, three playroom windows, living room window, and entry room window).

Figure 7 shows the window use in House 2. Windows in the master bedroom and playroom on the upper floor were left open for 13 hours (master bedroom) and 16 hours (playroom) per day on average. Windows in the living room and entry room on the lower floor were mostly closed. They were opened for 3.8 hours per day on average.

Figure 7 Monitoring data of window use in House 2.

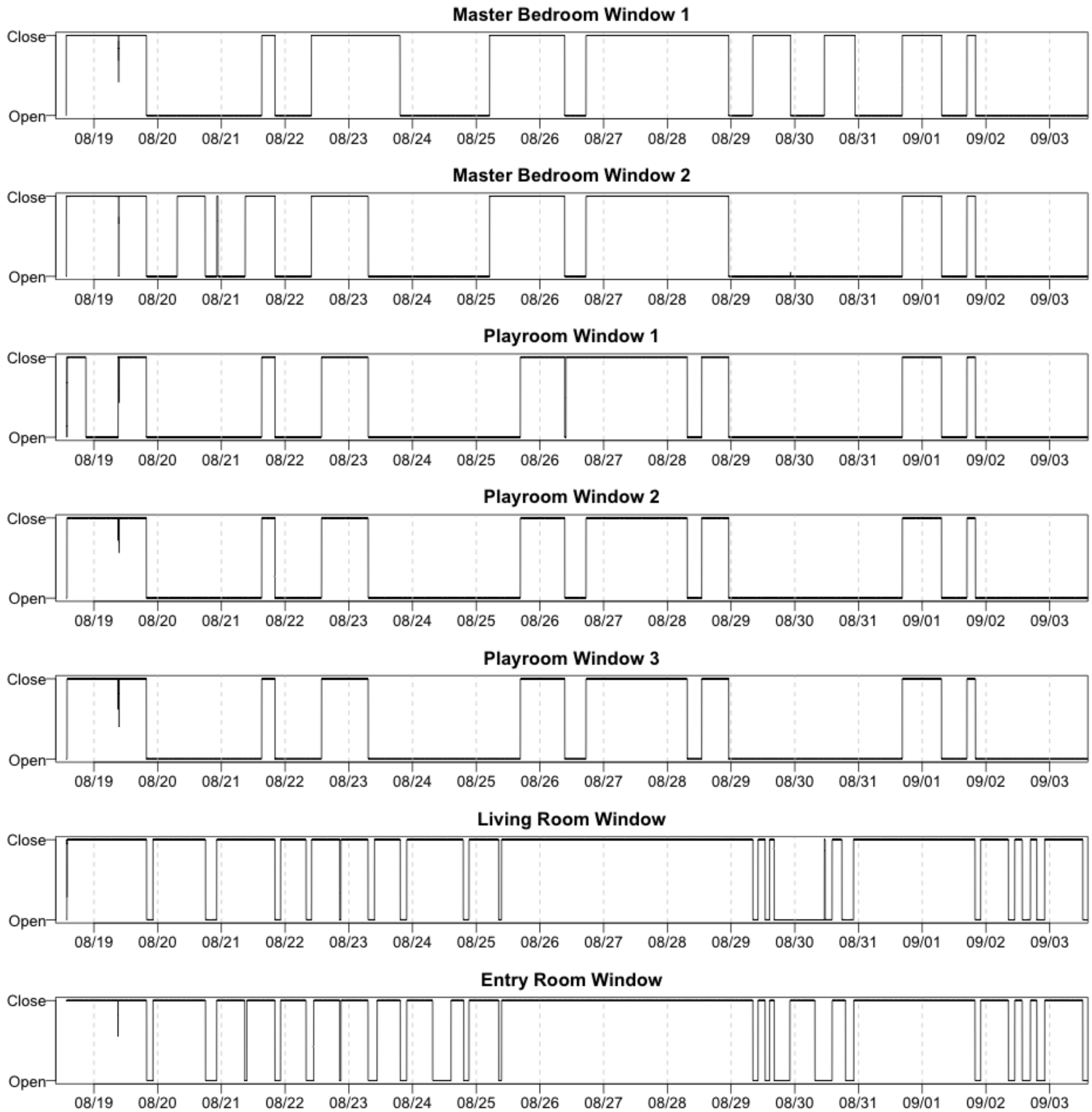


Figure 8 and Figure 9 show the temperature measured at the cooktop and oven in House 1 and House 2, respectively. Cooking events can be identified by a sudden increase in temperature, such as shown in Figure 10 and Figure 11 for example cooking events. The temperature data roughly correspond to the times and durations of cooktop and oven use reported by occupants in their daily activity logs.

Figure 8 Temperature measured outside of oven (in black) and on cooktop (lines in color indicating temperatures measured near different burners) in House 1.

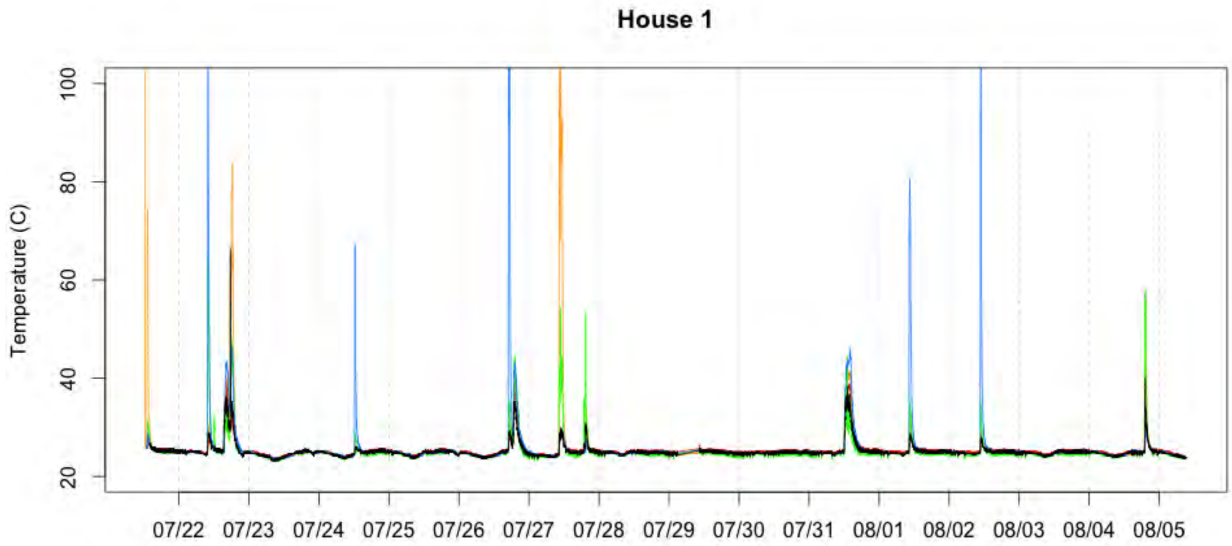


Figure 9 Temperature measured outside of oven (in black) and on cooktop (lines in color indicating temperatures measured near different burners) in House 2.

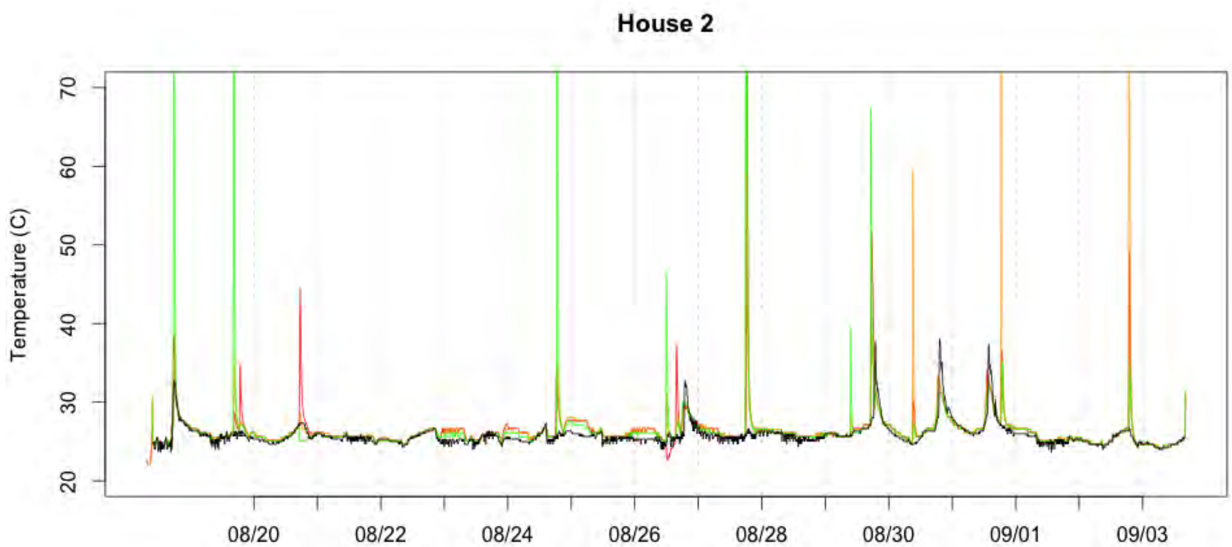
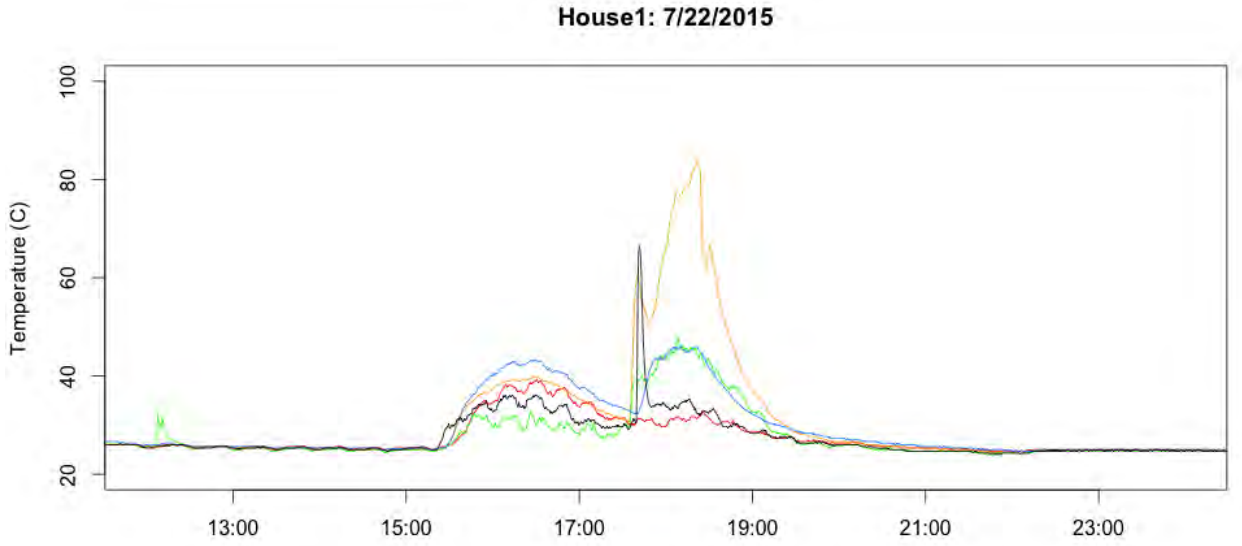
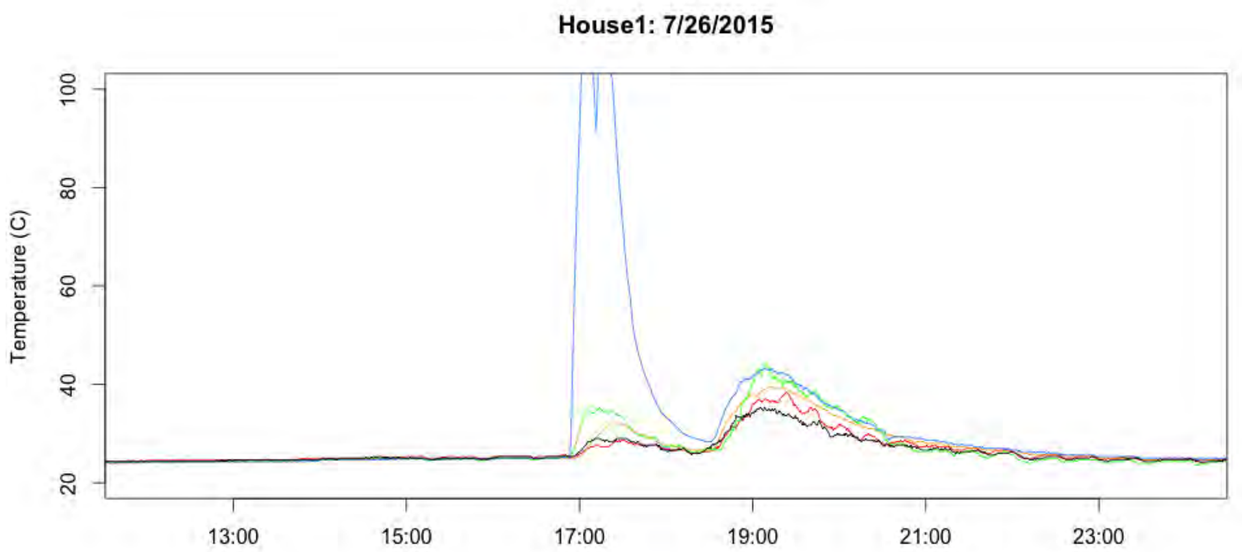


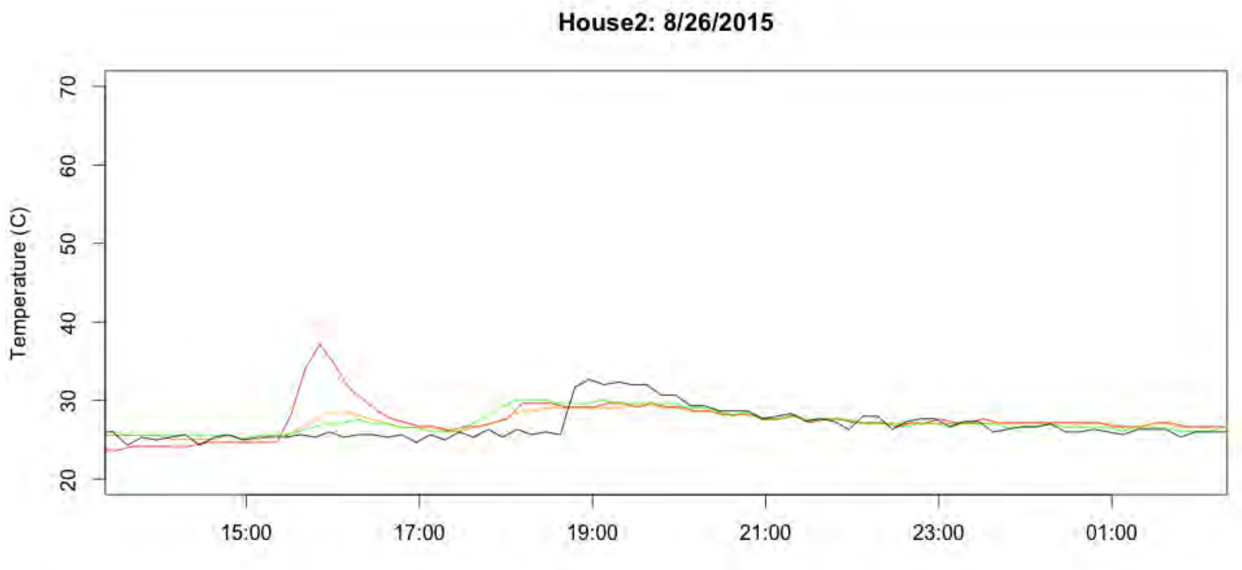
Figure 10 Temperature measured outside of oven (in black) and on cooktop (in colors).

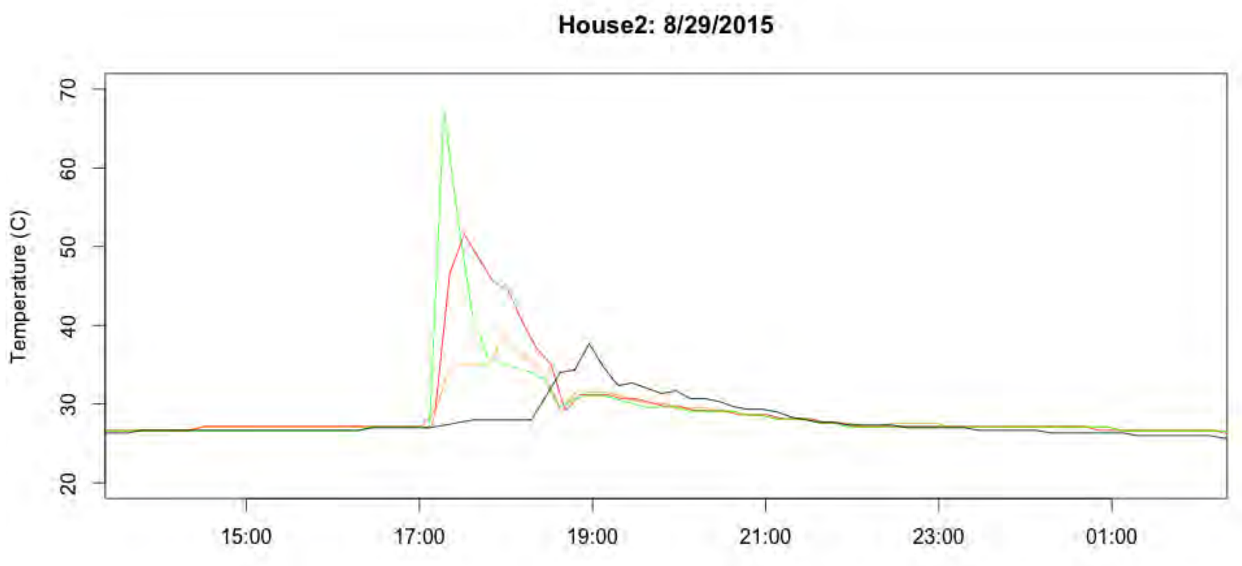




Occupants reported 45 minutes of oven use followed by 1.5 hours of cooktop use on July 22. On July 26, occupants reported 30 minutes of cooktop use followed by 30 minutes of oven use.

