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FINAL PROJECT REPORT

Effective Kitchen Ventilation for Healthy Zero Net Energy Homes with Natural Gas

Gavin Newsom, Governor
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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Effective Kitchen Ventilation in Healthy Zero Net Energy Homes with Natural Gas is the final report for the Effective Kitchen Ventilation in Healthy Zero Net Energy Homes with Natural Gas project (PIR-16-012) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

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ABSTRACT

Past studies indicate that kitchen ventilation that minimally complies with California's Residential Building Code is inadequate at controlling combustion pollutants from natural gas burners and particulate matter produced during cooking. Effectiveness is further limited by misperceptions that kitchen ventilation is infrequently needed. This project developed the technical basis for updating kitchen ventilation requirements to protect health in new California homes, especially in smaller homes common among low-income renters. Tasks included (1) a field study of ventilation equipment performance and indoor air quality in 23 low-income apartments at four sites; (2) analysis of range hood use related to cooking time and household parameters using data from 54 houses and 17 low-income apartments; (3) a measurement-based study to quantify performance of over-the-range microwave ovens with integrated exhaust fans; and (4) pollutant exposure simulations to inform capture efficiency standards. The field study found operational deficiencies with mechanical ventilation systems in a substantial fraction of low-income apartments that affected performance, resulting in higher exposures to pollutants generated indoors. Using gas cooking burners produced high short-term and weekly time-averaged nitrogen dioxide in apartments. Range hoods were used more frequently with cooking in houses (36 percent) than apartments (28 percent); use increased with overall cooking frequency in a home and with duration of cooktop but not oven events; actual use was correlated to, but lower than, self-reported use; and use was more frequent in houses when cooking generated any fine particulate matter ($PM_{2.5}$) or when high $PM_{2.5}$ resulted from cooking in apartments. Performance of over-the-range microwaves with integrated exhaust fans was similar to that of range hoods of comparable price. Simulation analysis found that performance standards need to be updated to ensure that kitchen exhaust ventilation adequately protects for substantial cooking in new California residences.

Keywords: Air pollutant exposures; Building Energy Efficiency Standards; cooking; healthy homes; indoor air quality; mechanical ventilation; residential.

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Introduction

California's aggressive climate change mitigation policies include reducing greenhouse gas emissions to 80 percent below 1990 levels by 2050 and achieving carbon neutrality by 2045. Maximizing energy efficiency savings is a key element of achieving those goals while also advancing energy affordability. For decades California has placed energy efficiency at the center of its energy policies with energy codes, standards, and programs that have saved Californians billions of dollars since the 1970s.

An airtight envelope is a core element of an energy efficient and resilient residential building. Reducing uncontrolled air exchange with the outdoors reduces heating and cooling loads and also enables better control of outdoor air pollution entry, which is particularly important during wildfire events. For multiunit buildings, reducing air leakage between units reduces the transfer of odors and pollutants and enables better control of thermal comfort and energy use. However, there is a risk that reducing air leakage could also reduce annual average outdoor air exchange as well as dilution and removal rates for air pollutants generated indoors, causing an increase in chronic exposures if no other action is taken.

To protect indoor air quality in airtight homes, California's Building Energy Efficiency Standards, Part 6 of the Title 24 Building Code, require new homes to have mechanical ventilation. The standards require: minimum airflow rates for ventilation to control long-term exposure to continuously emitted pollutants throughout the home; kitchen exhaust to manage odors, moisture and pollutants from cooking; and exhaust fans in bathrooms. The standards are periodically updated in light of new information about performance needs and newly available technologies and products.

Cooking is among the largest sources of air pollutant emissions inside many homes, with substantial adverse health impacts. Gas cooking burners produce carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), and ultrafine particles, while electric burners generate ultrafine particles. Nitrogen dioxide from gas cooking burners may commonly reach indoor concentrations that exceed the threshold of 100 parts per billion (ppb) over one hour that is used in the United States ambient air quality standard. In a 2013 study, Belanger et al. reported that higher residential exposures to NO_2 are associated with asthma severity. In a 2013 meta-review, Lin et al. reported that gas cooking and higher NO_2 exposure were each associated with increased risk of asthma, and higher NO_2 was associated with current wheeze, a commonly used proxy for active asthma. High-temperature cooking activities (such as frying and broiling) contribute odors and pollutants including hazardous organic gases, polycyclic aromatic hydrocarbons, and fine and ultrafine particles. Higher exposures to these pollutants are associated with adverse health effects. A study in Hong Kong, by Yu et al. in 2006, reported a dose–response relationship between lifetime exposure to cooking fumes and lung cancer.

Venting range hoods and combination "over the range" microwaves with integrated exhaust fans (OTRs) are designed to remove some fraction of the emitted pollutants to outdoors before they mix into the air volume of the kitchen and throughout the home. There are several relevant measures of range hood performance. The two most commonly used, and the measures for which data are most readily available, are airflow and sound level that are measured using standard test procedures published by the Home Ventilating Institute. The Home Ventilating Institute certifies and publishes test results in a free online directory that includes standard range hoods and over-the-range microwave and exhaust fan combined devices mounted above the cooktop.

A third metric, for which more limited data are available, is capture efficiency. Capture efficiency is the fraction of contaminants emitted at the cooktop that are directly pulled into the range hood and exhausted to the outdoors before mixing throughout the house. A capture efficiency of 100 percent means all cooking pollutants are exhausted directly to the outside, and a capture efficiency of zero means that no cooking pollutants are directly exhausted, allowing all of them to mix with indoor air. Capture efficiency was first studied decades ago and the metric received increasing attention after Lawrence Berkeley National Laboratory used it in studies conducted in the early 2010s. Several modeling and experimental studies have examined the benefits of range hood use to reduce cooking-related indoor air pollution.

Research conducted by Lawrence Berkeley National Laboratory before this project, with range hoods and OTRs in both laboratory and occupied home installations, found that capture efficiency for a given device depends strongly on airflow, the type of cooking and whether cooking is done on the front or back burners. The research team's studies also found that capture efficiency varies between devices. Also, based on just a few OTRs included in the studies, it appeared that the capture efficiency performance of OTRs could be appreciably lower than for range hoods at similar airflows.

Existing kitchen ventilation standards specify a minimum airflow and maximum sound rating at the minimum airflow. For any exhaust device placed over the cooktop, the requirement is for a minimum of 100 cubic feet per minute (cfm) of airflow at a maximum sound rating of 3 sones. Kitchen ventilation alternately may be provided with a higher airflow intermittent exhaust fan or a continuous exhaust fan in the kitchen. California's Building Energy Efficiency Standards require that the airflow of installed kitchen exhaust equipment must either be verified by onsite measurement or assured through use of a product that has had its airflow measured and certified by an approved testing and certification process. The approach of using a certified product also requires ducting that complies with prescriptive requirements. Until recently, the only organization approved by the state to certify range hood airflow measurements was the Home Ventilating Institute.

Recognizing that airflow is too coarse and imprecise a measure for range hood effectiveness, an effort was initiated in the mid-2010s to develop a standard test method for range hood capture efficiency. The intent was to establish a testing and certification system analogous to those existing for airflow and sound. Lawrence Berkeley National Laboratory conducted research to support this effort and the standard was developed through ASTM International (a standards organization formerly known as American Society for Testing and Materials), resulting in Method E3087. This method was developed to be repeatable and represent emissions from the burner and cooking.

The airflow of a range hood installed in a home can differ from the value published by the Home Ventilating Institute for several reasons, and airflows measured from range hoods in homes have often been lower than rated values.

Compared to standard range hoods, OTRs present a greater challenge for determining airflow as installed. When configured to operate in recirculation mode, air is drawn into OTRs through inlets on the underside and expelled through vents at the top and front, above the door. When configured to exhaust air to the outdoors (venting mode), air enters through openings at the bottom and above the door and is expelled through an opening at the top or back. The OTR flow dynamics complicate the measurement of airflow when there is no access to the outlet.