Figure 11 Temperature measured outside of oven (in black) and on cooktop (lines in color).

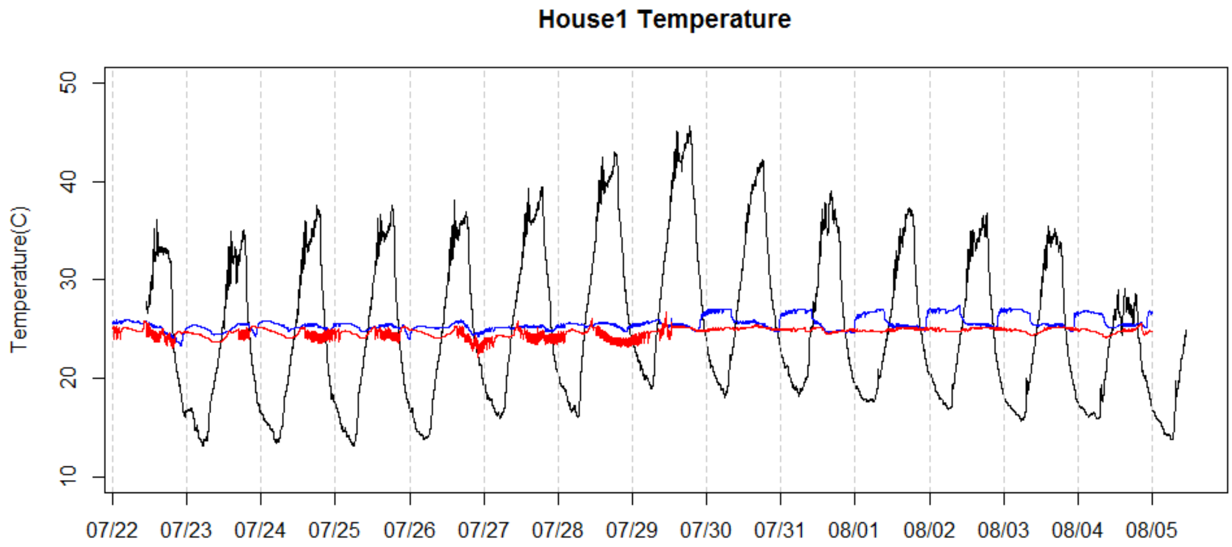




Occupants reported 30 minutes of cooktop use followed by 45 minutes of oven use on August 26. On August 29, occupants reported 40 minutes of cooktop use followed by 30 minutes of oven use.

Figure 12 and Figure 13 show the temperature and relative humidity measured outdoor in House 1 and 2, and also indoor in selected rooms. Indoor temperature and relative humidity were controlled within a fairly narrow range within both homes, despite that outdoor conditions varied greatly during the two weeks of monitoring. Usage of air conditioning could be inferred from rapid changes in temperature and relative humidity measured at a supply air grille of the central forced air system, as shown in Figure 14. From this data, House 1 used air conditioning more frequently than House 2, which likely explains the more stable indoor temperature in House 1 than in House 2.

Figure 12 Temperature and relative humidity measured outdoor (in black) and indoor (dinning room in red, master bedroom in blue).



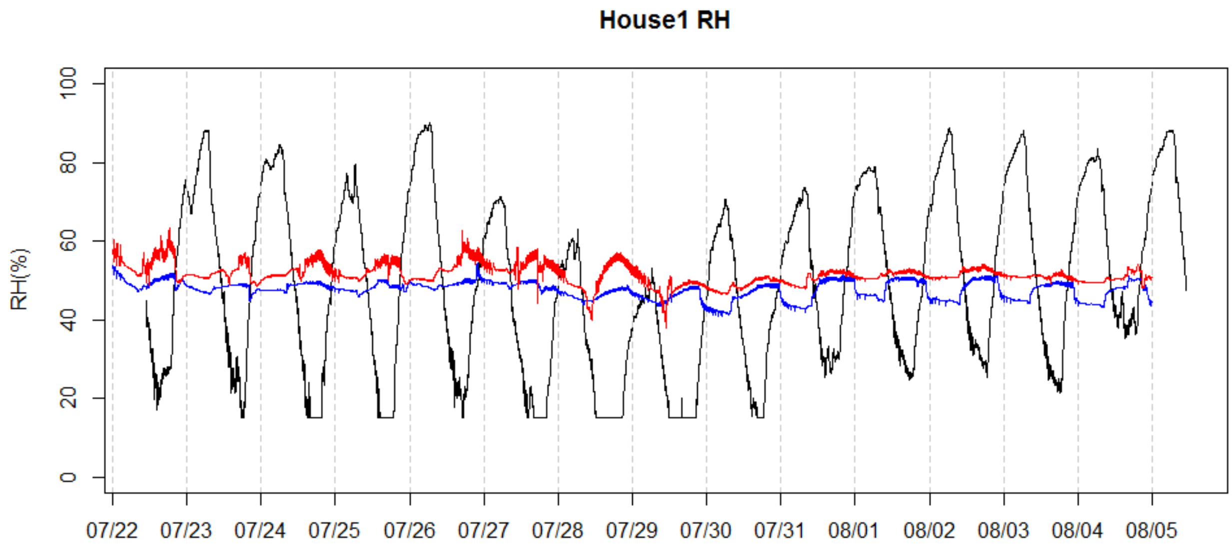
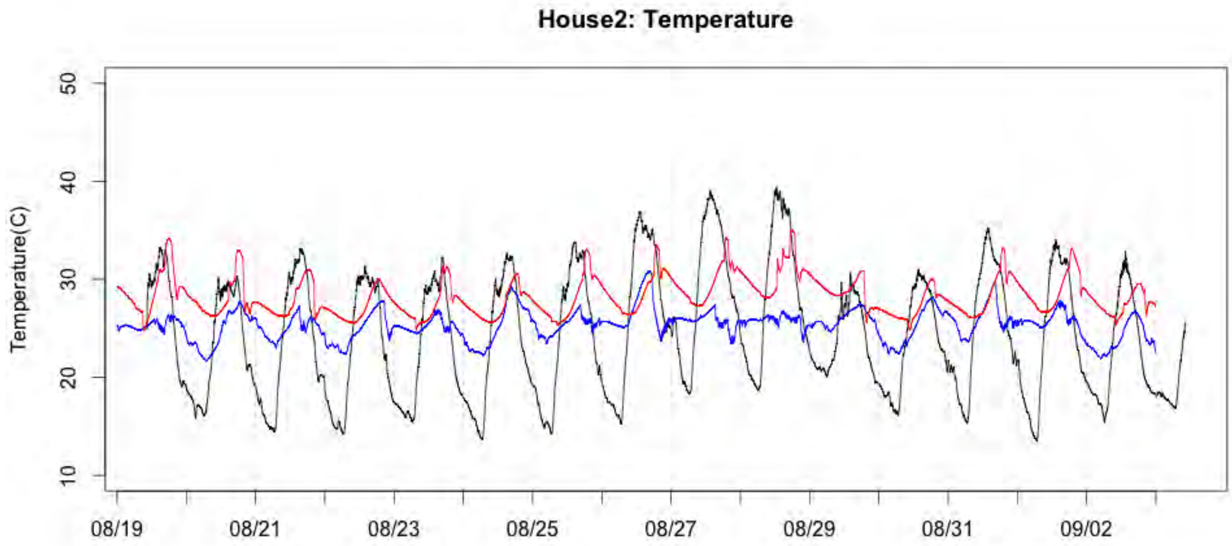


Figure 13 Temperature and relative humidity measured outdoors (black) and indoors (living room in red, master bedroom in blue).



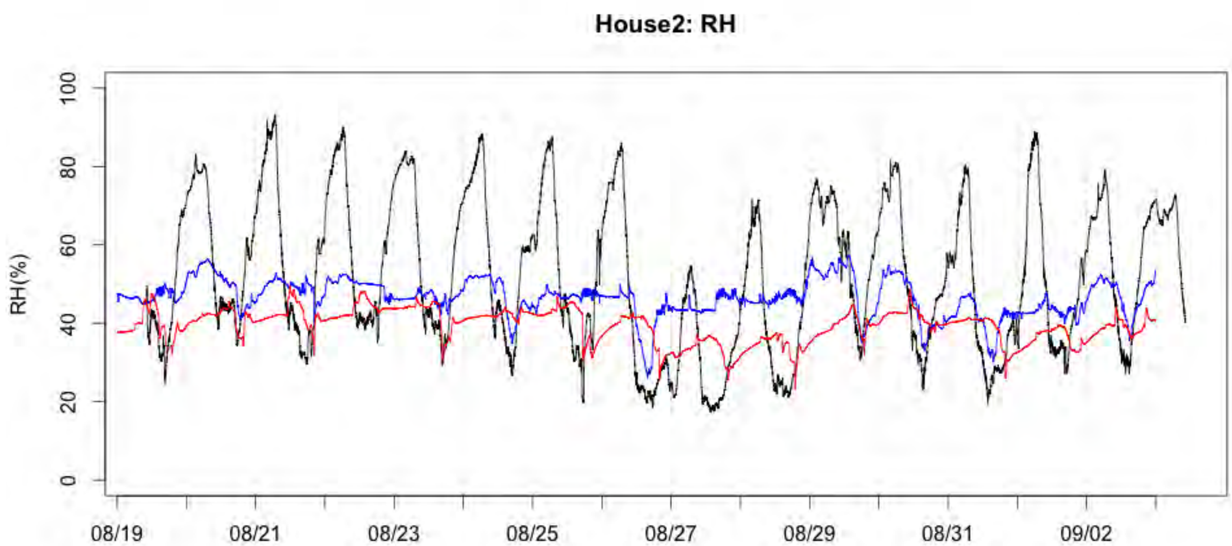
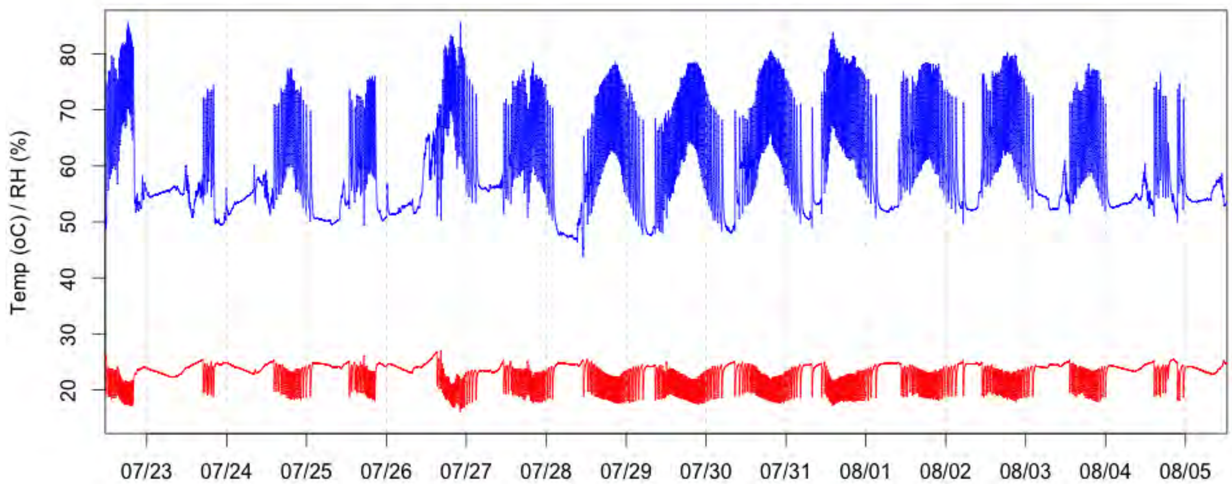


Figure 14 Temperature (in red) and relative humidity (in blue) measured at a supply air grille of the central forced air system in the two pilot homes.

House 1: Forced Air Supply Grille



House 2: Forced Air Supply Grille

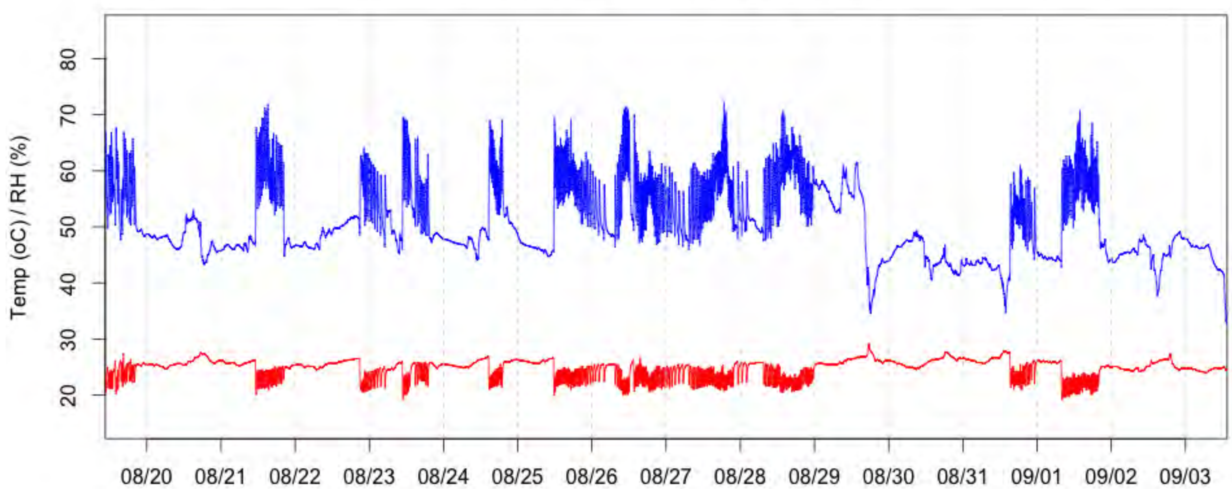
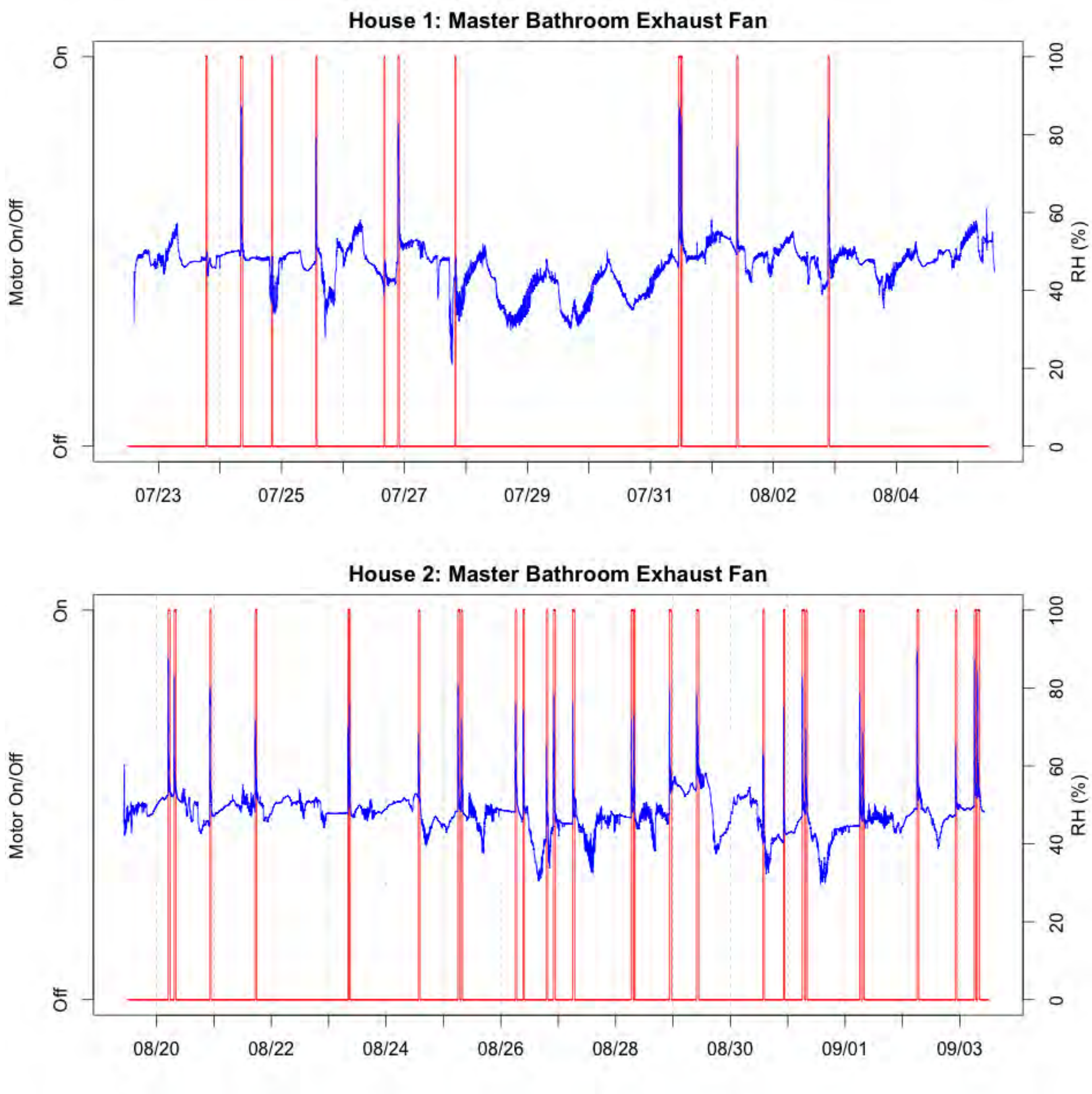


Figure 15 shows the relative humidity measured in the master bathroom, where the exhaust fan was controlled by a humidistat in both homes. It shows that the exhaust fan worked as expected by responding to a sudden increase in relative humidity, likely during showering.

Figure 15 Humidistat-controlled exhaust fans in master bathroom responding to a sudden increase in relative humidity.



Relative humidity was measured at the exhaust fan grille, as shown in Figure 16.

Figure 16 Data logger measuring temperature and relative humidity that was attached to a bathroom exhaust fan grille.

7 IAQ Sampling

Several contaminants that are indicators of IAQ and pollutants of a concern for health were measured for two weeks each in the two pilot test homes. Table 6 shows the list of instruments used to measure indoor air contaminant concentrations, the locations where instruments were placed, and the sampling resolution of the contaminant concentrations.

Table 6 Contaminant measurements made in the two pilot test homes.

Contaminant	Instrument	Sampling Locations	Sampling Resolution
$PM_{2.5}$	MetOne BT-642	Outdoor	1-minute
	MetOne BT-645	Indoor main (dinning or living room)	1-second
	TSI DustTrak II 8530	Indoor main	2-minute
	Thermo pDR-1500	Indoor main	1-second
PM counts	MetOne BT-637	Indoor main	1-minute, 6-channel*
	Dylos 700	Indoor main	1-minute, 2-channel >0.5 and >2.5 um
CO_2	Extech SD-800	Outdoor, indoor main, kitchen, master and other bedrooms	1-minute
CO	Lascar USB-EL-300	Outdoor, Indoor main	1-minute
NO_2	Aeroqual NO_2 monitor	Indoor main, master bedroom	1-minute
	Passive Ogawa samplers	Outdoor, indoor main, master bedroom	1-week
Formaldehyde	Shinyei formaldehyde monitor	Indoor main, master bedroom	30-minute
Volatile aldehydes	Passive DNPH cartridges	Outdoor, indoor main, master bedroom	1-week
Speciated VOCs#	Passive sorbent tubes	Outdoor, indoor main, master and other bedrooms, laundry room, garage	1-week

*The 6-channel size bins were >0.3, >0.5, >0.7, >1.0, >2.5, >10 um in House 1, and >0.3, >0.4, >0.5, >0.7, >1.0, >2.5 um in House 2.

#Method allows for determination of specific, individual volatile organic compounds. These samples were analyzed for 44 compounds.

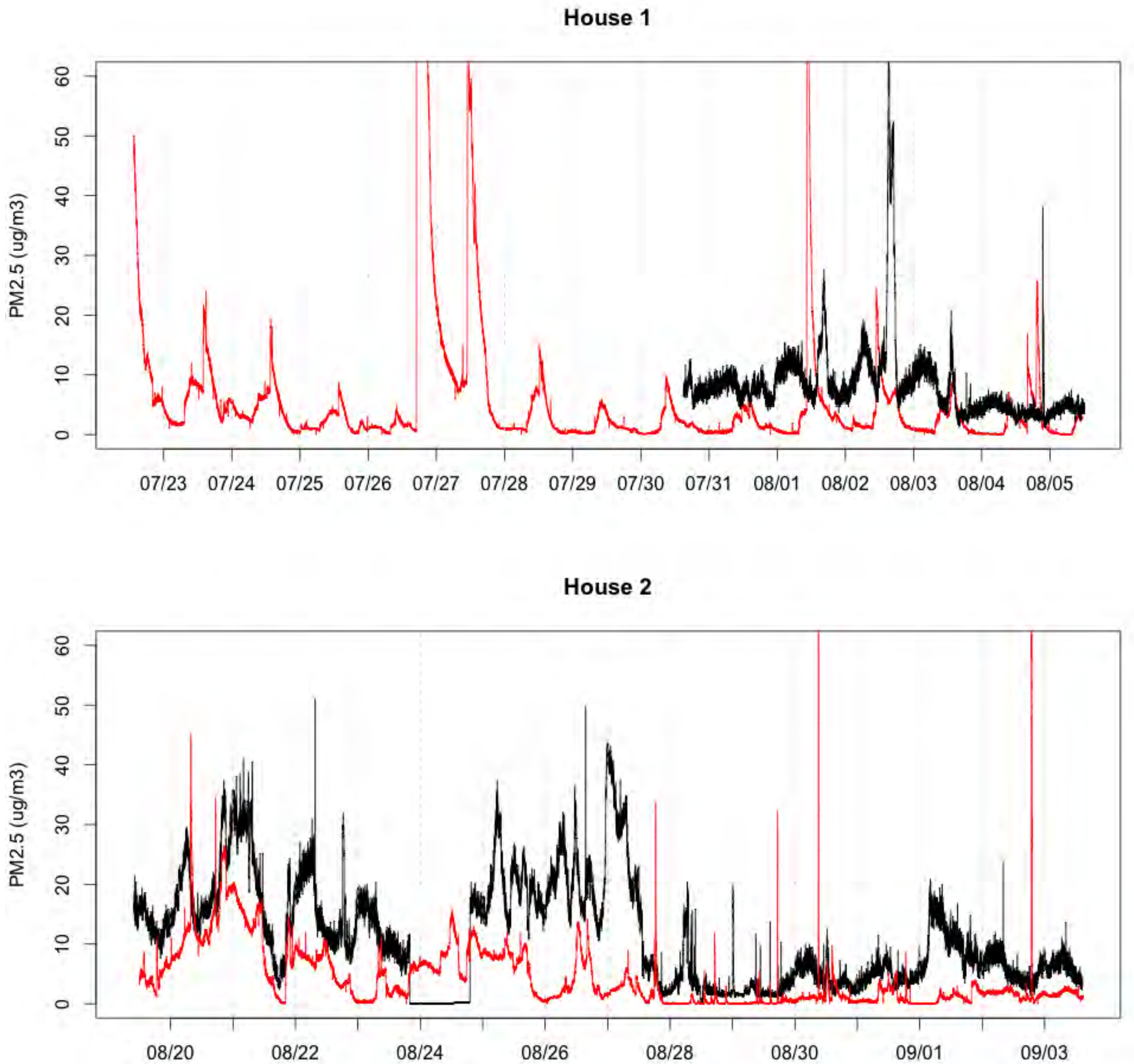
7.1 Particulate Matter (PM)

Indoor particulate matter (PM) concentrations were measured using different types of instruments to compare performance. Indoor concentrations tended to be lower than outdoors on average in the two homes. However, both homes had $PM_{2.5}$ sources that led to $PM_{2.5}$ concentrations sharply rising to levels that were higher and, in some cases, much higher than coincident outdoor concentrations for periods of tens of minutes to more than 10 h in one case. High $PM_{2.5}$ concentrations were measured in House 1 during times when cooking occurred (see Appendix C-3). In House 2, cooking was a less important source of $PM_{2.5}$.

Figure 17 shows outdoor $PM_{2.5}$ concentrations measured using a MetOne BT-642, and the indoor $PM_{2.5}$ concentrations measured using a BT-645. The BT-642 performs an auto-zero test once every hour (manufacturer default). The BT-645 does not have this function. All $PM_{2.5}$ instruments were recently calibrated by manufacturers. No adjustment factor was applied to the measured values.

The 24-hour average and daily 1-hour maximum $PM_{2.5}$ concentrations measured by other instruments indoor are shown in Figure 18 (House 1) and Figure 19 (House 2). $PM_{2.5}$ mass concentrations were estimated from particle number concentrations or "counts" measured by the Dylos and MetOne BT-637 instruments assuming spherical particles with a density of 1.65 g/cm^3. The Dylos measures number concentration for particles >0.5 and >2.5 um. To estimate $PM_{2.5}$ mass concentrations from these data, particles measured between 0.5 and 2.5 um were assumed a diameter of 1 um. The BT-637 measures number concentrations for particle >0.3, >0.5, >0.7, >1, >2.5, and >10 um in House 1, and >0.3, >0.4, >0.5, >0.7, >1, and >2.5 um in House 2. Particle counts measured in the first four bins (0.3-0.5, 0.5-0.7, 0.7-1, and 1-2.5 um) were used to estimated $PM_{2.5}$ mass concentrations in House 1. Particles diameters of 0.4, 0.6, 0.85, and 1.75 um were assumed for those four bins, respectively. A similar method was used for House 2, where particle diameters of 0.35, 0.45, 0.6, 0.85 and 1.75 um were assumed for the first five bins.

Figure 17 $PM_{2.5}$ concentrations measured outdoor (black) and in the main living space (red): dining room in House 1, living room in House 2.



Operator error led to outdoor $PM_{2.5}$ only available for week 2 in House 1.

Figure 18 Comparison of $PM_{2.5}$ mass concentrations measured by different particle instruments in House 1.

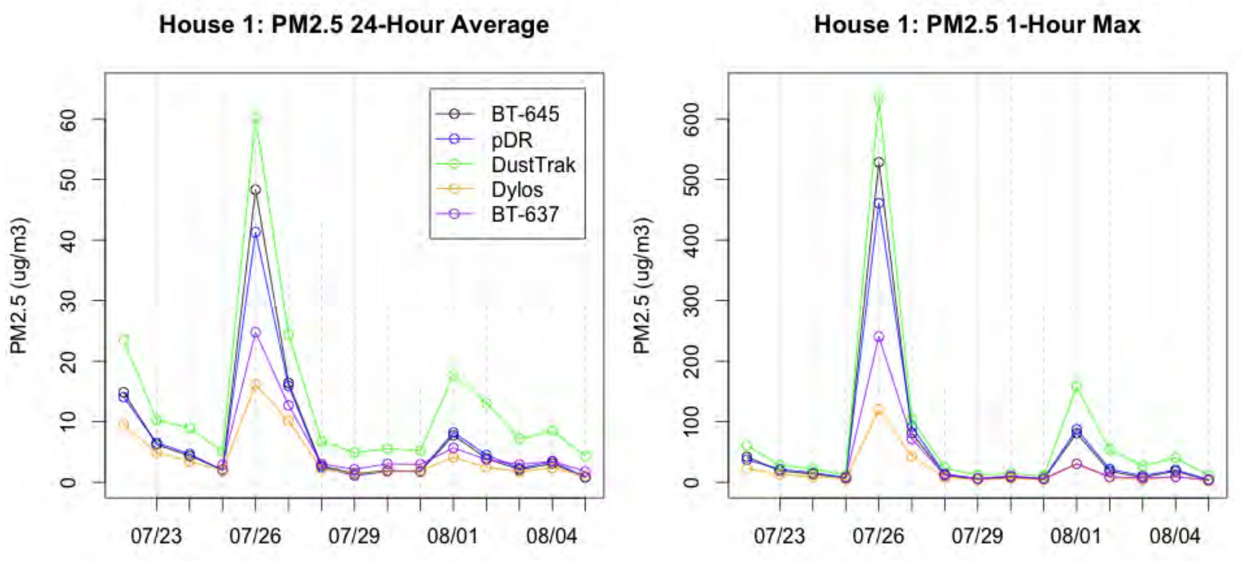


Figure 19 Comparison of $PM_{2.5}$ mass concentrations measured by different particle instruments in House 2.

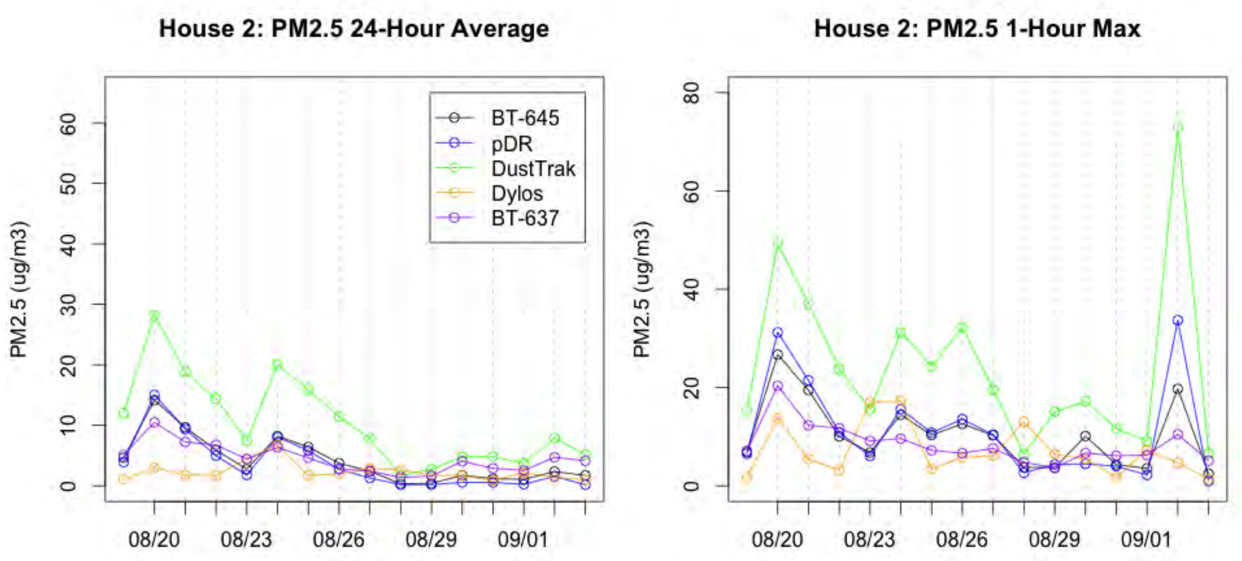


Table 7 compares the 24-hour average $PM_{2.5}$ concentrations measured by the other four instruments in comparison with the MetOne BT-645. The intercept, slope, and correlation coefficient (R^2) were obtained from a linear least-square regression fit of the 24-hour average $PM_{2.5}$ concentrations as shown in Figure 18 (House 1) and Figure 19 (House 2). Measurements by the pDR and DustTrak, which used similar measurement principle as the BT-645, were highly correlated ($R^2 = 0.97$ or greater) with the BT-645. Measurements by the Dylos and BT-637, which measured particle counts instead of $PM_{2.5}$ mass, agreed less well with the BT-645, especially in House 2. Overall, measurements by the pDR agreed with the BT-645 most closely in magnitude, with slope ~1, and intercept ~0. In comparison, DustTrak measured higher $PM_{2.5}$ mass than the BT-645, whereas the Dylos and BT-637 gave lower estimates of $PM_{2.5}$. This may be explained by the difference in wavelength of the laser light source used by the BT-645 (670 nm), pDR (880 nm), and DustTrak (780 nm), leading to different sensitivity to particles in the size range of 0.1 um. The Dylos and BT-637 counts particles >0.5 um and >0.3 um, respectively, so some fractions of the $PM_{2.5}$ mass made up by particles smaller than the cutoff diameter were not accounted for. Another potential contributing factor is the difference in particle density between indoor particles (assumed 1.65 g/cm^3) and the test dust used by manufacturers (2.6 g/cm^3) to calibrate instruments such as the BT-645, pDR, and DustTrak.

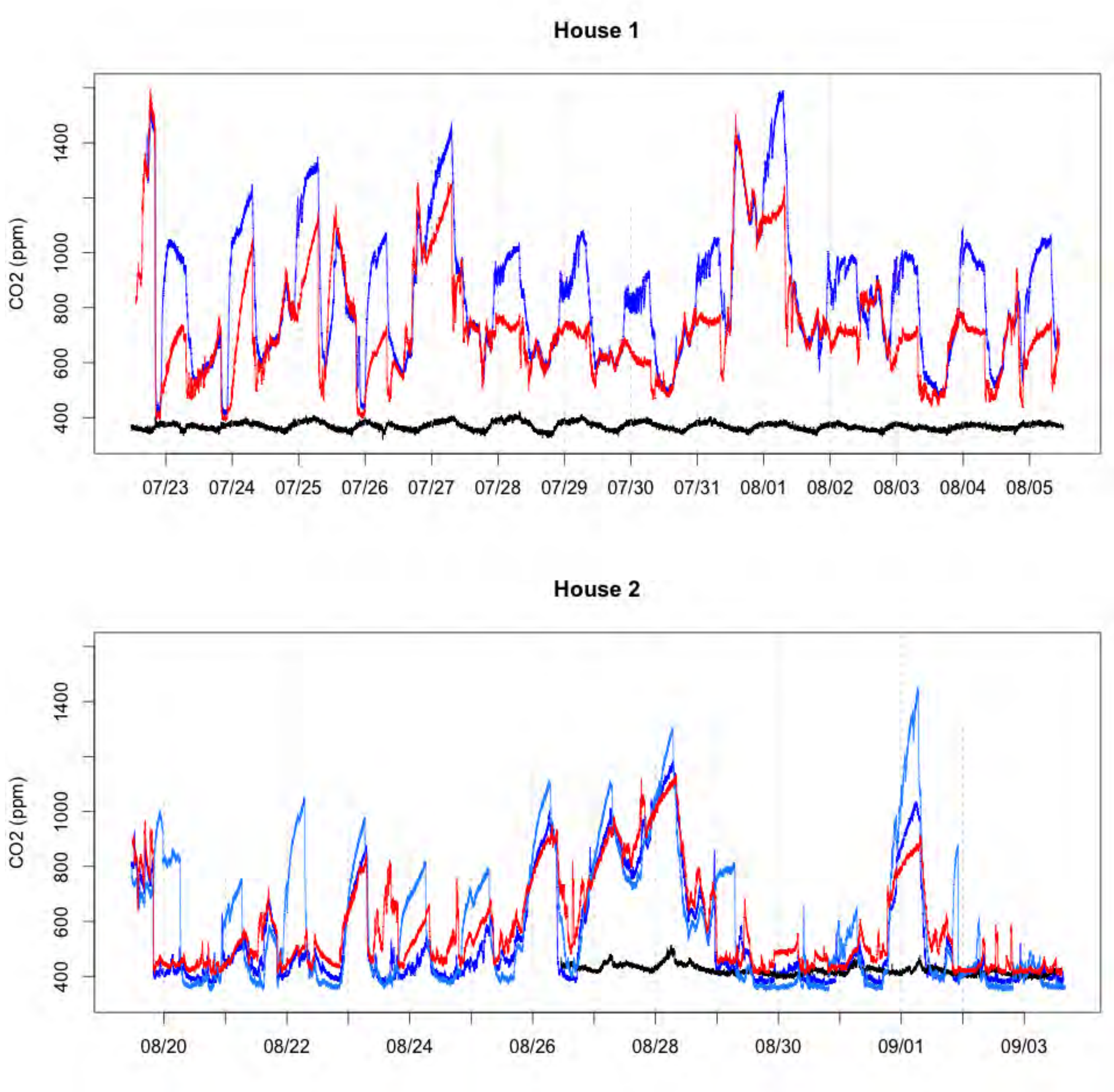
Table 7 Comparison of 24-hour average $PM_{2.5}$ mass concentrations measured by different particle instruments with respect to MetOne BT-645.