A recent California Energy Commission (CEC) funded field study of 70 single-detached homes built to comply with the state's mechanical ventilation requirements found that almost all of the homes had general mechanical ventilation equipment that met the requirements of California's Building Energy Efficiency Standards. Measurements during a one-week period in each home, with the general mechanical ventilation systems operating, found that concentrations of several measured air pollutants were generally low and few homes had pollutant concentrations that exceeded thresholds for ambient air quality standards. All homes in that study had gas cooking burners. However, because homes that participated in the study (dubbed the Healthy Efficient New Gas Homes study) were large, that raised the question of whether the results apply to smaller homes in which the same emission event produces much higher concentrations because of less dilution. A study that used a physics-based simulation model to assess the impacts of using average performance range hoods in a large, representative sample of homes in Southern California found that a substantial fraction exceeded the threshold of 100 ppb of NO_2 over a one-hour averaging period.

Another question raised by the Healthy Efficient New Gas Homes study was whether combined OTR microwave/exhaust fan appliances provide performance similar to that of conventional range hoods. In homes that participated in the study, there were more OTRs (n=38) than conventional range hoods (n=32), despite there being no OTRs at the time that were certified to meet airflow requirements of California's Building Energy Efficiency Standards. There was also a concern that the method used to measure OTR airflow in the Healthy Efficient New Gas Homes study may have caused a bias in the results by not including all air inlets.

Venting range hoods help with indoor air quality management only if they are used during cooking. It is thus important to know how frequently and under what conditions they are operated during cooking. In many studies, range hood use has been estimated by participant self-reporting. For example, in a study of 1,448 California houses built in 2003, 28 percent of respondents reported using a kitchen exhaust fan when cooking with cooktop burners and only 15 percent reported use when cooking with an oven. In a 2015 web-based survey of occupants in 2,781 California homes built since 2003, 34 percent reported using range hoods during cooking always or most of the time, 30 percent reported occasional use, and 32 percent reported rarely or never using a hood. In another California study, 34 percent of 372 homes reported using range hoods during cooking with higher frequencies during dinner and more use with longer cooking duration.

Project Purpose

The overarching aim of this project was to determine whether the provisions of the Building Energy Efficiency Standards within the California Building Code are sufficient to protect Californians from pollutants generated during cooking, particularly with gas burners. The project had four technical tasks:

1. Field study of ventilation and indoor air quality in new and renovated low-income apartments;
2. Analysis of range hood use patterns in homes with gas cooking burners;
3. Performance of combined over-the-range microwave and exhaust devices;
4. Pollutant exposure simulations to inform capture efficiency standards.

Project Approach

The objectives of the field study were to assess indoor air quality and the performance of code-required mechanical ventilation equipment in apartments in which gas cooking burners are used frequently. The study focused on properties serving income-qualifying tenants in buildings that were built or renovated under the state's residential building code requirements for mechanical ventilation. The researchers developed the study plan to complement the recent Healthy Efficient New Gas Homes study that focused on single-detached homes built with code-required ventilation since detached homes are larger with lower occupant densities. The study first identified qualifying buildings with owners or managers willing to provide the needed logistical support. The researchers then recruited tenant households through flyers and other outreach. The project team visited candidate sites to confirm the presence of compliant mechanical ventilation equipment by inspecting 2-4 unoccupied units.

Researchers surveyed participants to obtain information about satisfaction with air quality and thermal conditions in the home and routine activities that affect ventilation and indoor air quality. The project team documented characteristics of mechanical ventilation equipment, cooking appliances, and thermal conditioning systems and measured unit airtightness and ventilation equipment airflows. Temperature, humidity, carbon dioxide and air pollutant concentrations were measured inside each apartment and air pollutant concentrations were measured outdoors on site. The team installed sensors to monitor use of gas cooking burners, ventilation equipment, and natural ventilation. The researchers also asked participants to record occupancy and activities during each day of monitoring. Surveys and activity logs were collected and equipment was removed after one week of monitoring in each apartment.

The objective of the second technical task was to assess actual range hood use based on monitoring of cooking activities and range hood operation in occupied homes. The research team analyzed data collected over weeklong periods in 54 houses and 17 apartments which were recently constructed or renovated. Data were analyzed to determine the frequency of range hood use during part or all of the cooking events with a focus on the following parameters: (1) cooking burner(s) used (cooktop, oven or both); (2) home type (house or apartment); (3) range hood type (conventional hood or OTR); (4) cooking duration (minutes of burner use); (5) self-reported usage; and (6) fine particulate matter ($PM_{2.5}$) emissions during cooking. The research team also investigated whether the rate of range hood use in a home was associated with any household or equipment characteristics.

The objective of the third task was to assess whether OTRs, which at the time were not certified to meet the code specifications, could provide equivalent protection to conventional range hoods that are minimally compliant with code. After initiation, certified airflow and sound ratings were published for numerous over the range ventilation units via the Home

Ventilating Institute catalog. The task remained focused on the relative performance of OTRs and conventional range hoods of similar cost, with a focus on capture efficiency.

The task was also expanded to include an investigation of the bias in OTR airflows reported from the Healthy Efficient New Gas Homes field study. The research team conducted the following measurements:

- Measured airflows of OTRs installed in the research team's research facility with a fixed duct configuration that is a reasonable surrogate for many homes.
- Validated a new method for measuring airflows for OTRs with multiple air inlets.
- Measured capture efficiency and sound of OTRs installed as above.
- Compared capture efficiency vs. airflow relationship of OTRs to standard range hoods within similar cost range.
- Estimated bias of the method used to measure airflow in the Healthy Efficient New Gas Homes field study.

The objective of the fourth task was to inform consideration of changes to the Building Energy Efficiency Standards to specify a required level of range hood capture efficiency, rather than only focusing on airflow and sound requirements. The analysis sought to determine the capture efficiency needed to control NO_2 emitted from natural gas cooking burners and $PM_{2.5}$ emitted during cooking regardless of the cooking fuel used, that is, assuming that the same amount of $PM_{2.5}$ is produced by the meals considered whether they are cooked with gas, propane or electric burners.

The researchers assessed the indoor air quality implications of varied range hood performance levels using computer simulations of pollutant emissions and removal processes to determine time series of concentrations in homes with cooking. The simulations considered emissions from cooking and entry of pollutants with outdoor air, and accounted for removal by kitchen ventilation, continuous dwelling unit ventilation and deposition to surfaces. The simulations assumed that range hoods are used at least for the duration of all cooking events. Simulations were conducted in a "Monte Carlo" fashion in which key input parameters were selected from distributions at the start of the time series calculation for each individual home. Input parameters included home size and number of bedrooms (used in the assignment of the code-required dwelling unit ventilation rate), outdoor air pollutant levels, and deposition rates. Details about the simulation model and parameter distributions are provided in the following sections.

Project Results

Based on a very limited sample of 23 low-income apartments at four sites throughout California, findings from the research team's field study of multiunit buildings for income-qualifying Californians included:

- Mechanical ventilation systems in a substantial fraction of apartments may have operational deficiencies that affect their performance. These ventilation deficiencies likely translate to higher concentrations of air pollutants whose main source is indoor emission, compared to concentrations that would occur with operation of ventilation that meets the state building code.