	House 1			**House 2**		
	Intercept (ug/m^3)	Slope (-)	R2 (-)	Intercept (ug/m^3)	Slope (-)	R2 (-)
pDR	-0.75	1.16	1.00	0.98	0.90	0.99
DustTrak	-3.58	0.83	0.98	-1.19	0.51	0.97
Dylos	-3.89	2.70	0.90	2.28	0.82	0.04
BT-637	-3.88	2.01	0.98	-2.57	1.50	0.84

7.2 Carbon Dioxide (CO_2)

CO_2 concentrations were monitored in multiple indoor locations. Data from the pilot test homes (Figure 20) show that indoor CO_2 concentrations can vary substantially from room to room. Sensors used to monitor the open/close state of doors showed that in both houses, the master bedroom doors were closed all the way only for about an hour on average each day. However, doors may have been closed partly, which could still inhibit mixing of air between the master bedroom and the rest of the house. The mixing of air between the master bedroom and the rest of the house may have been affected by the runtime of the air handler system during some nights. In House 1, the air handler ran about 5 hours per day on average. In House 2, the air handler ran about 9 hours per day on average. The longer air handler runtime in House 2 would explain CO_2 concentrations being more uniform spatially than in House 1. Window use overnight would also explain lower CO_2 concentrations in House 2 (Figure 7).

Figure 20 CO_2 concentrations measured outdoor (black), main indoor living space (red), master bedroom (blue), and in another bedroom (light blue, House 2 only).



Operator error led to outdoor CO_2 data available only for week 2 in House 2.

7.3 Carbon Monoxide (CO)

Real-time CO concentrations measured in the two pilot test homes were generally below detection limit (<0.5 ppm). Maximum CO concentrations were below 3 ppm.

7.4 Nitrogen Dioxide (NO_2)

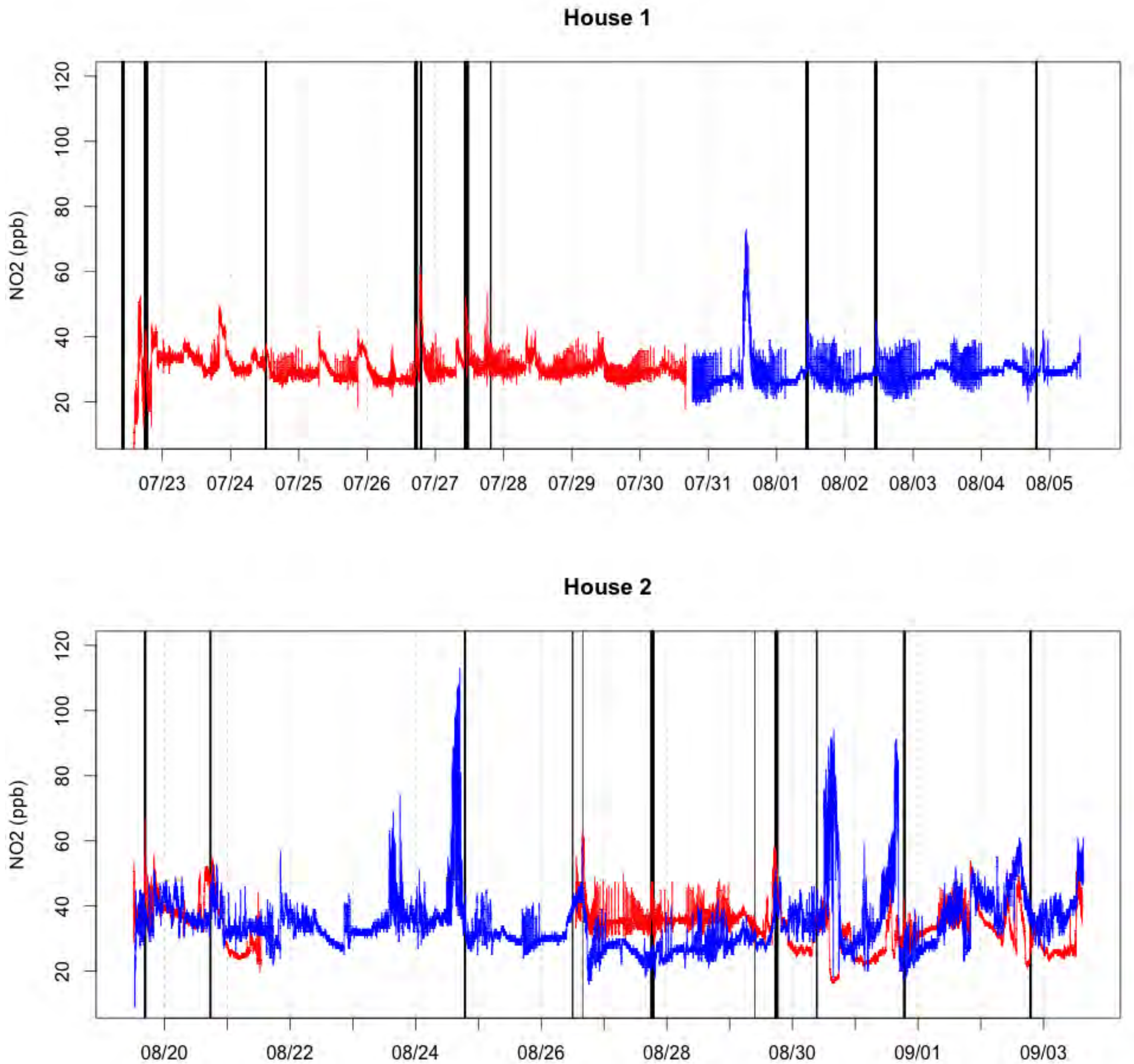
Table 8 shows the NO_2 concentrations measured using passive samplers (Mullen et al., 2015). The outdoor concentrations measured agree well with ambient monitoring data. The nearest ambient monitoring site with available hourly NO_2 data is located at downtown Sacramento (T Street) for House 1, and Bethel Island (Contra Costa county) for House 2, where the two-week average concentrations were about 5 ppb and 3 ppb, respective.

Table 8 NO_2 concentrations measured using passive Ogawa samplers.

		NO_2 Concentrations (ppb)	
		House 1	House 2
Outdoor	Week 1	3.4	5.5
	Week 2	2.9	3.8
Indoor Main	Week 1	4.5	4.8
	Week 2	3.6	4.0
Master Bedroom	Week 1	3.6	4.9
	Week 2	2.9	3.4
Garage	Week 2	1.5	--

Figure 21 presents time-resolved NO_2 data measured with the Aeroqual instruments. The instrument placed in the main living space required a span (slope = 0.65) and offset (-9 ppb) correction. This correction has been applied to the NO_2 concentrations plotted in Figure 21. The time resolved data at different locations in House 2 suggest that the instruments are responding to increases in NO_2 in the home. The increases in NO_2 in the dining / living room when cooking occurred (with gas cooking burners producing NO_2) suggests the instrument has utility at identifying NO_2 emission events. But a comparison to the well-validated time-integrated measurements collected at the same location (Table 8) suggests - as a minimum source of error - that the two Aeroqual measured higher NO_2 concentrations. Thus, this instrument requires a careful calibration check prior to each deployment.

Figure 21 NO_2 concentrations measured by real-time instrument in the main indoor living space (red) and in the master bedroom (blue).



Cooking events, as defined by cooktop temperature data, are indicated by black lines. Operator error led to data loss in House 1 such that only 1 week of data was collected at each of two sampling locations. In House 2, instrument in the living space was powered off for several days (reason unknown).

7.5 Formaldehyde

Figure 22 shows the formaldehyde concentrations measured by the real-time instruments in the common area and in the master bedroom of each home. Indoor formaldehyde concentrations measured passively using DNPH cartridges were about 50 ppb in House 1, and about 25 ppb in House 2 (Table 9). Lacking more suitable data, the passive uptake rates determined by Mullen et al. (2013) for winter conditions were used to calculate these concentrations. Passive measurements were significantly higher than the 25-35 ppb and 15-25 ppb respectively indicated by the real-time measurements. Both the passive and the real-time methods suggested that House 1 had higher formaldehyde concentrations than House 2 (Table 10). However, there are significant differences between the formaldehyde concentrations measured using the two sampling methods. The passive uptake rates determined by Mullen et al. (2013) will need to be checked against the well-established active sampling method using DNPH cartridges for a broader range of outdoor temperatures. Performance of the real-time formaldehyde monitors, which had been tested in laboratory setting (Carter et al., 2014), also requires further comparison with the DNPH method for field applications.

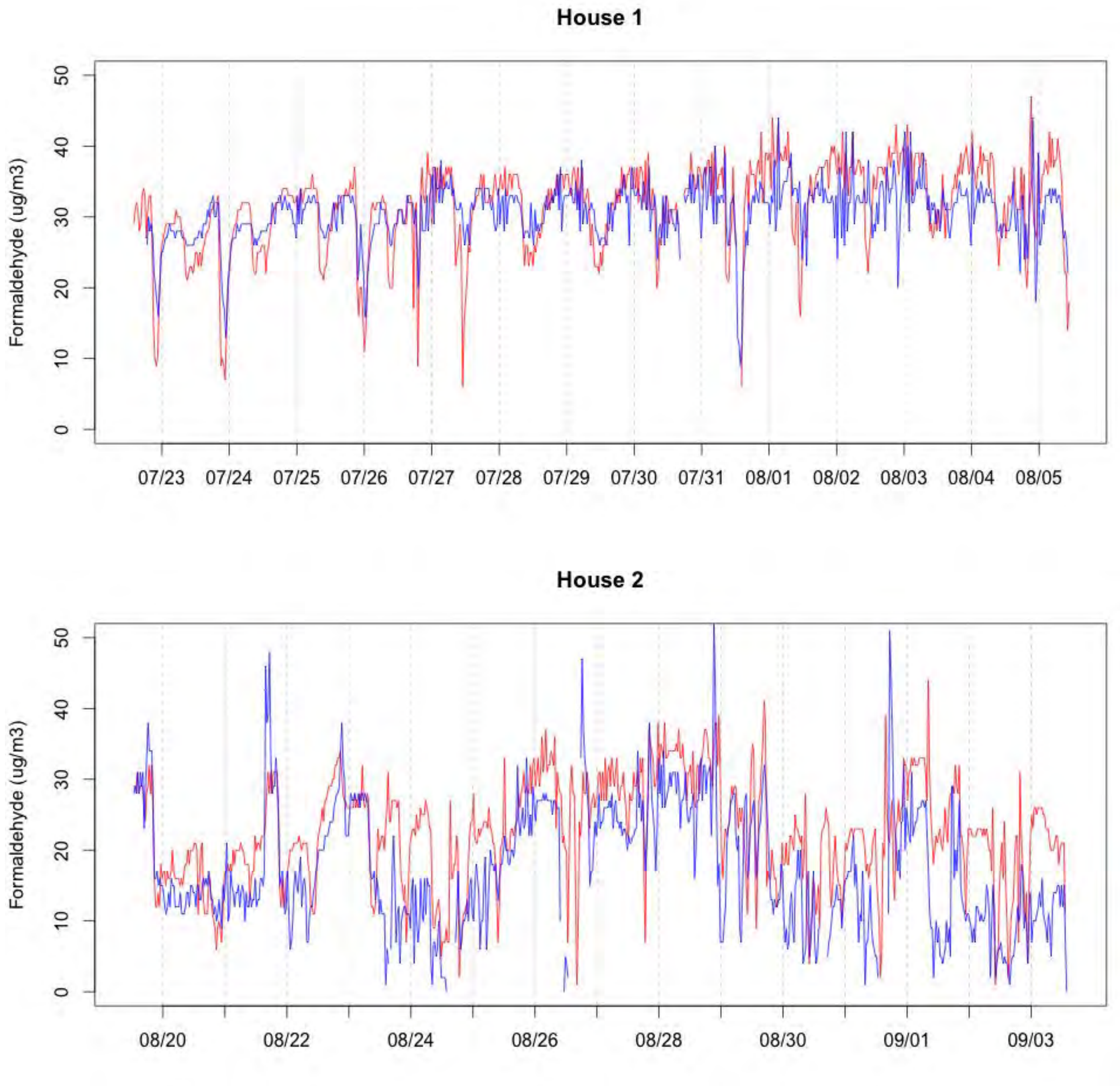
Table 9 Formaldehyde concentrations measured using passive DNPH cartridges.

		Formaldehyde Concentrations (ug/m^3)	
		House 1	**House 2**
Outdoor	Week 1	12	19
	Week 2	10	15
Indoor Main	Week 1	47	29
	Week 2	48	25
Master Bedroom	Week 1	47	24
	Week 2	56	21

Table 10 Average formaldehyde concentrations measured by the real-time instruments.

		Formaldehyde Concentrations (ug/m^3)			
		House 1		**House 2**	
		Instrument 1	**Instrument 2**	**Instrument 1**	**Instrument 2**
Indoor Main	Week 1	29	31	21	--
	Week 2	34	34	24	22
Master Bedroom	Week 1	30	25	17	16
	Week 2	32	28	18	16

Figure 22 Formaldehyde concentrations measured at 30-minute time integrated intervals in the main indoor living space (red) and in the master bedroom (blue).



7.6 Volatile Organic Compounds (VOCs)

Table 11 shows the maximum 1-week averaged VOCs concentrations measured in the two pilot test homes. Also shown for comparison are the maximum 24-hour averaged VOCs concentrations measured by Offermann (2009) in 108 new California homes, and the health guidelines used in that study as reference. Offermann (2009) measured 20 VOCs that were selected based on California Air Resources Board indoor air guidelines, California Office of Environmental Health Hazard Assessment Chronic exposure levels, and other available health standards. The study found that none of the maximum indoor concentrations of the 20 VOCs measured in 108 new California homes built between 2002–2004 exceed any of the indoor air contaminant guidelines (Table 11). No VOCs at concentrations above health guidelines were found.

In addition to the 20 VOCs listed in Table 11, another 24 VOCs were also analyzed. Many of these compounds were below quantitation limits in many of the samples. However, a few VOCs were above odor thresholds, such as from fragrances used in House 1, e.g., hexanal (75 to 110 ug/m3), a-pinene (280 to 350 ug/m3), and d-limonene (35 to 45 ug/m3). House 1 also had relatively high concentrations of D5-siloxanes (100 to 200 ug/m3), likely emitted from personal care products. Table 12 shows the sum of 44 VOCs measured. In comparison, House 2 had relatively low VOCs concentrations. The concentrations measured in the central location (e.g., great room) generally represent the range of indoor concentrations found indoors.

Table 11 Maximum indoor VOCs concentrations in comparison to health guidelines.

	Ref Health Guideline (ug/m^3)	Maximum Indoor Concentration (ug/m^3)				
		Offermann (2009)	HENGH Pilot Test			
			House 1	Garage	House 2	Garage
Tetrachloroethane	35 [a]	23	0.1	2	0.1	0.1
Naphthalene	9 [a]	5	0.2	0.2	0.2	1.5
Toluene	300 [a]	115	5	9	8	47
Ethylene glycol	400 [a]	120	--	--	--	--
1,4-Dichlorobenzene	800 [a]	219	1.3	1.2	0.04	0.03
Benzene	60 [a]	15	2	0.3	2	11
m,p-Xylene	700 [a]	60	13	8	4	30
Styrene	900 [a]	62	14	19	2	1.2
2-Butoxyethanol	3000 [b]	180	18	7	110	5
Trichloromethane	300 [a]	12	2	0.2	0.4	0.2
Phenol	200 [a]	7	4	7	3	2
o-Xylene	700 [a]	20	7	3	2	10
a-Pinene	2800 [b]	65	352	73	32	12
1,2,4-Trimethylbenzene	3125 [b]	13	0.4	0.5	1.3	11
1-Methyl-2-pyrrolidinone	2000 [b]	8	--	--	--	--
n-Hexane	700 [a]	24	0.8	1.0	2	14

	Ref Health Guideline (ug/m^3)	Maximum Indoor Concentration (ug/m^3)				
		Offermann (2009)	HENGH Pilot Test			
			House 1	Garage	House 2	Garage
Vinyl acetate	200 [a]	0.3	--	--	--	--
Caprolactam	500 [b]	0.1	--	--	--	--
Hexanal	na	35	110	59	56	17
d-Limonene	na	152	43	9	150	4

a OEHHA chronic reference exposure levels.

b 1/40th of the 8-hour occupational health guideline in ug/m3 (e.g., Cal/OSHA permissible exposure limits).

8 Passive Tracer Gas Measurements

Three perfluorocarbon tracers (PFTs), PDCB (C_6F_{12}), PMCH (C_7F_{14}), and mPDCH (C_8F_{16}), were used to estimate the dilution rate of an indoor emitted air contaminant in the two pilot test homes. Five to seven PFT emitters of each compound were distributed in the pilot test homes. One of three PFTs was placed in the garage to estimate the transfer rate of chemicals into the house from the garage. The other two PFTs were distributed in the main living space. PFTs concentrations were measured passively using sorbent tubes. The 1-week average concentrations were typically on the order of 1 ppb.

Measured PFTs concentrations, C (g/m^3), were used to calculate the dilution rate of a constant indoor-generated chemical, k (h^{-1}), as follows:

$$k\ (h^{-1}) = E\ (g/h)\ /\ [\ C\ (g/m^3) \times V\ (m^3)\ ]$$

where E (g/h) is the emission rate measured by weighing PFT vials before and after at the test house, and V (m^3) is the house volume estimated by floor area times the ceiling height (see Table 1). Placement of PFTs emitters and their emission rates are described in Table 12 (House 1) and Table 13 (House 2). House average dilution rates were computed using average PFTs concentrations measured in Table 14 and Table 15.

In House 1, the dilution rate of an indoor emitted air contaminant was about 0.2 h^{-1}, calculated based on PMCH that was distributed in the living space (Table 14). Results suggest that with the exception of Bedroom 2 in week 2, dilution of a distributed source was spatially uniform in House 1. The dilution rate estimated using PDCB that was emitted from the kitchen area only gave similar results.

In House 2, dilution rate was about 0.3 h^{-1} in week 1, and slightly lower at 0.2 h^{-1} in week 2 (Table 15). The dilution rates calculated for the lower floors were very different if mPDCH or if PDCB measurements were used. On the other hand, the dilution rates calculated for the upper floors were more similar. This suggests that the house is not well mixed, especially for chemicals emitted from the upper floors.

Table 12 Placement of PFTs emitters in House 1 and their emission rates determined by weighing of vials.

	Week 1	Week 2
PDCB – 5 emitters distributed in kitchen area (connected to great room)		
E (mg/h) – Per Vial	0.67 (0.64–0.75)	0.60 (0.57– 0.68)
Total	3.33	2.99
PMCH – 5 emitters distributed in throughout the house		
E (mg/h) – Per Vial	0.68 (0.50–1.14)	0.61 (0.45–1.01)
Total	3.42	3.04
mPDCH – 5 emitters distributed in attached garage		
E (mg/h) – Per Vial	0.38 (0.32–0.49)	0.34 (0.30–0.43)
Total	1.88	1.70

Table 13 Placement of PFTs emitters in House 2 and their estimated emission rates.

	Week 1	Week 2
PDCB – 7 emitters distributed in upper floor		
E (mg/h) – Per Vial	0.57 (0.55–0.61)	0.58 (0.55–0.62)
Total	4.02	4.09
PMCH – 6 emitters distributed in the attached garage		
E (mg/h) – Per Vial	0.72 (0.48–1.51)	0.83 (0.50–2.05)
Total	4.33	4.99
mPDCH – 7 emitters distributed in lower floor		
E (mg/h) – Per Vial	0.26 (0.24–0.29)	0.26 (0.25–0.30)
Total	1.81	1.85

Table 14 Estimated dilution rate (h-1) based on PFTs measurements in House 1.

	Week 1		Week 2	
	PMCH (distributed throughout house)	**PDCB (emitted from kitchen)**	**PMCH (distributed throughout house)**	**PDCB (emitted from kitchen)**
Master Bedroom	0.24	0.33	0.22	0.31
Master Bathroom	--	--	0.25	0.32
Bedroom 2	0.24	0.29	0.47	0.56
Dining Room	0.24	0.26	0.22	0.24
Great Room	0.22	0.23	0.20	0.22
Kitchen*	0.22	0.21	0.20	0.17
Laundry Room	0.26	0.28	0.24	0.27
Hallway	--	--	0.22	0.26
Den	--	--	0.23	0.26
House Average	0.24	0.26	0.23	0.26

*** Kitchen is connected to the great room.**

Table 15 Estimated dilution rate (h-1) based on PFTs measurements in House 2.

	Week 1		Week 2	
	mPDCH (emitted from lower floor)	PDCB (emitted from upper floor)	mPDCH (emitted from lower floor)	PDCB (emitted from upper floor)
Rooms in upper floor				
Master Bedroom	0.48	0.40	0.26	0.29
Bedroom 2	0.55	0.40	0.31	0.31
Bedroom 3	0.52	0.38	0.31	0.30
Playroom	0.46	0.40	0.31	0.30
Rooms in lower floor				
Living Room*	0.26 (0.26)	0.55 (0.56)	0.20 (0.21)	0.36 (0.37)
Laundry Room	0.27	0.64	0.21	0.42
Bedroom 4	0.20	0.42	0.19	0.43
House Average	0.33	0.45	0.24	0.34

*** Replicate sample in parenthesis.**

The percentage of PFTs entering into the house from the attached garage was calculated using the same method used by Offermann (2009).

$$F\ (\%) = C_h\ (g/m^3) \times k\ (h^{-1}) \times V\ (m^3) / E_g\ (g/h)$$

where E_g (g/m³) is the emission rate of PFT released in the attached garage, and C_h (g/m³) is the concentration of that PFT measured inside the house.

The percentage of PFTs entering into House 1 was about 10% for both sampling weeks. In House 2, the estimated percentage was 27% for week 1, and 21% for week 2. These results were calculated using house average dilution rates based on PMCH measurements in House 1, and mPDCH measurements in House 2.

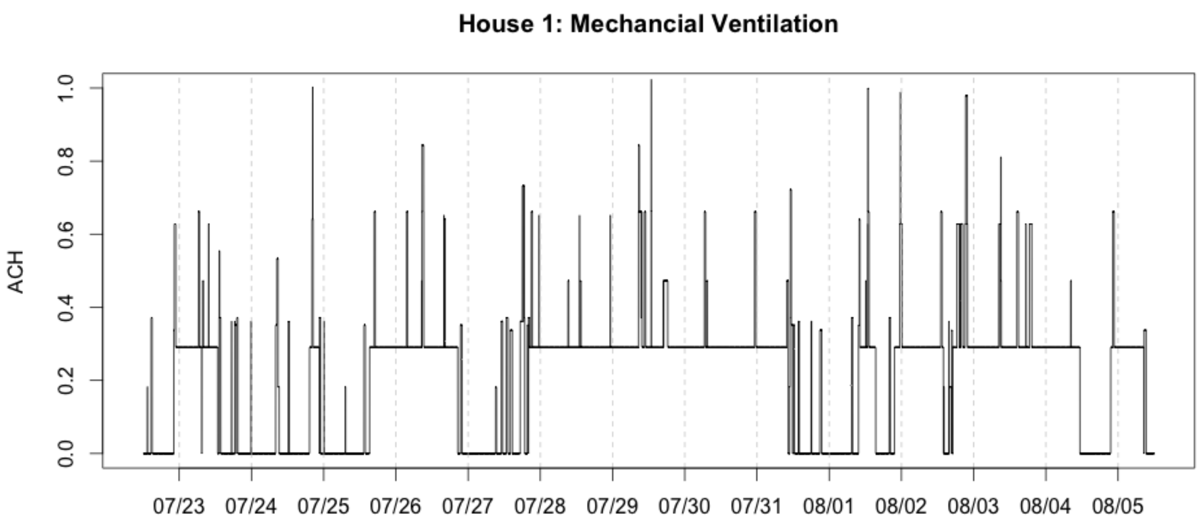
The percentage of air in the house that came from the garage can be calculated by the ratio of C_h/C_g, where C_g (g/m³) is the concentration of the PFT released in the attached garage. Using PFT concentrations shown in Appendix C-4, House 1 had 2% of air coming from garage. House 2 had 10% of first floor air, and 5% of second floor air, coming from garage.

These estimates suggested that even though a significant fraction of garage emissions (in this case, 10% to 27%) entered into the house, the airflow from the garage only made up a minor (2% to 10%) of the total air exchange of the house. The result is that the in-house concentrations of contaminants where garage was the likely source (e.g., benzene, toluene, and xylene) were low relative to health guidelines (see Table 11).

9 Calculation of Mechanical Ventilation Rates

Figure 23 shows the mechanical ventilation calculated by summing the airflow from the three bathroom exhaust fans, range hood, and clothes dryer in House 1. The average mechanical ventilation in House 1 was 0.2 Air Changes per Hour (ACH). The airflow of the clothes dryer vent was not measured, so an assumed value of 100 CFM was used in this calculation. The anemometer data provided some indication of the range hood speed setting that was used. For this calculation, the medium setting airflow (107 CFM) was used. Table 5 shows the daily average runtime of the devices considered in this calculation.

Figure 23 Estimates of mechanical ventilation in House 1 by summing airflows from three bathroom exhaust fans, laundry room exhaust fan, range hood, and clothes dryer.

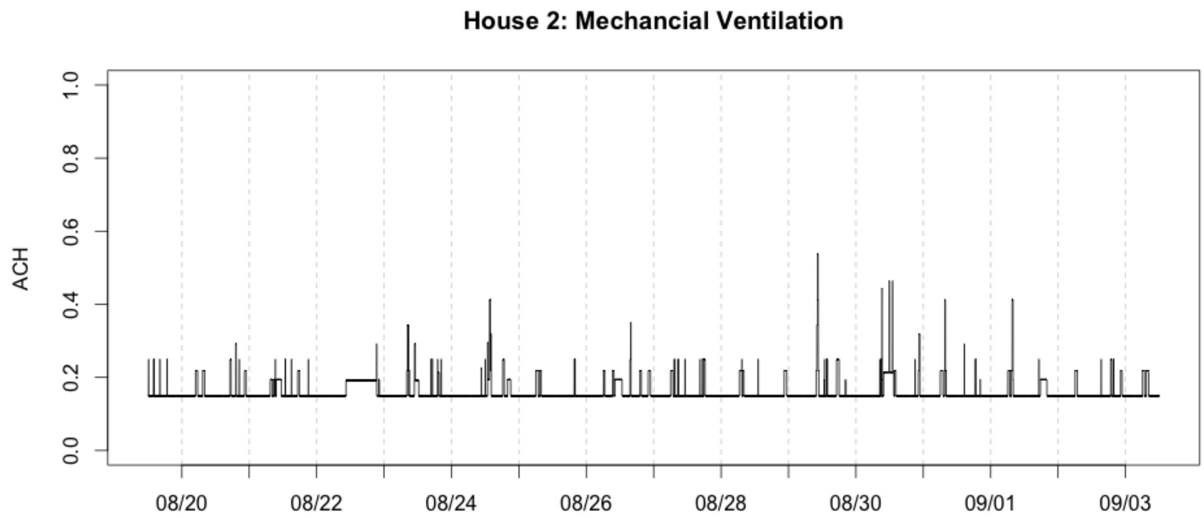


Assuming that the inline fan was designed to provide sufficient ventilation per Title 24:

$$Q_{cfm} = 0.01\ (A_{floor}) + 7.5\ (N_{br} + 1) = 67\ CFM$$

where the conditioned floor area (A_{floor}) = 2990 ft^2 and number of bedrooms (N_{br}) = 4. Figure 24 shows the estimated air changes per hour provided by mechanical ventilation in House 2. The inline fan alone was estimated to provide 0.15 h^{-1} of ventilation. Mechanical ventilation was calculated by the larger of the supply airflow provided by the inline fan and the sum of exhaust airflow from exhaust fans in bathrooms and laundry room, use of range hood and clothes dryer. This resulted in an estimated average mechanical ventilation of 0.16 h^{-1}.

Figure 24 Estimates of mechanical ventilation in House 2 by summing airflows from three bathroom exhaust fans, laundry room exhaust fan, range hood, and clothes dryer.



10 Summary

Learning from the pilot test conducted in two homes will be incorporated to develop the field experimental protocol. For example, steps to identify the whole-house ventilation system need to be described in more details, including instructions of how to measure airflow of an inline supply fan that is buried in insulation. The protocol will include detail procedures to measure building envelope air leakage and duct leakage using blower door and deltaQ test. It will describe various methods for monitoring indoor activities. In cases where more than one method may be used, directions will be given to field team to select an option that is the easiest to implement given field conditions. IAQ sampling of PM2.5, CO_2, CO, NO_2, and formaldehyde will mostly be performed using real-time instruments. Passive samples requiring chemical analysis may only be collected for NO_2 and formaldehyde. In comparison, measurements of VOCs may be a lower priority because indoor concentrations appear to be low relative to health guidelines, as observed by Offermann (2009). Other studies, such as Logue et al. (2012), also concluded similarly, but with formaldehyde and acrolein being the exception where indoor concentrations tend to exceed the health guideline. Assuming that homes relied mostly on mechanical ventilation, then the monitoring of supply and exhaust airflows using activity sensors may provide more detail information than the weekly averages estimated from PFTs measurements. The field experimental protocol will describe operations of IAQ instruments, including calibration and other checks to make sure that the data quality is satisfactory. As discussed, performance of the real-time NO_2 (Aeroqual) and formaldehyde (Shinyei) monitors will be checked against well-established measurement methods prior to the field study. The protocol will specify preferred siting of IAQ instruments indoors and outdoors. LBNL research team will prepare a standard format for field data upload to a central database.

11 Reference

ASTM (2013) E1554 / E1554M-13 Standard Test Methods for Determining Air Leakage of Distribution Systems by Fan Pressurization, ASTM International.

Bendt, P. (2010) Are we missing energy savings in clothes dryers?, *ACEEE Summer Study on Energy Efficiency in Buildings, August 15-20*, Pacific Grove, CA.

Carter, E.M., Jackson, M.C., Katz, L.E. and Speitel, G.E. (2014) A coupled sensor-spectrophotometric device for continuous measurement of formaldehyde in indoor environments, *J. Expo. Sci. Environ. Epidemiol.*, 24, 305-310.

CEC (2008) 2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings, Sacramento, CA, California Energy Commission.

Logue, J.M., Price, P.N., Sherman, M.H. and Singer, B.C. (2012) A Method to Estimate the Chronic Health Impact of Air Pollutants in US Residences, *Environ. Health Perspect.*, **120**, 216-222.

Mullen, N.A., Li, J., Russell, M.L., Spears, M., Less, B.D. and Singer, B.C. (2015) Results of the California Healthy Homes Indoor Air Quality Study of 2011–2013: impact of natural gas appliances on air pollutant concentrations, *Indoor Air*, n/a-n/a.

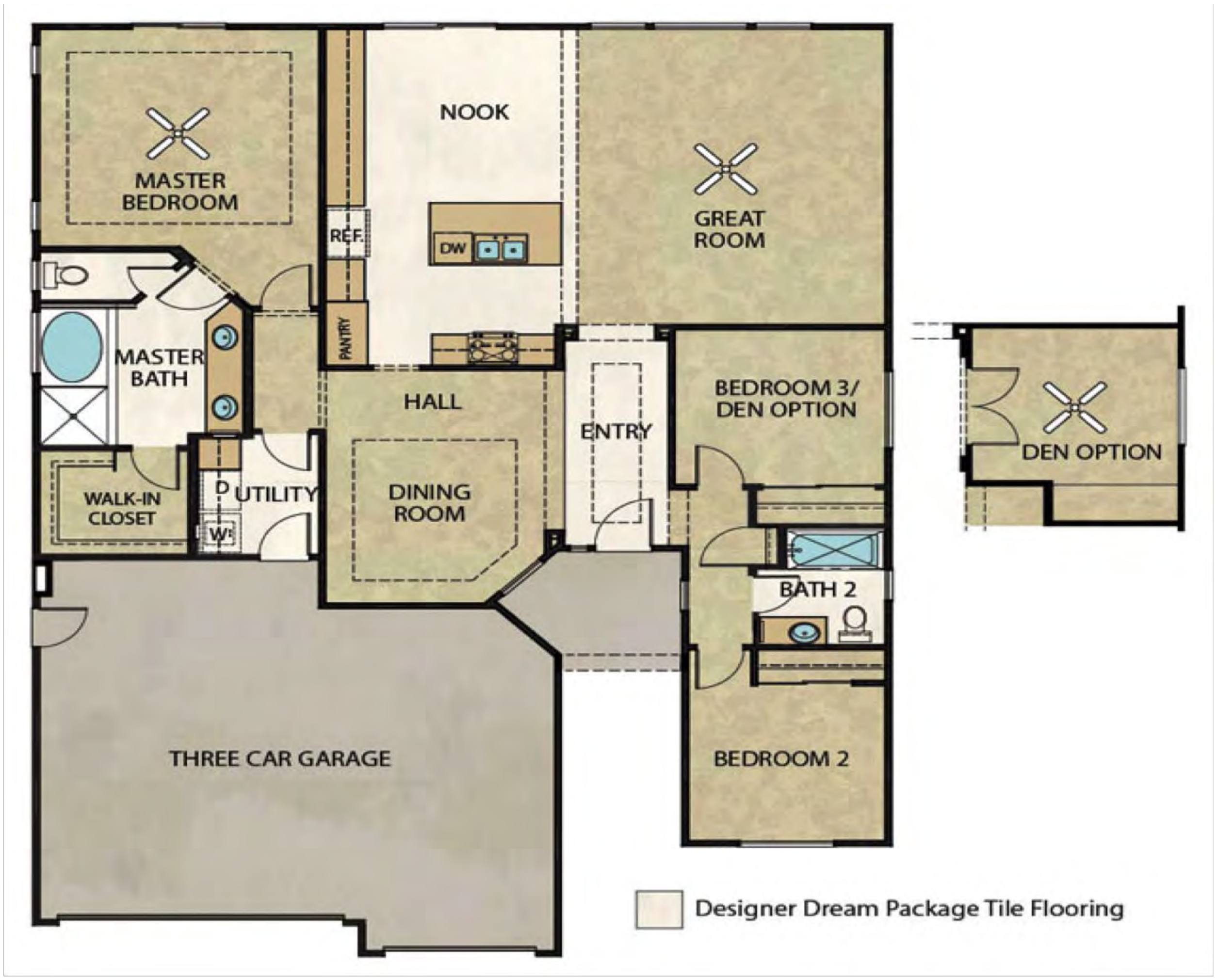
Mullen, N.A., Russell, M.L., Lunden, M.M. and Singer, B.C. (2013) Investigation of formaldehyde and acetaldehyde sampling rate and ozone interference for passive deployment of Waters Sep-Pak XPoSure samplers, *Atmos. Environ.*, **80**, 184-189.

Offermann, F.J. (2009) Ventilation and Indoor Air Quality in New Homes. California Air Resources Board and California Energy Commission, PIER Energy-Related Environmental Research Program.