- Compared to a group of single-detached houses with code-required mechanical ventilation that were examined in a recent study, apartments were more likely to have dwelling unit ventilation equipment operating but airflows were generally much lower relative to equipment ratings compared to equipment found in houses.
- Measurements of $PM_{2.5}$ and NO_2 during a week of monitoring in apartments and houses suggest that in a substantial minority of homes, concentrations may exceed health-based limits set by the United States Environmental Protection Agency and the California Environmental Protection Agency for ambient air quality or by the World Health Organization for personal exposure. Formaldehyde concentrations were lower in apartments than in houses; but still routinely above the chronic reference exposures levels set by the California Environmental Protection Agency.
- Data collected in the apartments affirm prior research showing that use of gas cooking burners produces high short-term and weekly time-averaged NO_2. While concentrations of $PM_{2.5}$ were similar in apartments and houses with similar levels of cooking, NO_2 was much higher in the apartments.

The research team's investigation of range hood use for 784 cooking events in 71 homes, including 54 houses and 17 low-income apartments, found:

- Range hoods were used more frequently in single family houses (36 percent) than in the apartments (28 percent).
- Range hood use by home generally increased with cooking frequency.
- In both houses and apartments, range hood use increased with cooktop use duration, but not with oven use duration.
- Participants who self-reported frequent use actually used their hoods more frequently; however, actual use was much lower than self-reported, with range hoods being used only 45 percent and 36 percent of the time in houses and apartments where occupants self-reported use of range hoods always, usually, or most of the time.
- Residents in single family houses used range hoods more often when cooking events generated any level of $PM_{2.5}$. In apartments, residents used the range hood more often only if high concentrations of particles were generated during cooking.

Findings from the research team's investigation of the performance of OTRs included:

- Airflows measured with a transition that covered both the top and bottom inlets of an OTR match those measured at the outlet; this supports the use of this method for field studies and potentially also for code enforcement.
- The airflow measurement method used in the Healthy Efficient New Gas Homes field study — in which the top inlet was taped and airflow was measured going into the bottom inlet — underestimated OTR airflows, presumably by changing flow dynamics inside the hood. Correction factors were determined for the 6 hoods and used to correct data for 20 OTRs in the Healthy Efficient New Gas Homes dataset.
- Airflows of OTRs were similar to range hoods of similar cost, when an adjustment is made for the functionality of the microwave (which adds cost).

- Airflows of OTRs not listed in the HVI catalog were similar to those that were listed and met the airflow requirements of Standard 62.2, set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) building performance society.
- OTR capture efficiency generally increases with airflow, and the trend was consistent with capture efficiencies reported for OTRs in previous lab and field studies using the same method.
- OTRs and standard range hoods both have much lower capture efficiencies when emissions occur on front vs. back burners and capture efficiency is a function of airflow for both types of exhaust devices, and for both front and back burners.
- The central relationship of capture efficiency to airflow is similar for OTRs and range hoods for both front and back burners, but capture efficiencies for range hoods as a group were much more variable than capture efficiencies of OTRs when emission occur on the front burners.
- Capture efficiency depends greatly on the specific conditions of the test method.

The research team's simulation-based study of NO_2 and $PM_{2.5}$ concentrations resulting from cooking in California new homes while using range hoods with varied performance levels, found the following:

- It is possible to provide kitchen exhaust ventilation that, when used routinely, will allow cooking to occur safely in homes of all sizes, with either electric or gas burners, and considering both acute and chronic exposures to cooking-related air pollutants that have established health-based guideline or benchmark levels.
- To maintain low risk (less than 1 percent) of exceeding the health-based threshold of 100 ppb averaged over one hour in homes with gas burners, range hoods should have the following performance:
  - For homes larger than 1,500 ft^2, a capture efficiency measured by the ASTM test method of 70 percent or a confirmed (verified or certified) airflow of 180 cfm.
  - For homes with 1,000-1,500 ft^2, a capture efficiency of 80 percent or an airflow of 250 cfm.
  - For homes smaller than 1,000 ft^2, a capture efficiency of 85 percent or an airflow of 280 cfm.
- To maintain low risk (less than 1 percent) of exceeding the health-based threshold of 25 micrograms/cubic meter $PM_{2.5}$ averaged over 24 hours, every home should have a range hood that minimally meets the following specifications:
  - For homes larger than 1,000 ft^2, a capture efficiency of 50 percent or an airflow of 110 cfm.
  - For homes with 750–1,000 ft^2, a capture efficiency of 55 percent or an airflow of 130 cfm.
  - For homes smaller than 750 ft^2, a capture efficiency of 65 percent or an airflow of 160 cfm.

Since pollutants are generated from cooking with any energy source, excluding gas cooking appliances does not eliminate the need for effective kitchen ventilation. However, as seen from the requirements noted above, the exclusion of gas effectively mitigates the hazards of combustion pollutants, principally NO_2, and provides more flexibility in kitchen ventilation.

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

The project team provided extensive technical support to the codes and standards enhancement team that was assigned to develop proposals for the 2022 Building Energy Efficiency Standards and to the CEC standards team as they translated those proposals to requirements for improved kitchen in the 2022 Building Energy Efficiency Standards. The research team's technical support included presenting and serving on a panel at a public workshop on September 30, 2020 and two memoranda with technical comments submitted to the public docket; the latter addressed specific questions raised by stakeholders at the public workshop and by CEC staff. The research team also provided multiple briefings to translate the research team's technical papers and analyses to stakeholders, including a builder and several non-governmental organizations; technical support to other entities that develop or maintain codes and standards related to kitchen ventilation in efficient residences (including ASHRAE, Heating Ventilation Institute, and the Association for Home Appliance Manufacturers); and technical support to other researchers studying air pollutant emissions from residential gas cooking burners and the resulting exposures to Californians.

The researchers have shared the results of this project with the public principally via technical reports and papers and presentations at scientific conferences, including:

- Three papers published in peer-reviewed archival journals. All content is freely available to the public via the publications page of Lawrence Berkeley National Laboratory's energy technologies area website (https://eta.lbl.gov/publications).
- Two datasets published on the open-access Dryad platform.
- Two Lawrence Berkeley National Laboratory technical reports, which are also available via the energy technologies area website.
- Three papers or extended abstracts in the Proceedings of Indoor Air 2020.
- Three presentations and one symposium at the Indoor Air 2020 conference.

Benefits to California

There is a substantial body of research demonstrating that use of natural gas cooking burners without adequate ventilation can relatively commonly result in acute NO_2 concentrations inside kitchens that exceed health-based limits set for outdoor air quality. Particles produced and emitted during cooking can lead to fine particulate matter concentrations that exceed World Health Organization guidelines. Effective kitchen ventilation enables Californians to safely cook in their homes without having to experience hazardous air pollutant exposures.

The public health burden of exposure to NO_2 from gas cooking burners and $PM_{2.5}$ from cooking is substantial. A 2012 study by Logue et al. of Lawrence Berkeley National Laboratory estimated annual health costs of $940,000 and 19.2 disability adjusted life years (DALYs) lost per year per 100,000 people when cooking without range hood use. To estimate benefits, the research team set the cost of a DALY at $100,000 and assume the following: 85 percent of the 13.6 million Californians live in homes with natural gas cooking; range hoods are used during

35 percent of cooking events; and hoods are 55 percent effective on average. Under this baseline situation, researchers estimate the benefit of range hood use reducing acute exposures at about $63 million annually. If capture efficiency is increased to 95 percent, the total benefit would be $110 million annually for a net benefit of $47 million annually. If range hood use is doubled with high capture efficiency hoods, the total avoided health costs would be $220 million or about $160 million incremental benefit. These estimates were developed from simulations of homes in southern California. The estimate of 55 percent capture was based on measurements from a 2012 study and the range hood use estimates were approximated from surveys conducted by Lawrence Berkeley National Laboratory over the past decade.

Surveys indicate that many Californians feel that their kitchen ventilation equipment is too noisy or ineffective. Standards that address these performance issues will result in products that are used more – and thus more effectively – and provide comfort and health benefits to consumers.

The results of this project helped the CEC formulate and establish science-based performance requirements that are no more strict than essential for maintaining public safety, leading to significant but hard-to-estimate cost savings relative to the potential alternative of a more onerous and restrictive standard that could have occurred in the absence of this work.

There are also substantial benefits to equity and environmental justice as the populations most harmed by inadequate kitchen ventilation performance standards are those living in smaller homes, which are disproportionately lower-income Californians.

CHAPTER 1: Introduction

An airtight envelope is a core element of an energy efficient and resilient residential building. Reducing uncontrolled air exchange with outdoors reduces heating and cooling loads – in part because the highest rates of uncontrolled air movement occur when outdoor temperatures are most different from the desired indoor temperatures – and also reduces the entry of outdoor air pollution, which is particularly important during wildfire events. For multiunit buildings it is also important to reduce pathways for air to move between units, as movement within the building can transfer odors and pollutants as well as impact thermal comfort and energy use. Reducing air leakage can also reduce outdoor air exchange and consequently reduce dilution and removal rates for air pollutants generated indoors. The California Building Code addresses this challenge by requiring mechanical ventilation to be installed in all new construction.

Starting in 2008 California's Building Energy Efficiency Standards (BEES), commonly referred to as "Title 24," have required new homes to have mechanical ventilation that is consistent with Standard 62.2 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), a professional society concerned with building performance. Standard 62.2, Ventilation and Indoor Air Quality in Residential Buildings, and the BEES require minimum airflow rates for dwelling unit ventilation to control long-term exposures to continuously emitted pollutants, kitchen exhaust ventilation to manage odors, moisture and both short- and long-term exposures to pollutants from cooking and other activities in the kitchen, and exhaust ventilation in bathrooms and toilet rooms for odor and moisture control (California Energy Commission 2008; ANSI/ASHRAE 2019). Both ASHRAE 62.2 and the BEES are periodically updated in light of new information about performance needs and in consideration of available technologies and products.

Cooking is among the largest sources of air pollutant emissions inside many homes. Gas cooking burners produce carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO) and ultrafine particles and electric burners generate ultrafine particles in substantial quantities (L. Wallace et al. 2008; Dennekamp et al. 2001; Moschandreas and Relwani 1989; L. A. Wallace, Emmerich, and Howard-Reed 2004; Mullen et al. 2016; Less 2012; B. C. Singer, Pass, et al. 2017). NO_2 from gas cooking burners may commonly result in indoor concentrations that exceed the threshold of 100 ppb over one hour that is used in the U.S. ambient air quality standard (B. C. Singer, Pass, et al. 2017; Logue et al. 2014). Belanger et al. (Belanger et al. 2013) reported that higher residential exposures to NO_2 was associated with asthma severity. In a meta-review, Lin et al. (Lin, Brunekreef, and Gehring 2013) reported that gas cooking and higher NO_2 exposure were each associated with increased risk of asthma and higher NO_2 was associated with current wheeze. High temperature cooking activities (for example, frying and broiling) contribute odors and pollutants including hazardous organic gases, polycyclic aromatic hydrocarbons, and fine and ultrafine particles (Abdullahi, Delgado-Saborit, and Harrison 2013; Buonanno, Morawska, and Stabile 2009; Fortmann, Kariher, and Clayton 2001; Fullana, Carbonell-Barrachina, and Sidhu 2004; Seaman, Bennett, and Cahill 2009; Zhang et al. 2010; Y. J. Zhao and Zhao 2018; Torkmahalleh et al. 2017; Chen et al. 2020). Higher exposures to these pollutants are associated with adverse health effects

(US EPA 2009). A study in Hong Kong (Yu et al. 2006) also reported a dose-response relationship between lifetime exposure to cooking fumes and lung cancer. Both gas burners and cooking generate water vapor that may contribute to excess indoor moisture and associated problems if not adequately managed (Liu et al. 2020).

Venting range hoods and combination "over the range" (OTR) microwave/exhaust fans mounted above the cooktop are designed to remove some fraction of the emitted pollutants to outdoors before they mix into the air volume of the kitchen and throughout the home. There are several relevant measures of range hood performance. The two most commonly used, and the measures for which data are most readily available, are airflow and sound level. These metrics are measured using standard test procedures published by the Home Ventilating Institute (HVI Publications 914 and 915) (HVI 2013a; 2013b). HVI certifies and publishes test results in a free online directory, which includes both standard range hood and OTRs. HVI also provides guidance on minimum and recommended exhaust hood airflow rates in units of cubic feet per minute (cfm) per linear foot (lf) of cooking appliance width. For a 30-inch (76.2 cm) wide range, these translate to minimum and recommended airflows of 100 cfm (47 L/s) and 250 cfm (118 L/s).

Several modeling and experimental studies have examined the performance of range hood use to reduce cooking-related indoor air pollution (Mullen et al. 2016, 201; B. C. Singer, Pass, et al. 2017, 201; Logue et al. 2014; Delp and Singer 2012, 201; Rim et al. 2012; B. C. Singer et al. 2012; Lunden, Delp, and Singer 2015; Y. Zhao and Zhao 2020; Dobbin et al. 2018; O'Leary et al. 2019). Exhaust devices at the cooktop, including range hoods, OTRs and potentially even downdraft exhaust devices that pull air down toward an inlet at or near the cooktop, may do this more effectively than an exhaust fan at the ceiling or upper wall.

A third metric, for which more limited data are available, is capture efficiency (CE). Capture efficiency is defined as the fraction of contaminants emitted at the cooktop that are directly pulled into the range hood and exhausted to the outdoors before mixing throughout the house. A CE of 100 percent means all of the cooking pollutants are exhausted directly to the outside, and a CE of zero means that none of the cooking pollutants are directly exhausted, allowing all of them to mix with indoor air. Capture efficiency was first studied decades ago (for example, (Revzan 1986; Li and Delsante 1996)) and the metric has received increasing attention since it was used in studies conducted by LBNL in the early 2010s (Delp and Singer 2012; B. C. Singer et al. 2012).

Research conducted by the research team's group prior to the current project, with range hoods and OTRs in both laboratory and occupied home installations, found that CE for a given device depends strongly on airflow, the type of cooking and whether cooking is done on the front or back burners (B. C. Singer, Pass, et al. 2017, 201; Delp and Singer 2012; B. C. Singer et al. 2012; Lunden, Delp, and Singer 2015). The research team's studies also found that CE varies between devices. And based on just a few OTRs included in the studies, it appeared that the CE performance of OTRs could be appreciably lower than for range hoods.

Kitchen ventilation requirements traditionally have specified a minimum certified airflow and maximum certified sound rating at the minimum airflow. For any exhaust device placed over the cooktop, the requirement is for a minimum of 100 cubic feet per minute (cfm) of airflow at a maximum sound rating of 3 sones. Kitchen ventilation alternately may be provided with a higher airflow intermittent exhaust fan or a continuous exhaust fan in the kitchen. Both ASHRAE 62.2 and the BEES have required for several years that the airflow of installed kitchen exhaust ventilation equipment must either be verified by on site measurement or assured through use of a product that has had its airflow measured and certified by an approved testing and certification process. (And the approach of using a certified product also requires ducting that complies with prescriptive requirements.) Until recently, the only organization approved by the state to certify range hood airflow measurements was the Home Ventilating Institute, or HVI.

Recognizing that airflow is too coarse and imprecise of a measure for range hood effectiveness, an effort was initiated in the mid-2010s to develop a standard test method for range hood capture efficiency. The intent was to establish a testing and certification system analogous to those existing for airflow and sound. The research to support this effort was conducted by LBNL (Kim, Walker, and Delp 2018) and the standard was developed through ASTM, resulting in Method E3087 (ASTM 2018). It is important that this method was developed to be repeatable and to represent emissions from both the burner which is focused around the edges, and cooking, which is focused in the centers of burners.