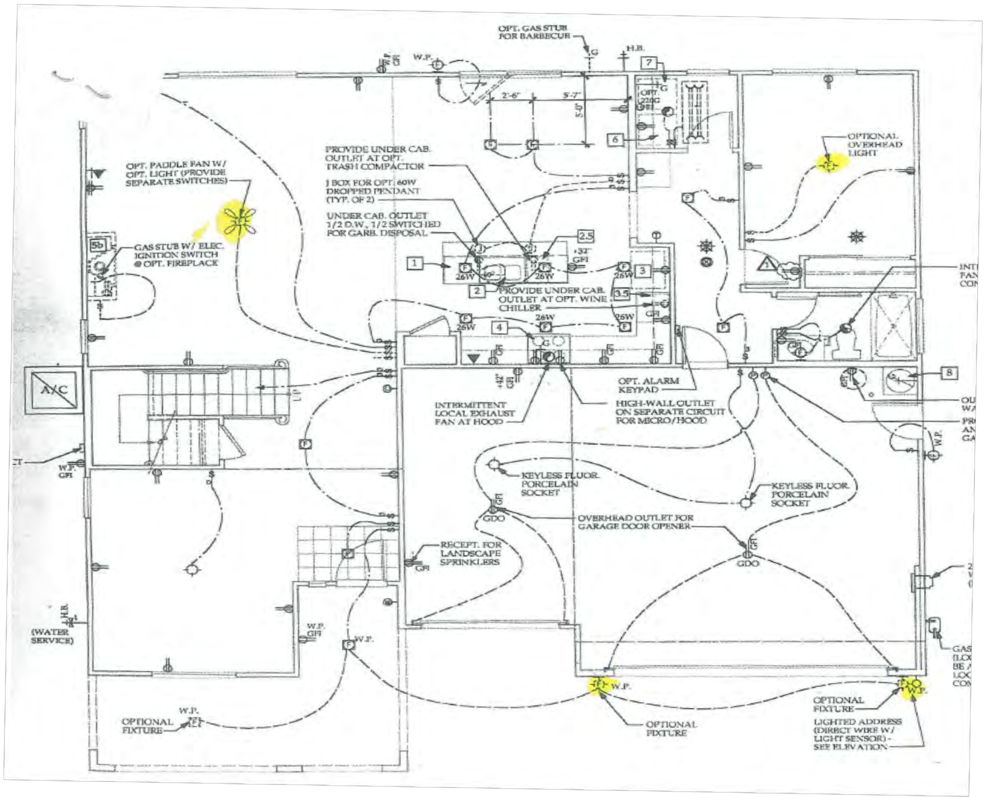
Walker, I.S., Sherman, M.H., Wempen, J., Wang, D., Mcwilliams, J.A. and Dickerhoff, D.J. (2001) Development of a New Duct Leakage Test: DeltaQ. LBNL-47308. Lawrence Berkeley National Laboratory, Berkeley, CA.

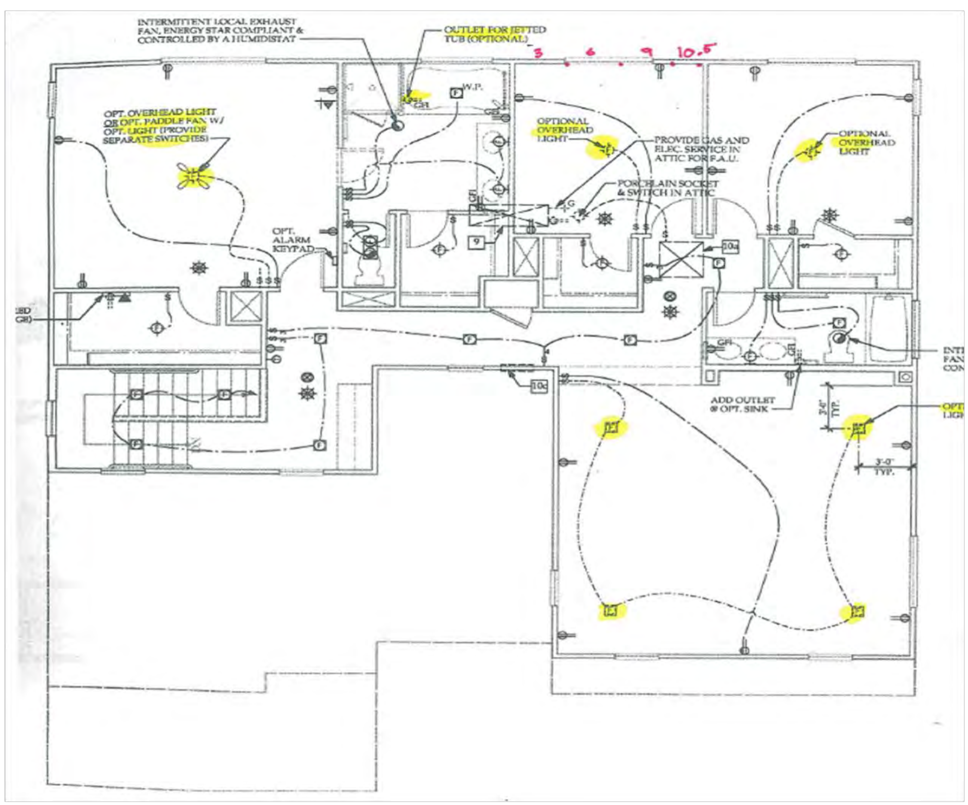
Appendix C-1

House 1 floor plan.



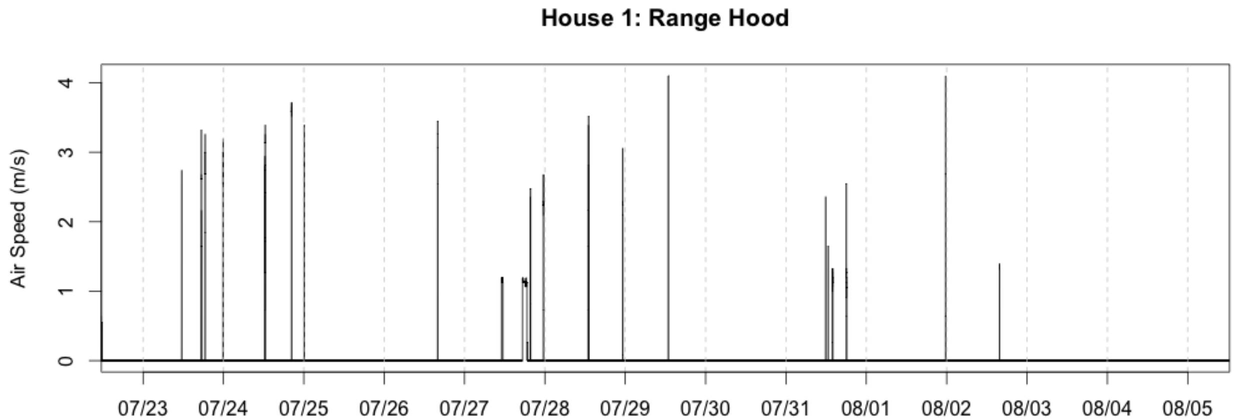
House 2 floor plan: upper floor (top) and lower floor (bottom).

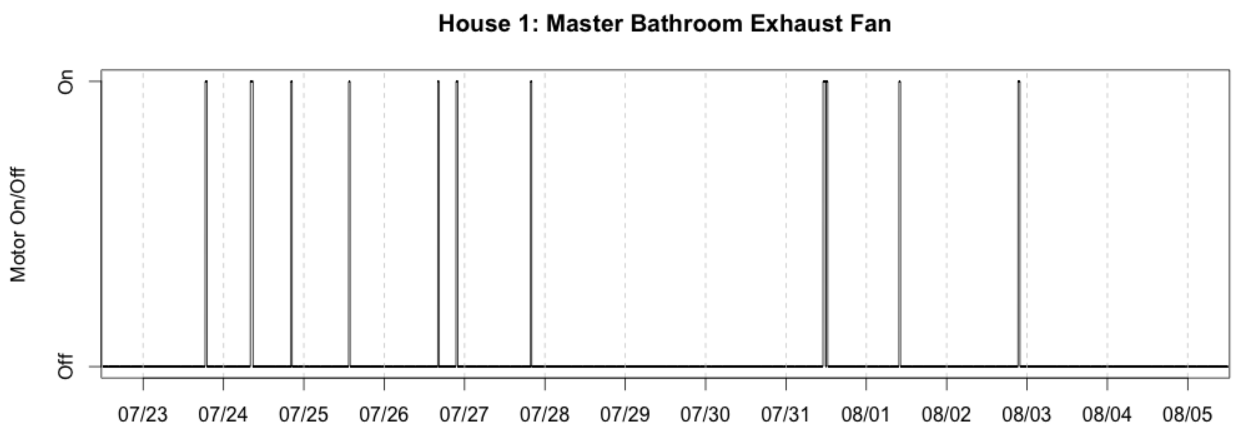


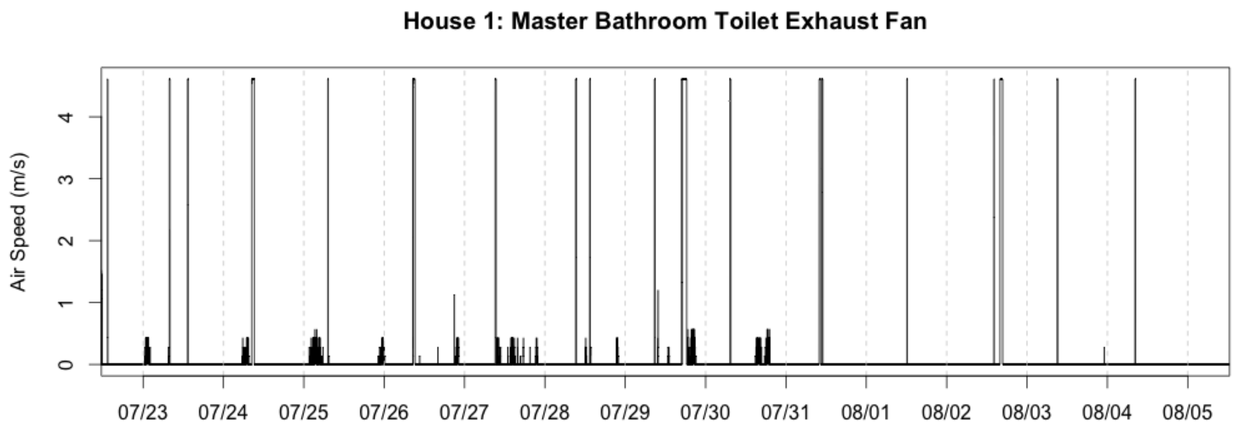


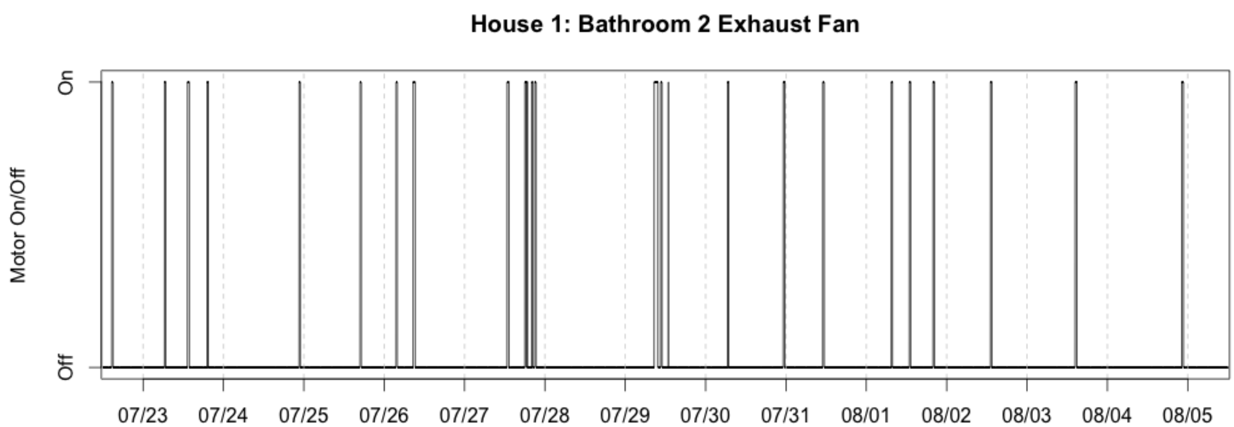
Appendix C-2

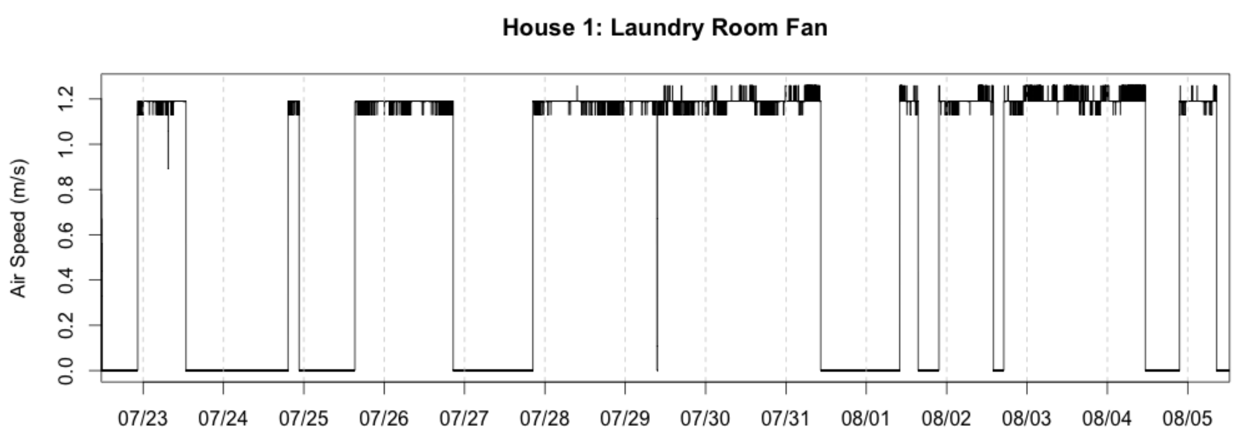
Usage data collected using a number of monitoring devices, including digital anemometers that measured air speeds, on/off state loggers that measured motor operations, power meter readings, and temperature/relative humidity measurements.

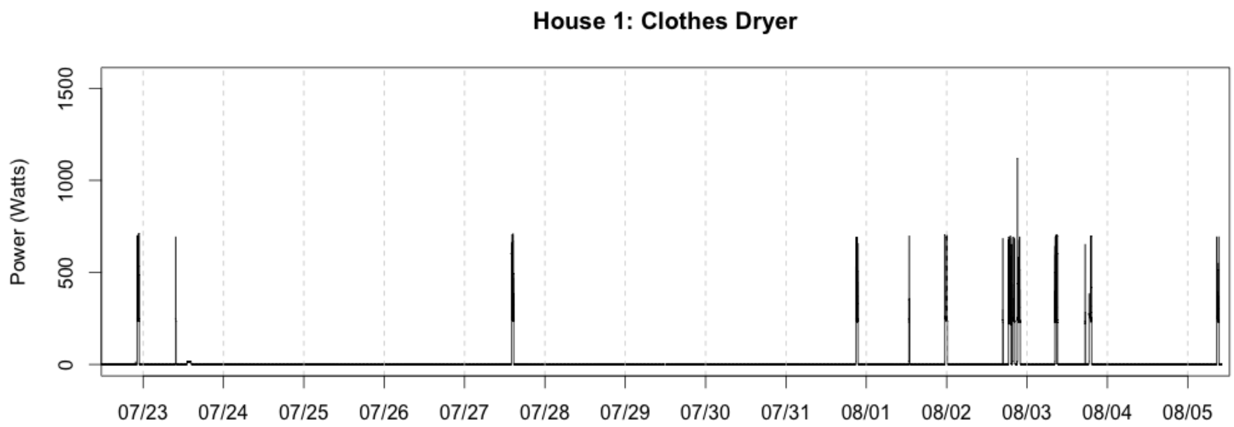


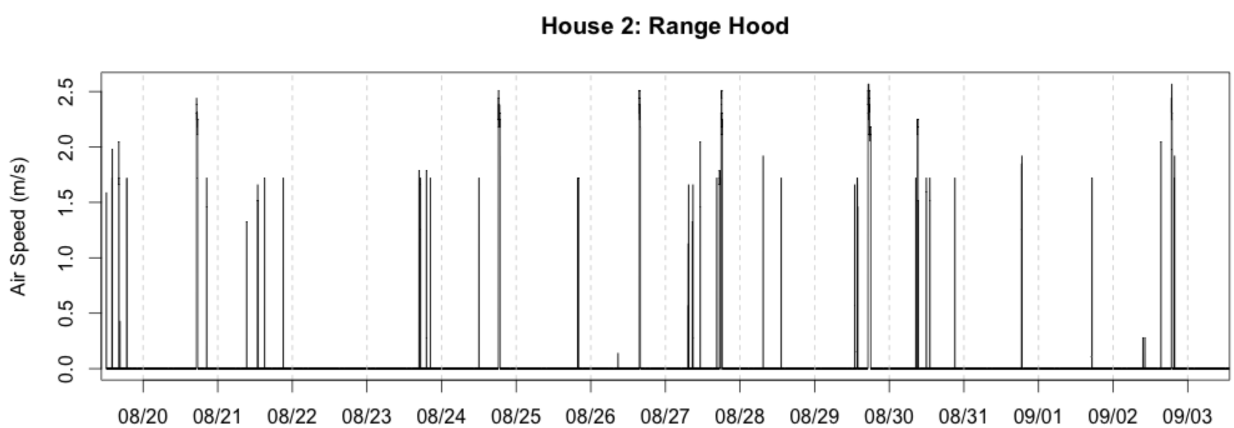


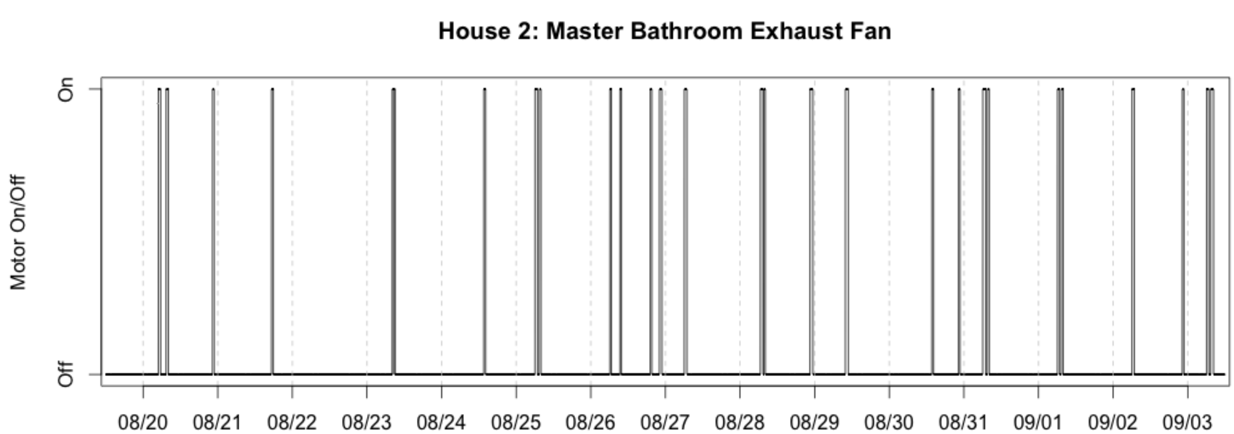

House 1: Master Bathroom Toilet Exhaust Fan
Air Speed (m/s)
0
1
2
3
4
07/23
07/24
07/25
07/26
07/27
07/28
07/29
07/30
07/31
08/01
08/02
08/03
08/04
08/05

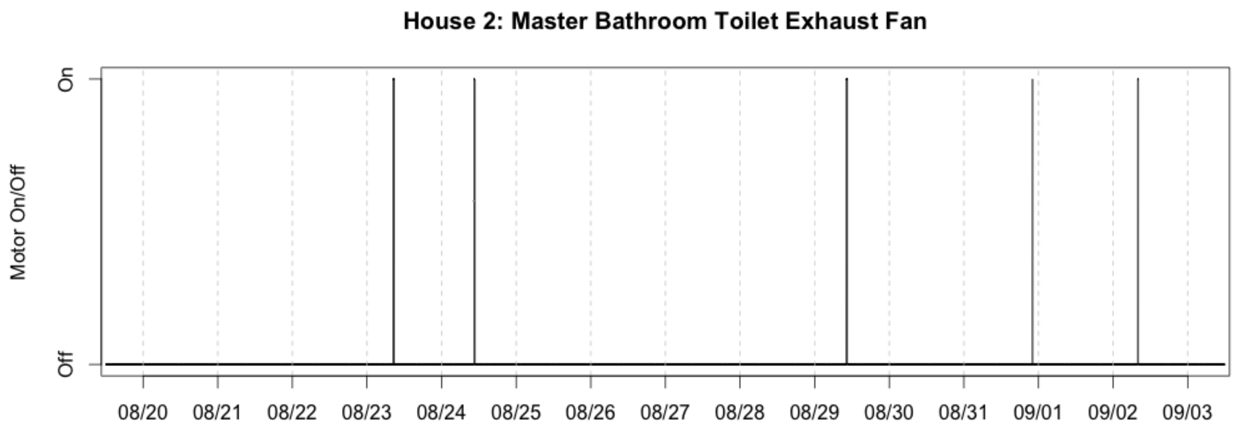

House 1: Bathroom 2 Exhaust Fan
Motor On/Off
On
Off
07/23
07/24
07/25
07/26
07/27
07/28
07/29
07/30
07/31
08/01
08/02
08/03
08/04
08/05

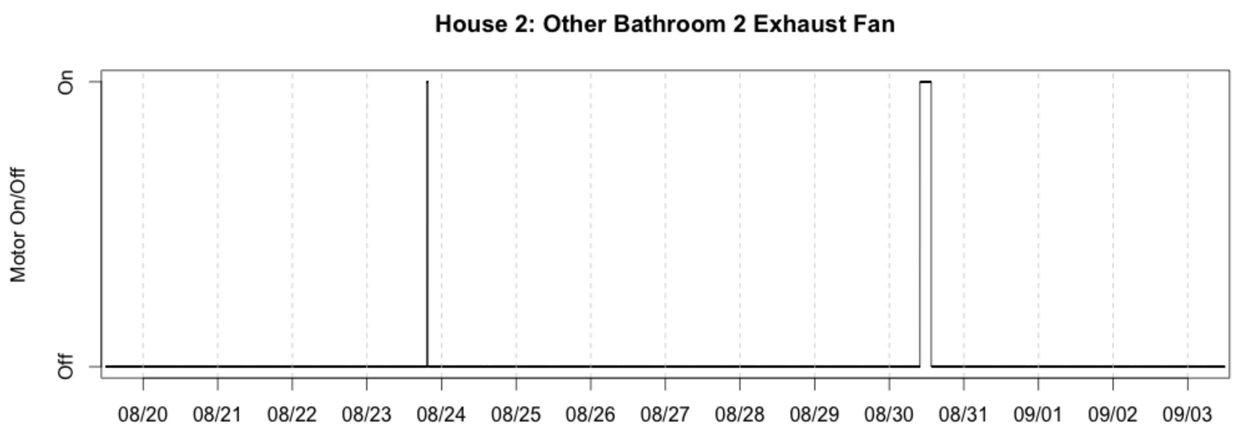

House 1: Laundry Room Fan
Air Speed (m/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
07/23
07/24
07/25
07/26
07/27
07/28
07/29
07/30
07/31
08/01
08/02
08/03
08/04
08/05

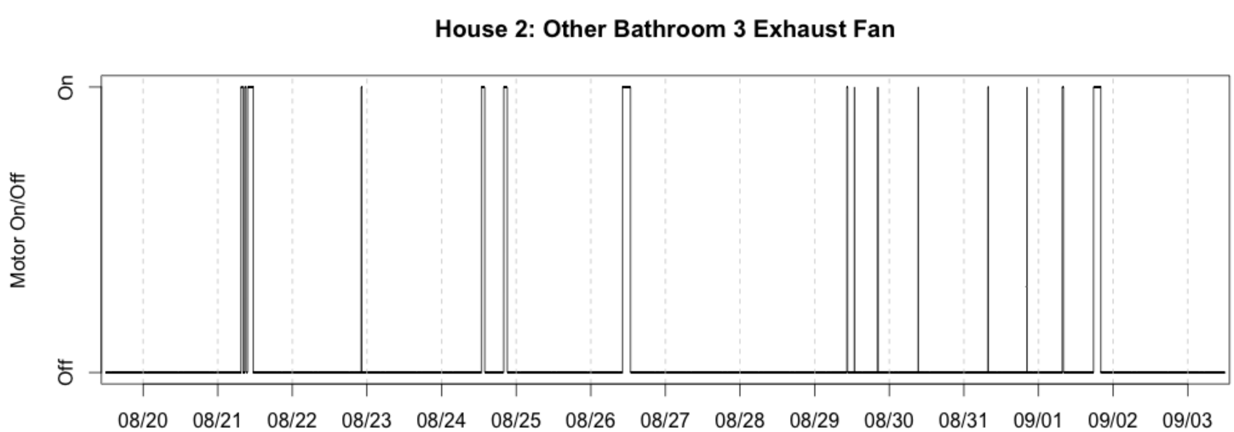

House 1: Clothes Dryer
Power (Watts)
0
500
1000
1500
07/23
07/24
07/25
07/26
07/27
07/28
07/29
07/30
07/31
08/01
08/02
08/03
08/04
08/05

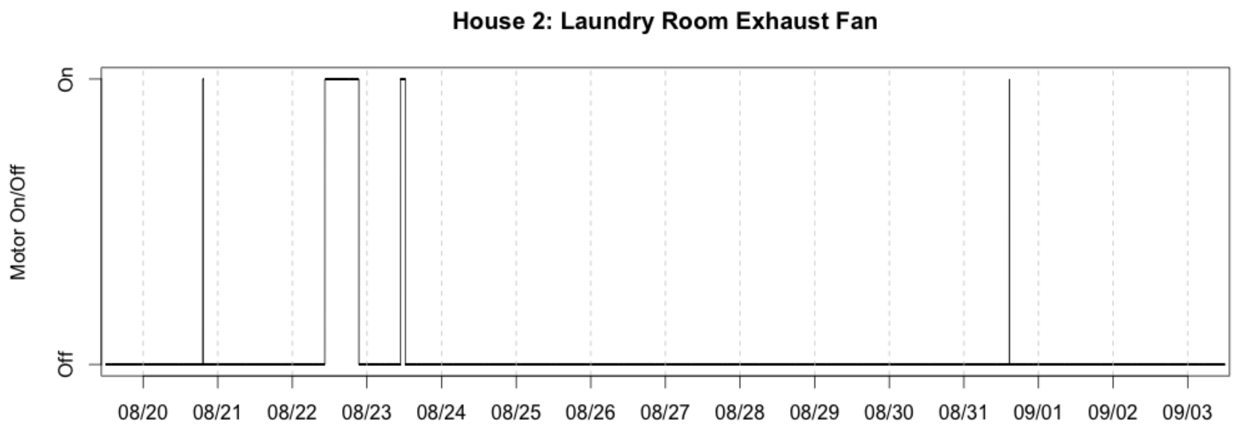

House 2: Range Hood
Air Speed (m/s)
0.0
0.5
1.0
1.5
2.0
2.5
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03

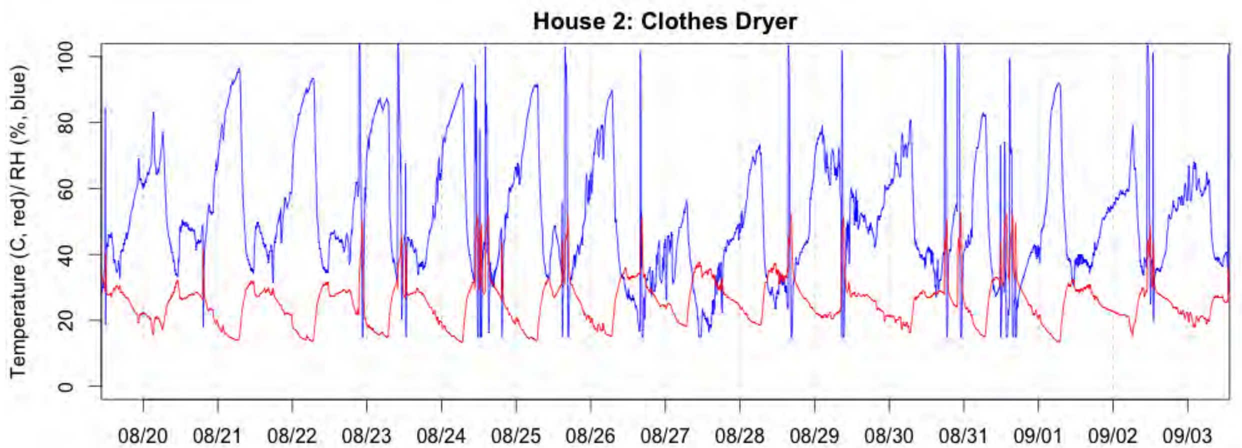

House 2: Master Bathroom Exhaust Fan
Motor On/Off
On
Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Master Bathroom Toilet Exhaust Fan
On
Off
Motor On/Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Other Bathroom 2 Exhaust Fan
On
Off
Motor On/Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Other Bathroom 3 Exhaust Fan
On
Off
Motor On/Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Laundry Room Exhaust Fan
Motor On/Off
On
Off
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03


House 2: Clothes Dryer
Temperature (C, red)/ RH (%, blue)
0
20
40
60
80
100
08/20
08/21
08/22
08/23
08/24
08/25
08/26
08/27
08/28
08/29
08/30
08/31
09/01
09/02
09/03

Appendix C-3

Comparison of $PM_{2.5}$ mass concentrations measured by five particle instruments: MetOne BT-645, Thermo pDR-1500, TSI DustTrak II 8530. $PM_{2.5}$ mass concentrations measured by MetOne BT-645, Thermo pDR-1500, and TSI DustTrak are plotted as-measured. Particle counts measured by Dylos and MetOne BT-637 were used to estimate $PM_{2.5}$ mass concentrations assuming spherical particles having a density of 1.65 g/cm^3, as follows:

Dylos: $PM_{2.5}$ (ug/m^3) = N (#/m^3) $\pi/6$ (1 um)^3 (1.65 g/cm^3) (10^6 ug/g) (cm^3/10^{12} um^3)

where N is the particle counts measured between the two channels (>0.5 and >2.5 um).

MetOne BT-637:

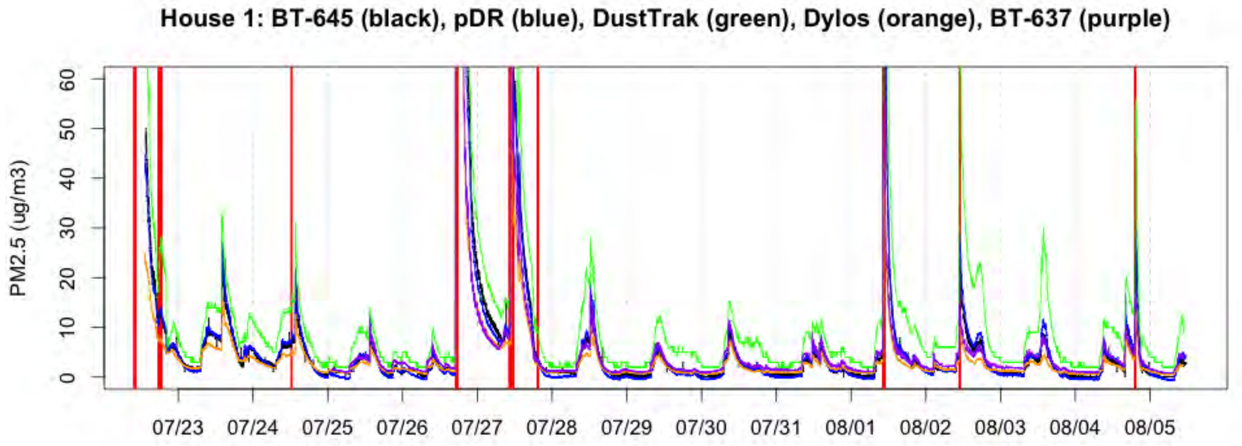
$PM_{2.5}$ (ug/m^3) = Σ N_i (#/m^3) $\pi/6$ (dp_i)^3 (1.65 g/cm^3) (10^6 ug/g) (cm^3/10^{12} um^3)

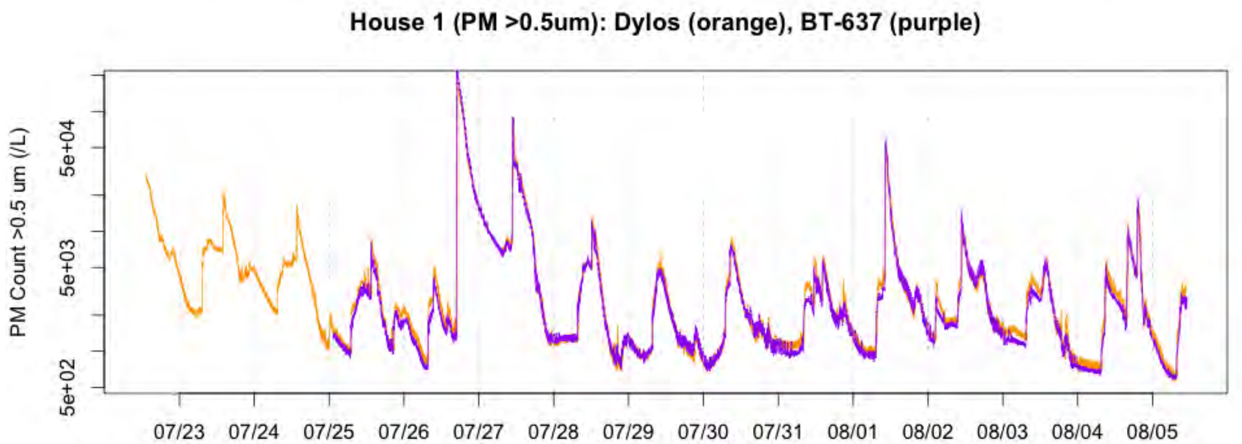
where N_i is the particle counts measured within a given size bin, and dp_i is the representative diameter of the particle.

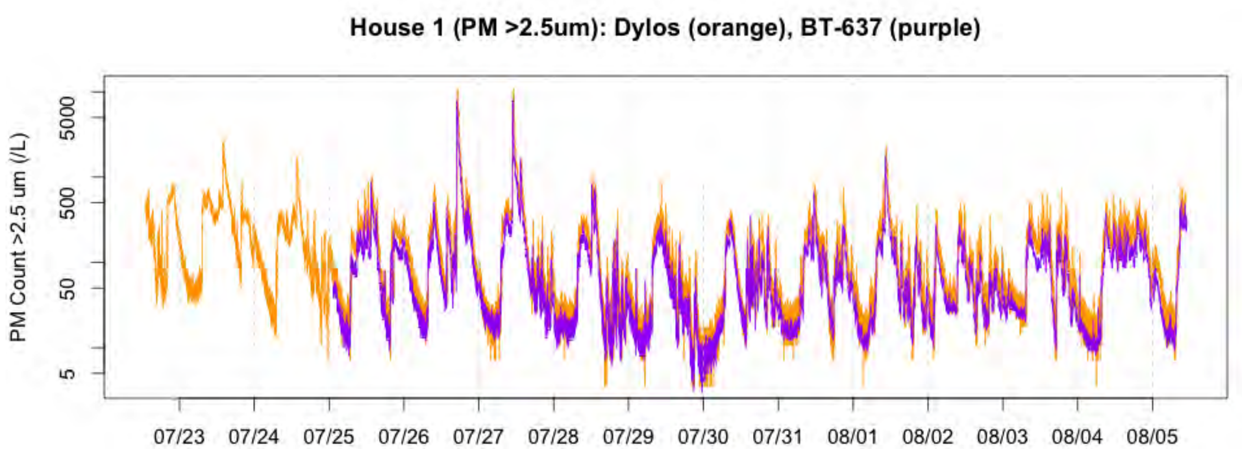
In House 1, N_i were measured at these size bins: 0.3-0.5, 0.5-0.7, 0.7-1, 1-2.5 um, were used to calculate $PM_{2.5}$ mass concentrations. The assumed dp_i was 0.45, 0.6, 0.85, and 1.75 um, respectively. In House 2, N_i were measured at these size bins: 0.3-0.4, 0.4-0.5, 0.5-0.7, 0.7-1, 1-2.5 um, were used to calculate $PM_{2.5}$ mass concentrations. The assumed dp_i was 0.35, 0.45, 0.6, 0.85, and 1.75 um, respectively.