The airflow of a range hood installed in a home can differ from the value published by HVI because the static pressure in the duct system may be substantially higher than the duct static pressure in the HVI test. And the effect of higher downstream duct pressures varies based on the performance curve of the fan and the relationship of airflow to pressure in the duct system, both of which are non-linear. The HVI test procedure sets a downstream pressure for the range hood fan operating at its highest setting then measures airflow at other settings using the same system pressure curve. The ASHRAE 62.2 and California Title 24 standards require range hoods that move at least 100 cfm or 50 L/s of airflow with a downstream duct static pressure of 62.5 Pa. Yet the vast majority of range hoods listed in the HVI catalog have been tested at downstream static pressures of only 25 Pa when the fan is operating at high speed. This operating condition establishes the relationship between airflow and static pressure (which is described by the airflow vs. static pressure system curve) for the test configuration. When the test is performed at "working speed", which is usually the setting designed to meet the standard flow requirement of 100 cfm or 50 L/s, the static pressure is thus much lower than 25 Pa.

The installed sound level can also be higher than the value reported in a standard test, resulting from vibrations in the duct system or a loose mounting of the hood. However, the test that provides sound level results in sones cannot be replicated in a field setting.

In consideration of the potential differences between rated and installed airflows, it is important to collect data on airflows of hoods as installed in homes. A method to conduct airflow measurements of range hoods and other exhaust (or supply) fans was described by Walker et al. (Walker et al. 2001). Briefly, the method involves affixing a calibrated fan to the exhaust (or supply) fan via a transition piece that allows for the differential pressure between the transition and the room to be measured. The calibrated fan is adjusted to the point that the pressure between the transition and the room is balanced. At that point, the airflow through the calibrated fan is matching the airflow through the exhaust (or supply) fan. For range hoods and OTRs, the challenge is to construct a transition that covers all large air inlets from the room into the exhaust device.

Compared to standard range hoods, OTRs present a greater challenge for determining airflow as installed. When configured to operate in recirculation mode, air is drawn into OTRs through inlets on the underside and expelled through vents at the top and front, above the door. When configured to exhaust air to the outdoors (venting mode), air is expelled through an opening at the top or back (which must be punched out during installation); and air enters through the openings at the bottom and through the vents above the door. Air can additionally enter through small holes and gaps in the outer shell; but due to their small cumulative area these pathways likely contribute very little as inlets. The OTR flow dynamics complicate the measurement of airflow when there is no access to the outlet. Applying the balanced-pressure flow method requires a customized transition box that covers air inlets at the bottom and top of the device.

A CEC-funded field study of 70 single-detached homes that were built to comply with the state's mechanical ventilation requirements found that almost all of the homes had general mechanical ventilation equipment that met the requirements of California's BEES (B. C. Singer et al. 2020; W. R. Chan et al. 2019). Measurements during a one-week period in each home, with the general mechanical ventilation systems operating, found that concentrations of several measured air pollutants were generally low and few homes had pollutant concentrations exceed thresholds for ambient air quality standards (B. C. Singer et al. 2020). The homes in that study all had gas cooking burners, and the study was dubbed the Healthy Efficient New Gas Homes study, or HENGH. However, since the homes in that study were generally very large, a key unanswered question was how applicable the results are to smaller homes, where the same emission event would lead to much higher concentrations because of less dilution within the home. When Logue et al. (Logue et al. 2014) used a physics-based simulation model to assess the impacts of range hood use on a large, representative sample of homes in Southern California, they found that use of hoods with average performance (based on the field study of Singer et al. (B. C. Singer et al. 2012)) would still result in a substantial fraction exceeding the threshold of 100 ppb NO2 averaged over 1 hour (h).

Another question from the HENGH single-detached home study is whether combined OTR microwave/exhaust fan appliances provide similar performance as conventional range hoods. This question is particularly important in light of the following observations. (1) There were actually more OTRs (n=38) than conventional range hoods (n=32) in the houses in the HENGH study. (2) The preponderance of OTRs over conventional range hoods occurred despite there being no OTRs available on the US market that were certified to meet airflow requirements of the BEES for much or all of the time prior to the field study. And (3) a recognition after the HENGH study was completed that the reported airflows may have been biased low because the approach used in that study to measure OTR airflows did not include all air inlets from the room (H. Zhao et al. 2020). There was also the issue noted previously of OTRs potentially having worse capture efficiency performance relative to range hoods.

Venting range hoods help with indoor air quality (IAQ) management only if they are used when cooking occurs. It is thus important to know how frequently and under what conditions they are operated during cooking. In many studies, range hood use has been estimated based on participant self-reporting. Studies have inquired of generic use (yes/no) and sometimes queried the frequency or reasons for using or not using the devices. For example, in a study of 1448 detached houses in California built in 2003, 28 percent of survey respondents reported using a kitchen exhaust fan when cooking with cooktop burners but only 15 percent reported exhaust fan use when cooking with an oven (Piazza et al. 2007). In a web-based survey of occupants in 2781 California homes built since 2003, 34 percent of households reported using their range hoods during cooking always or most of the time, 30 percent reported occasional (sometimes) use and 32 percent reported rarely or never using a hood (W. R. Chan et al. 2019). In another California study, 34 percent of 372 homes reported using their range hoods during cooking, with higher frequencies during dinner and more use with longer cooking duration (Klug, Lobscheid, and Singer 2011). Higher resolution information on self-reported range hood use is available from daily activity logs recorded in some IAQ studies. In a study of 132 Canadian homes, Liu and Wallace found that only 13 percent of households reported range hood use during cooking events in winter and use decreased to 10 percent of cooking events in summer (Sun and Wallace 2020).

The overarching aim of this project was to determine whether the extant provisions of the BEES within the California Building Code were sufficient to protect Californians from pollutants generated during cooking, particularly with gas burners. The project had the following four technical tasks:

- Field study of ventilation and indoor air quality in new and renovated low-income apartments;
- Analysis of range hood use patterns in homes with gas cooking burners;
- Performance of combined over-the-range microwave and exhaust devices;
- Pollutant exposure simulations to inform capture efficiency standards.

The approach, results and conclusions of the first two tasks have been reported in detail in scientific papers published in peer-reviewed archival journals (Haoran Zhao, Chan, Cohn, et al. 2020b; Haoran Zhao, Chan, Delp, et al. 2020) and the final two tasks have been reported in detail in published technical reports (H. Zhao et al. 2020; W. R. Chan et al. 2020). The content of each report is available to the public via the publications database maintained by the Energy Technologies Area of Lawrence Berkeley National Laboratory (https://eta.lbl.gov/publications).

This report provides summaries of the technical tasks in Chapters 2 through 5.

CHAPTER 2:
Field Study of Ventilation and Indoor Air Quality in New and Renovated Low-Income Apartments

Objective and Overview

The objective of this task was to assess indoor air quality and the performance of code-required mechanical ventilation equipment in apartments in which gas cooking equipment is present and used frequently. The intent of the study was to focus on multifamily properties that serve income-qualifying tenants in buildings that comply with the state's residential building code requirements for mechanical ventilation. The study was developed as a complement to the recently completed Healthy Efficient New Gas Homes (HENGH) study (B. C. Singer et al. 2020), which focused on single-detached homes that were also built with code-required ventilation but were much larger with lower occupant densities.

The details of this study are reported in a peer-reviewed journal article (Haoran Zhao, Chan, Cohn, et al. 2020b), whose content is available to the public via the publications database maintained by the Energy Technologies Area of Lawrence Berkeley National Laboratory (https://eta.lbl.gov/publications). A database of data collected in the field study is also publicly available (H. Zhao, Chan, Cohn, et al. 2020a). This chapter presents only a brief summary of the methods along with the main results and conclusions.

Approach

The study inclusion criteria were for apartment units to have mechanical ventilation (MV) equipment meeting the requirements of California's Title 24 residential building code and a natural gas cooking appliance that is used on a daily or almost daily basis. Participation also required that the household have a prohibition on smoking in the apartment and agreement to refrain from using windows or doors as a means of regular ventilation during the week of monitoring. The study was approved by the institutional review board of LBNL. The incentive of a $300 gift card was provided for completion of all study elements.

Candidate buildings were identified by the subcontractor, the Association for Energy Affordability (AEA), through outreach to property owners and managers, focusing on those who had previously participated in an energy-efficiency upgrade program. Sites with owners/managers that expressed interest were visited to confirm the presence of compliant MV equipment; this was done by inspecting 2-4 unoccupied units per site. Recruitment proceeded at sites with compliant equipment. Recruitment was done through direct outreach by AEA to tenants, initially through flyers in mailboxes or posted on community bulletin boards, then limited door-to-door as needed.

Each participant was asked to complete a survey to obtain information about satisfaction with air quality and thermal conditions in the home and routine activities that impact ventilation and IAQ. Characteristics of mechanical ventilation equipment, cooking appliances, and thermal conditioning systems were documented and unit airtightness and ventilation equipment airflows were measured. Temperature, humidity, carbon dioxide and air pollutant concentrations were measured inside each apartment and air pollutant concentrations were measured outdoors on site. Sensors were installed to monitor use of gas cooking burners, ventilation equipment, and natural ventilation. Participants were asked to record occupancy and activities during each day of monitoring. Surveys and activity logs were collected and equipment was removed after one week of monitoring in each apartment. Details about the measurement equipment and methods, quality assurance procedures, and data processing and analysis procedures are provided in the published paper.

Results

Apartment Characteristics

Data collection occurred in 23 apartments at 4 sites that provided below market-rate rents to income-qualifying residents; subsequently described as "low-income" apartments. Studied buildings were in Alameda, San Francisco, Los Angeles, and San Diego counties. Summary characteristics of the studied apartments are compared to those from the recent HENGH study of California single detached houses in Table 1: Selected Home Characteristics of Apartments in this Study and Houses in Previously Published HENGH Study .

Mechanical Ventilation Equipment

All of the studied apartments had kitchen and bath exhaust fans that would comply with the mechanical ventilation airflow and sound requirements of the 2007 (through 2016) California BEES if the fans were operating and performing according to specifications. However, measured airflows met the 2007 code requirements for all mechanical equipment (bath exhaust, range hood and continuous MV) in only 8 apartments. Three units lacked a complete set of operational equipment: one didn't have a functioning bath/central MV fan and two others didn't have working range hoods. Of the 21 apartments with airflow measurements for at least one continuous dwelling unit ventilation fan, 16 met the minimum required by the code that was applicable when they were built or renovated and 13 met the minimum requirement in the recently implemented 2019 code. Another four units were within 90 percent of the 2007 code requirements.

Sites 2 and 3 had mean values of measured apartment air leakage that met the limit specified in the 2019 state building code for apartments using unbalanced ventilation. While none of the sites were subject to this code when they were built or renovated, it is noteworthy that the target was met at Site 2, built in 1976 and renovated in 2016, and by Site 3, built in 2016, though not by Site 4, built in 2013.

All of the bath exhaust fans and range hoods installed in apartments had rated airflows certificated by the Home Ventilating Institute (hvi.org). Most of the installed airflows were much lower than values listed in product specifications and ratings certified by HVI. Across all apartments, mean and 10th–90th percentiles of the measured to rated airflow ratios were 54 percent and 21–90 percent for bath fans and 68 percent and 36–90 percent for range hoods. Decrements in installed performance were similar across sites for the bath fans whereas the range hoods at Sites 3 and 4 had airflows much closer to the rated values than did the range hoods at Sites 1 and 2. It is assumed that differences between rated and actual airflows result from higher duct static pressure as installed compared to the conditions used in the rating test. Twenty-two apartments had exhaust fans that were running to provide continuous ventilation when the research team first arrived at the apartment.

Table 1: Selected Home Characteristics of Apartments in this Study and Houses in Previously Published HENGH Study

Characteristic	Apartment sample	House sample
Year built/renovated	Built or renovated 2013–2016	Built 2011–2017
Units studied	23 units at 4 sites	70 detached houses
Building heights	Sites 1–3: 1–3 stories Site 4: 5 stories	1–2.5 stories
Monitoring dates	02/2019–11/2019	07/2016–04/2018
Mean floor area in m^2	76	244
Median floor area in m^2 (10th–90th percentile)	85 (35–106)	243 (146–339)
Mean density (m^2/occupant)	38	88
Median density, m^2/occupant (10th–90th percentile)	33 (24–62)	77 (45–143)
Mean ACH50[a]	8.0	4.6
Median ACH50[a] (10th–90th percentile)	8.6 (2.0–14.3)	4.4 (3.4–6.0)
Mean AER (hr^{-1})	0.55, Mechanical only[b]	0.33, Total[c]
Median AER in hr^{-1} (10th–90th percentile)	0.54 (0.26–0.90)	0.30 (0.20–0.46)
Mean ventilation airflow (L/s)	26, Mechanical ventilation only[b]	56, Total ventilation[c]
Median ventilation airflow in L/s (10th–90th percentile)	20 (17–39)	55 (38–73)

[a] Air change rate at 50 Pascal pressure difference was measured by depressurizing each dwelling unit using a Minneapolis blower door system. For apartments, the leakage air comes from outdoor, corridors and other adjacent apartments. For single family houses, the leakage air comes from outdoors.

[b] Mechanical ventilation airflow and estimated mechanical AER were calculated from 21 out of 23 apartments, excluding one unit of which the ventilation airflows were not measured and one unit in which the continuous MV fan was not working.

[c] Total ventilation airflow and estimated total AER were calculated from 57 out of 70 detached houses, excluding 7 houses of which the ventilation airflows were not measured and 6 houses of which MV system were not properly operated.

Source: B. C. Singer et al. 2020

Occupant Activities

According to both activity log and sensor data, there was substantial window and door opening for ventilation in several apartments. The mean fraction of occupied hours in apartments was 85 percent with 10th–90th range of 68–100 percent.

Apartments had means of 2.2 burner events and 51 min of cooktop burner use, per day. The overall sample of single detached houses in the HENGH study had means of 1.3 events and 31 cooktop burner min, per day. To provide comparisons of indoor air quality in apartments and homes with similar levels of cooking, the research team selected the subset of 40 houses that did the most cooking; those houses had means of 2.1 cooking burner events per day and 48 cooktop burner min/day.

Additional details about cooking activities and range hood use are provided in the next chapter of this report.

Time-Integrated Air Pollutant Concentrations

Table 2: Air Pollutant Concentrations Over One Week in Apartments and Houses with Similar Amounts of Cooking with Gas Burners presents summary statistics of the time-integrated air pollutant concentrations measured at the central indoor locations of the low-income apartments in this study and in the detached houses with frequent cooking of the HENGH study.