Raw particle counts measured by Dylos and MetOne BT-637 were compared in the middle and bottom charts.

In House 1, cooking events are defined by thermocouple measuring >120 ºF (49 ºC), as indicated by red lines in the top chart.

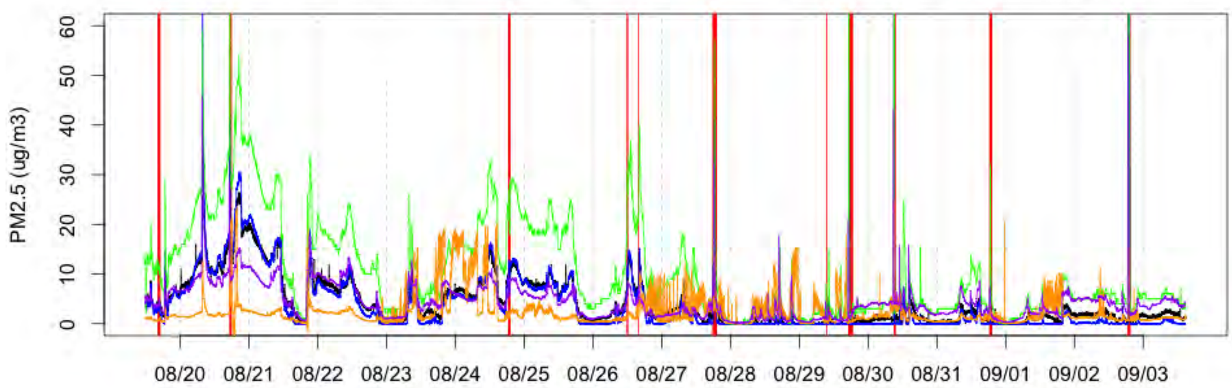




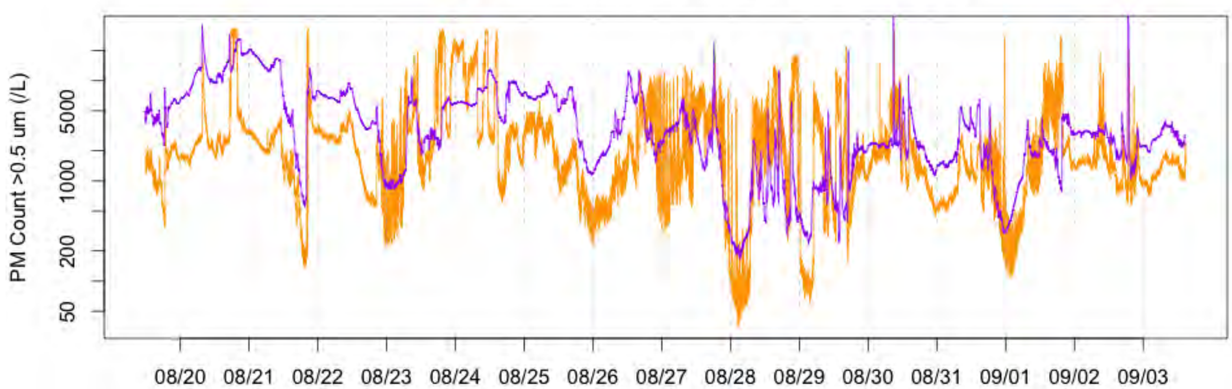


In House 2, cooking events are defined by iButton measuring >35 °C, as indicated by red lines in the top chart.

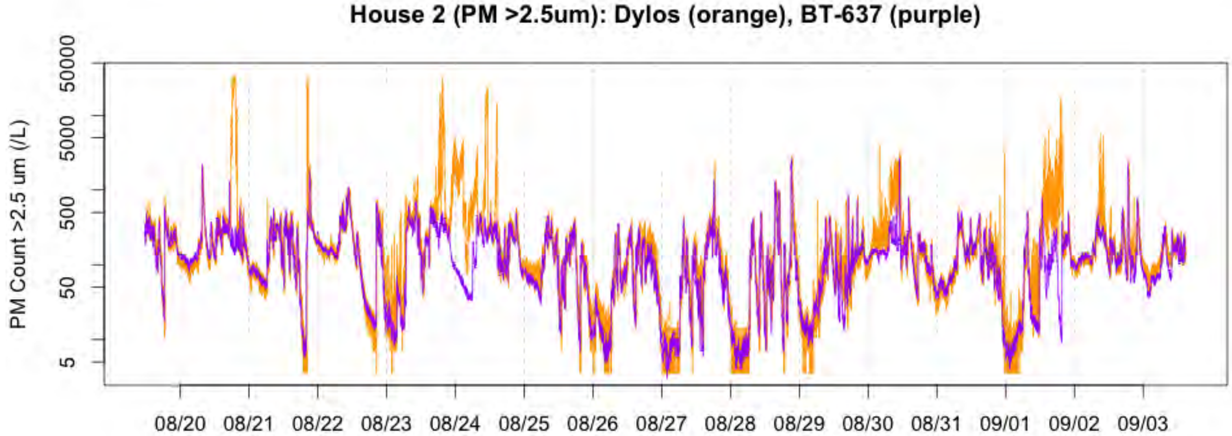
House 2: BT-645 (black), pDR (blue), DustTrak (green), Dylos (orange), BT-637 (purple)



House 2 (PM >0.5um): Dylos (orange), BT-637 (purple)



House 2 (PM >2.5um): Dylos (orange), BT-637 (purple)



Appendix C-4

PFTs concentrations (ug/m^3) measured in House 1.

	PDCB (emitted from kitchen area)		PMCH (emitted throughout the house)		mPDCH (emitted from attached garage)	
	Week 1	**Week 2**	**Week 1**	**Week 2**	**Week 1**	**Week 2**
Master Bedroom	20.1	19.1	27.9	27.1	1.7	1.5
Master Bathroom	--	18.4	--	24.4	--	1.8
Other Bedroom 1	23.0	10.6	28.3	12.9	1.3	0.4
Dining Room	25.5	24.3	28.6	27.2	1.4	1.2
Great Room	28.8	27.4	30.7	29.8	1.3	1.2
Kitchen*	32.2	34.6	30.4	30.9	1.3	1.1
Laundry Room	23.6	22.2	26.4	25.3	2.8	2.3
Hallway	--	22.5	--	27.8	--	1.2
Den	--	23.0	--	26.3	--	1.2
Garage	2.6	2.0	2.3	2.0	64.2	57.8

*** Kitchen is connected to the great room.**

PFTs concentrations (ug/m^3) measured in House 2.

	PDCB (emitted from upper floor)		PMCH (emitted from attached garage)		mPDCH (emitted from lower floor)	
	Week 1	Week 2	Week 1	Week 2	Week 1	Week 2
Rooms in upper floor						
Master Bedroom	13.1	18.8	2.8	4.3	5.0	9.2
Other Bedroom 1	13.1	17.2	2.9	4.2	4.3	7.9
Other Bedroom 2	13.9	18.1	3.7	4.9	4.6	7.8
Home Office	13.3	17.6	3.1	3.9	5.1	7.9
Rooms in lower floor						
Living Room	9.6	14.9	4.3	5.5	9.1	12.2
(replicate sample)	9.4	14.3	4.6	5.4	9.1	11.6
Laundry Room	8.2	12.9	7.0	9.3	9.0	11.6
Other Bedroom 3	12.6	12.5	8.4	8.0	11.8	12.8
Garage	1.7	2.3	68.0	77.0	0.2	0.7

APPENDIX D:
Daily Activity Log and Occupant Survey

Provided below is the top page of the activity log. Participants were asked to complete a log table for each calendar day during which measurements were being made in the home. Participants were provided with paper sheets containing a log for each day.

Healthy Efficient New California Homes Study
Occupancy and Indoor Activities Data Log

<u>Instructions</u>: Please fill out this data log each day, or on the following day.

Please enter your best estimates. If you are unsure, please provide your best guess.
Do not list the names of any people.

Code number for home __________

Day 1: Date ____________________ Date completed ________________

	Midnight to 7am	7am to 11am	11am to 1pm	1pm to 5 pm	5pm to 9pm	9pm to Midnight
Number of people in home						
Cooktop use Number of minutes						
Oven use Number of minutes						
BBQ/outdoor grill Number of minutes						
Vacuuming Number of minutes						
Window Use Number of minutes						
Other notable* indoor/outdoor events						

* For example, use of fireplace, candle, air freshener, air cleaner, humidifier, unusual outdoor air quality (wood smoke, wildfire), and so on.

Occupant Survey

Welcome to the 2015 California New Homes Survey!

This survey is part of a research study on new homes in California. This research will help inform how new homes can provide adequate ventilation and good indoor air quality, while reducing air infiltration and energy use.

This survey takes about 15 minutes to complete. It asks questions about your home, household activities, and demographics. You can skip questions that you do not want to answer.

This research is being conducted by Lawrence Berkeley National Laboratory (LBNL) with funding from the California Energy Commission. Results will be used only for research on how to provide adequate ventilation and improve indoor air quality. In order to protect your privacy, the data will be encrypted and password protected.

Please return your completed survey in the envelope provided.

If you have questions about the research study, please contact:

Max Sherman, Ph.D.
Principal Investigator, Residential Building Systems Group
Lawrence Berkeley National Laboratory
mhsherman@lbl.gov (510) 486 4022

Code number for home __________ Date completed ________________

Please answer to the best of your knowledge. You can skip any questions that you do not want answer.

A. Home and Household Characteristics

1. What year was your house built?

   Year Built: ………………

2. What is the size (floor area) of your home?

   Square Feet: ………………

3. What year did you move into this home?

   Year Moved In: ……………….

4. Do you own or rent your home?

   ……. Own (If yes → 5, skip otherwise)

   ……. Rent

   ……. Other

5. Are you the first owner of the property? Yes / No
6. How many people currently live in your home?

   Number of People: ……………..

B. Air Quality In and Around Your Home

7. To what extent are you satisfied or dissatisfied with the indoor air quality in your home?

Very Dissatisfied				Neutral				Very Satisfied
☐	☐	☐	☐	☐	☐	☐	☐	☐

8. How would you rate the outdoor air quality near where you live?

Very Poor				Neutral				Excellent
☐	☐	☐	☐	☐	☐	☐	☐	☐

9. How would you rate your home in protecting you from outdoor air pollution?

Very Ineffective				Neutral				Very Effective
☐	☐	☐	☐	☐	☐	☐	☐	☐

C. Comfort Level in Your Home

10. In winter, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times in a month	Few times a week	Every day
Too hot in some room(s).	☐	☐	☐	☐	☐
Too cold in some room(s).	☐	☐	☐	☐	☐

11. In summer, how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too hot in some room(s).	☐	☐	☐	☐	☐
Too cold in some room(s).	☐	☐	☐	☐	☐

12. How often do the following conditions affect the comfort of occupants in your home?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too much air movement.	☐	☐	☐	☐	☐
Not enough air movement.	☐	☐	☐	☐	☐
Indoor air is too dry.	☐	☐	☐	☐	☐
Indoor air is too damp.	☐	☐	☐	☐	☐
Indoor air has musty odor.	☐	☐	☐	☐	☐

D. Natural Gas Appliances and Mechanical Ventilation

13. Which of the following heating appliances are used in your home? Select all that apply.

…….. Central gas furnace

…….. Gas fireplace/ log set

…….. Gas wall furnace

…….. Freestanding gas heater

…….. Central electric heating or heat-pump

…….. Baseboard electric wall heater

…….. Freestanding electric heater

……. Wood fireplace

…….. Freestanding propane heater

…….. Freestanding kerosene heater

…….. Other. Please describe: ...………………………….

…….. Don't know

14. How often is the kitchen range hood or kitchen exhaust fan used when cooking with a cooktop?

…….. Always (5 out of 5 times)

…….. Most of the Time (4 out of 5 times)

…….. Sometimes (2 to 3 out of 5 times)

…….. Rarely (1 out of 5 times)

…….. Never (0 out of 5 times)

…….. Don't know

15. If the kitchen range hood or kitchen exhaust fan is NOT always used, what are the reasons for not using it? Select all that apply.

…….. Forget to turn it on

…….. Not needed for what is being cooked

…….. Too noisy

…….. Doesn't seem to remove cooking fumes or odors

……. Open window instead

…….. Uses too much energy

…….. Other. Please describe: ……………..

16. Was the operation of the mechanical ventilation system explained to you when you bought or moved into the home?

…….. Yes

…….. No

…….. Don't know

17. Do you feel you understand how to operate your mechanical ventilation system properly?

…….. Yes

…….. No

…….. Not Sure

18. To what extent are you satisfied or dissatisfied with your mechanical ventilation system?

Very Dissatisfied				Neutral				Very Satisfied
☐	☐	☐	☐	☐	☐	☐	☐	☐

19. If you are NOT very satisfied with your mechanical ventilation system, what are the reason(s) for dissatisfaction? Select all that apply.

…….. Too noisy

…….. Too drafty

…….. Difficult to operate

…….. Difficult to maintain

…….. Uses too much energy

…….. Brings in dust, odor, or air pollutants from outdoor

…….. Not effective

…….. Other. Please describe: …………………………………..

E. Occupancy and Indoor Activities

20. On average, how many hours per day is your home occupied by at least one person, including day and night hours?

	Fewer than 8 hours per day	8 to 12 hours per day	12 to 16 hours per day	16 to 20 hours per day	More than 20 hours per day
Weekday	☐	☐	☐	☐	☐
Weekend	☐	☐	☐	☐	☐

21. On average, how many times per week is your cooktop and/or oven used for cooking, including boiling water?

	0 time per week	1 to 2 times per week	3 to 4 times per week	5 to 6 times per week	7 times per week
Breakfast	☐	☐	☐	☐	☐
Lunch	☐	☐	☐	☐	☐
Dinner	☐	☐	☐	☐	☐
Other cooking	☐	☐	☐	☐	☐

22. On average, how many times per week do the following activities occur inside your home? Enter "0" if occurrence is less frequent than once a week.

Use shower (Times per week) …………………

Use bath or indoor Jacuzzi (Times per week) …………………

Use dishwasher (Times per week) …………………

Use washing machine (Loads per week) …………………

Hang clothes to dry indoors (Loads per week) …………………

F. Window Opening

23. On average, how many hours per day are your windows open?

	0 hour per day	1 to 2 hour per day	2 to 8 hours per day	8 to 16 hours per day	More than 16 hours per day
Summer	☐	☐	☐	☐	☐
Fall	☐	☐	☐	☐	☐
Winter	☐	☐	☐	☐	☐
Spring	☐	☐	☐	☐	☐

G. Indoor Activities

24. On average, how often do the following activities occur inside your home?

	Never	Few times a year	Few times a month	Few times a week	Every day
Smoking	☐	☐	☐	☐	☐
Burn candle or incense	☐	☐	☐	☐	☐
Vacuuming	☐	☐	☐	☐	☐
Use cleaning agent for floor cleaning	☐	☐	☐	☐	☐
Use spray air freshener	☐	☐	☐	☐	☐
Use pesticide spray	☐	☐	☐	☐	☐
Use paints, glue, solvents (e.g., hobbies, home repairs)	☐	☐	☐	☐	☐
Use humidifier	☐	☐	☐	☐	☐
Use dehumidifier	☐	☐	☐	☐	☐

H. Other Indoor Sources

25. Are plug-in or stick air fresheners, or other scented decorations, used in your home?

    ….… Yes

    ….… No

    ….… Don't know

26. Do occupants wear shoes in your home?

    ….… Yes

    ….… No

    ….… Don't know

27. How many dogs, cats, or other furry pets are in the home?

    Number of Pets: ………………

I. Use of Air Cleaners

28. Do you use a stand-alone (portable) air filter, air purifier, or air cleaner in the home?

    ….… Yes

    ….… No

    ….… Don't know

29. Where is your stand-alone (portable) air filter, air purifier, or air cleaner located in your home? Select all that apply.

…….. Master bedroom

…….. Other bedroom(s)

…….. Living room

…….. Home office

…….. Other. Please describe: ……………......................................

30. Has anyone in the household been diagnosed with asthma?

…….. Yes

…….. No

…….. Don't know

31. Has anyone in the household been diagnosed with allergies?

…….. Yes

…….. No

…….. Don't know

J. Demographic Information

The next questions will help us interpret the results of the survey. All responses will be kept confidential.

32. Please indicate the number of household member(s) in the following age categories.

	Number of household member(s)
0 to 17 Years old	………………………………………
18 to 65 Years old	………………………………………
Over 65 Years old	………………………………………

33. What is the highest education level of head of household?

.... No schooling completed

.... 1 to 8th grade

.... 9th to 12th grade

.... Completed high school (high school diploma, GED credential)

.... Some college

.... Associate's degree

.... College degree (Bachelor's degree)

.... Graduate degree (Master's, Professional school, Doctorate degree)

34. Please indicate <u>all</u> races and/or ethnicities of people living in your household.

.... American Indian, Alaska Native

.... Asian or Pacific Islander

.... Black, African American

.... Hispanic/ Latino

.... White, Caucasian

.... Other, specify: ....

.... Mixed race, specify: ....

35. What is the total income of all member(s) of your household combined?

.......Less than $35,000

.......$35,000 to $ 49,999

.......$50,000 to $ 74,999

.......$75,000 to $ 99,999

.......$100,000 to $150,000

.......Greater than $150,000

K. End of Survey

Thank you for filling out this survey! Your data is very valuable to our understanding of indoor air quality and mechanical ventilation in new California homes.

Please return your completed survey in the envelope provided.

If you have any questions about the survey, please contact:

Max Sherman, Ph.D.
Principal Investigator, Residential Building Systems Group
Lawrence Berkeley National Laboratory
mhsherman@lbl.gov (510) 486 4022

For more information about the results of this survey, please visit our website:
http://hengh.lbl.gov/

Energy in Buildings and
Communities Programme

www.iea-ebc.org

EBC is a programme of the International Energy Agency (IEA)