Table 2: Air Pollutant Concentrations Over One Week in Apartments and Houses with Similar Amounts of Cooking with Gas Burners

Measure	HCHO (ppb) Apts	HCHO (ppb) Houses	$PM_{2.5}$ (μg/m^3) Apts	$PM_{2.5}$ (μg/m^3) Houses	NO_2 (ppb) Apts	NO_2 (ppb) Houses	CO_2 (ppm) Apts	CO_2 (ppm) Houses
Indoor	N=21	N=40	N=21	N=40	N=22	N=38	N=23	N=40
Mean	14.1	18.7	7.7	8.0	18.8	7.1	741	628
Median	10.9	17.7	3.9	4.9	16.6	5.5	680	625
10th–90th	8.1–22.4	12.8–27.2	1.8–15.0	2.4–17.9	10.8–30	1.5–14.2	584–955	519-765
Outdoor	N=21	N=40	N=21	N=39	N=22	N=37	No data	No data
Mean	1.7	2.2	7.5	10.1	10.1	6.1	No data	No data
Median	1.4	2.2	5.6	9.1	8.4	3.2	No data	No data
10th–90th percentile	0.8–2.8	1.5–2.9	4.8–14.2	5.3–16.4	4.5–20	0.1–13.4	No data	No data

Source: Lawrence Berkeley National Laboratory

Formaldehyde was substantially lower in the apartments than in the detached houses with the difference statistically significant (p=0.005 based on Mann-Whitney test). This is an expected result since (a) the apartments were older than the houses and (b) because higher air change rates reduce formaldehyde (Huangfu et al. 2019; Hult et al. 2015). Building age is important because formaldehyde concentrations decrease substantially over the first few years after a building is constructed (Park and Ikeda 2006) and 48 of 70 houses in the HENGH study were measured when they were less than 3 years old. Formaldehyde was slightly lower outside of the apartments than outside of the houses, but the difference was small compared to the indoor difference. While formaldehyde in the apartments was lower than in the HENGH houses, concentrations still substantially exceeded the chronic and 8-h references exposure levels of the California Office of Environmental Health Hazard Assessment, set at 7 ppb for both time frames.

$PM_{2.5}$ concentrations inside the houses and apartments were not significantly different based on the Mann-Whitney test ($p=0.73$); but $PM_{2.5}$ was higher outside of the HENGH houses ($p=0.02$). The higher ratios of indoor to outdoor indicate more impact of indoor sources in the apartments. Mean indoor / outdoor $PM_{2.5}$ concentrations at the four sites were 8.1 / 5.0, 3.4 / 6.0, 4.7 / 4.9, and 14.9 / 13.6 $\mu g/m^3$.

Four out of 20 apartments (20 percent) had weekly average indoor $PM_{2.5}$ above the annual average $PM_{2.5}$ of 12 $\mu g/m^3$ allowed in the California and U.S. EPA Ambient Air Quality Standards (AAQS). Similarly, seven of 40 HENGH houses (18 percent) selected for comparison had weekly average $PM_{2.5}$ above 12 $\mu g/m^3$. Two of 21 apartments (11 percent) had 24-h $PM_{2.5}$ concentrations above the US EPA AAQS of 35 $\mu g/m^3$, including one apartment that had a broken range hood and indications of smoking indoors. Similar fractions of apartments and houses had instances of 24 h average concentrations exceeding the World Health Organization exposure guideline of 25 $\mu g/m^3$. Among the 20 apartments with valid data, four (20 percent) had at least one 24-h period with $PM_{2.5}$ above 25 $\mu g/m^3$. In the 40 comparison houses from the HENGH study, adjusted photometer data indicated nine (23 percent) with at least one 24-h period of $PM_{2.5}$ above 25 $\mu g/m^3$.

NO_2 concentrations were both substantially and significantly higher inside the apartments than inside the detached houses ($p<0.01$) and also higher outside of the apartments than outside of the houses ($p<0.01$). Mean indoor / outdoor NO_2 concentrations were 20.4 / 9.8 ppb at Site 1, 18.4 / 4.6 ppb at Site 2, 14.0 / 7.9 ppb at Site 3, and 22.0 / 19.7 ppb at Site 4. The effect of outdoor NO_2 is expected to be highest at Site 4 because that site had both the highest outdoor NO_2 concentration and also the highest air exchange rates. Indoor measurements of time-integrated NO_2 did not exceed the U.S. annual average AAQS of 53 ppb in any apartment or house, but three apartments (and no houses) had indoor NO_2 concentrations above the California AAQS of 30 ppb during the week of monitoring. An apartment that used the oven for overnight heating had the 3rd highest weekly-averaged indoor NO_2 (30.6 ppb) and the highest weekly-averaged NO_x concentration (97.6 ppb).

The higher indoor NO_2 in apartments is partly caused by higher outdoor concentrations but may also result from differences in emissions or emissions being less diluted by smaller volumes in apartments. To explore the magnitude of these factors, the research team estimated the indoor concentration resulting from indoor emissions in houses and selected apartments by material balance analysis, treating each housing unit as a well-mixed air volume with steady-state indoor and outdoor concentrations equal to the weekly averages and other influencing parameters. Details are provided in the Supporting Information of the published paper. The analysis was conducted for 37 houses that had all required data and for 10 apartments which had outside entrance doors (not corridors) and window opening time less than one hour per day based on activity logs and monitored data. This analysis provided a mean indoor NO_2 concentration from indoor emission of 14.0 ppb and range of 4.8–32.4 ppb in the 10 selected apartments and mean of 4.8 ppb and range of 0–16.3 ppb in the 37 houses. There were similar frequencies of cooking events with gas burners in the apartments and houses, with somewhat higher amounts of burner use at the lower end of the distribution for cooking events in apartments.

CO_2 concentrations were generally higher in the apartments than in the detached houses of the HENGH study; but the differences in incremental CO_2 (above an assumed outdoor background of ~400 ppm) are not proportional to the more than 2x higher occupant densities in the apartments. The higher mechanical air exchange rates in the apartments – along with substantial natural ventilation in at least 5 apartments – resulted in a 90th percentile weekly mean CO_2 below 1,000 ppm, a commonly used indicator of adequate ventilation. Mean indoor CO_2 concentrations were 643, 767, 828 and 725 ppm for the four sites.

Several parameters were measured using the same device in both a central location and master bedroom in most apartments: time-integrated NO_2 and NO_X and time-resolved CO_2 and $PM_{2.5}$. NO_2 in the central areas was >10 percent higher than in the bedrooms in 12 apartments, as expected since the source of NO2 emitted indoors is the kitchen. $PM_{2.5}$ concentrations were similar at central and bedroom locations.

Acute Impacts of Fine Particulate Matter and Nitrogen Dioxide Emission Events

The research team assessed the potential impact of indoor emission events on IAQ by examining hourly concentrations of mass-adjusted $PM_{2.5}$ and baseline-adjusted NO_2 in apartments and houses. This analysis considered the 3rd highest hourly concentration of each pollutant in each home, which is roughly the 98th percentile over the ~160 h of data available in most homes. While the subgroup of houses selected for frequent cooking had a higher median value of 3rd. highest $PM_{2.5}$ than the apartments, the ranges were similar. Short-term NO_2 was much higher in apartments, with median 3rd highest 1-h NO_2 of 41 ppb in 14 apartments with data and 18 ppb in 30 houses with data. While different devices were used to measure time-resolved NO_2 in the two studies, and each has high uncertainty, the higher 1-h concentrations are consistent with the higher weekly-averages.

Satisfaction with Indoor Air Quality

The comparison of satisfaction and discomfort with environmental conditions is limited by the use of slightly different questions in the two studies and small samples sizes, but obvious differences were found for some comfort conditions. Eleven of 19 apartments (58 percent) were problematically too cold in winter, compared with only 30 percent of houses being too cold a few times per week. In summer, too hot was a problem in 74 percent of apartments (14/19) but occurred a few times per week or more in only 30 percent of the houses. Not enough air movement was a problem in 32 percent of apartments and 22 percent of houses. The data suggest higher rates of IEQ discomfort in the apartments.

Limitations

This study had several substantial limitations. The most important is the unknown bias of a small and non-random sample. The working condition of ventilation equipment at the four sites and the measured indoor air quality parameters over a single week in 23 apartments cannot be assumed to represent conditions throughout the state, let alone the US; all results therefore must be regarded as exploratory and suggestive, rather than robust or certain.

Comparisons between measured IAQ parameters in houses and apartments may be influenced by multiple household and home characteristics. The research team focused on cooking and gas burners as major indoor sources for nonsmoking households and selected a subgroup of houses with similar cooking levels to compare to apartments. Aside from the smaller volumes, higher densities and higher mechanical air exchange rates in apartments, IAQ also may have been impacted by more natural ventilation from window and door opening in at least 21 percent (5/23) of apartments compared to an estimated <10 percent of the houses. In addition to these differences, the request that residents not use windows and doors to provide natural ventilation during the week of monitoring may have impacted air pollutant concentrations relative to typical behavior in those homes. Air exchange rates were not measured previously in the houses or in the apartments in this study and it is not known how much of the mechanically-induced air exchange in the apartments came from outdoors and how much from other spaces within the building, via. internal leakage. For air pollutant comparisons, there were differences in instrumentation used by the two studies that could result in differences despite calibrations and quality assurance procedures. While outdoor concentrations of $PM_{2.5}$ and NO_2 are reported, their impact on indoor levels has not been formally quantified for apartments in the present study or for the prior study of houses; such an analysis would require a reliable estimate of overall outdoor air exchange and the pathway of air entry into apartments. Indoor pollutants concentrations were compared to thresholds used in outdoor standards, which may not directly translate to safe levels inside homes.

Conclusions

Notwithstanding the limitations noted above, several qualified conclusions may be drawn from the comparisons of mechanical ventilation equipment and indoor air quality measured in the current study and the same parameters reported in the recent study of detached houses subject to similar code requirements. While the apartments much more commonly had dwelling unit MV equipment operating, the airflows were generally much lower than equipment ratings compared to the houses. Measurements of $PM_{2.5}$ and NO_2 during a week of monitoring suggest that in a substantial minority of homes, concentrations may exceed health-based limits set by the US and California EPA for ambient air quality or by the World Health Organization (WHO) for personal exposure. Formaldehyde concentrations were lower in apartments than in houses; but still routinely above the chronic reference exposures levels set by the California EPA. Data collected in the apartments affirm prior research showing that use of gas cooking burners produces high short-term and time averaged NO_2. While concentrations of $PM_{2.5}$ were similar in apartments and houses with similar levels of cooking, NO_2 was much higher in the apartments.

Based on a very limited sample, the findings of this study suggest that mechanical ventilation systems in a substantial fraction of apartments may have operational deficiencies that impact their performance. These ventilation deficiencies likely translate to higher concentrations of air pollutants whose main source is indoor emission, compared to those that would occur with operation of ventilation meeting the state building code.

CHAPTER 3: Analysis of Range Hood Use Patterns in Homes with Gas Cooking Burners

Objective and Overview

The objective of this task was to assess actual range hood use based on monitoring of cooking activities and range hood operation in occupied homes. This study presents an analysis of data collected over weeklong periods in 54 houses and 17 apartments which were recently constructed or renovated in California. Data were analyzed to determine the frequency of range hood use during part or all of the cooking events with a focus on the effects of the following parameters: (1) cooking burner(s) used (cooktop, oven or both); (2) home type (house or apartment); (3) range hood type (conventional hood or OTR); (4) cooking duration (minutes of burner use); (5) self-reported usage; and (6) fine particulate matter ($PM_{2.5}$) emissions during cooking. The research team also investigated whether the rate of range hood use in a home was associated with any household or equipment characteristics.

The details of this study are reported in a peer-reviewed journal article (Haoran Zhao, Chan, Delp, et al. 2020), whose content is available to the public via the publications database maintained by the Energy Technologies Area of Lawrence Berkeley National Laboratory (https://eta.lbl.gov/publications). Data used in this analysis are available in two published datasets (H. Zhao, Chan, Cohn, et al. 2020a; W. Chan et al. 2020). This chapter presents only a brief summary of the methods along with the main results and conclusions.

Approach

This study used data collected during the recent HENGH study of single-detached homes (B. C. Singer et al. 2020) and the field study described in Chapter 2 and in a recently published paper (Haoran Zhao, Chan, Cohn, et al. 2020b). All homes had natural gas cooktop burners and at least one oven, but some ovens were electric. All homes had venting range hoods and dwelling unit mechanical ventilation systems installed to satisfy state building code requirements. The Healthy, Efficient New Gas Homes (HENGH) study collected data in 2016–2018 in 70 single, detached houses that were built in 2011–2017. The apartment study collected data in 2018–2019 in 23 apartment units at 4 properties constructed or renovated in 2013–2017. Both of the field studies were conducted using protocols approved by the Lawrence Berkeley National Laboratory Human Subjects Committee.

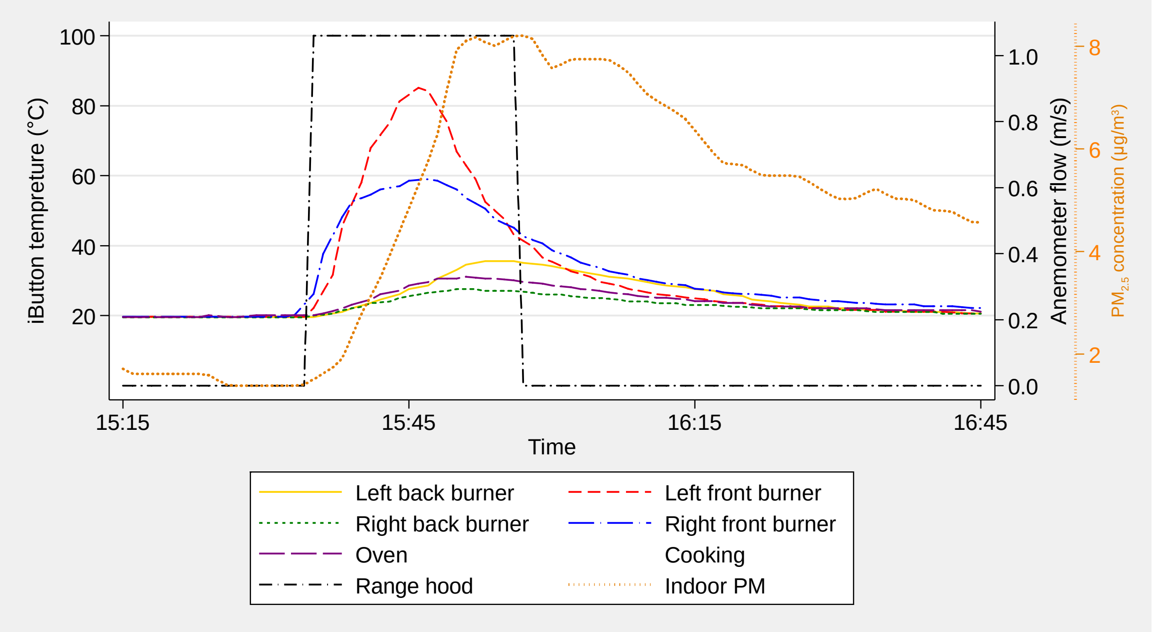
The apartments were occupied by income-qualifying households and participants affirmed that they used their gas cooking burners on a daily or almost daily basis. HENGH homes had a mix of venting range hoods (n = 32) and OTRs (n = 38). All apartments had a venting range hood.

In this task the research team analyzed the following time-resolved data collected in the homes. Temperatures measured alongside cooking burners were analyzed to identify burner use events. Airspeed measured at the inlet to the range hood was analyzed to determine range hood usage. Particulate matter concentrations were analyzed to determine when there were indoor emission events.

Cooking Burner Events

Temperature data recorded by iButton sensors placed alongside each burner were analyzed to identify individual burner use events with specified start and end times. The start of a cooking event was identified by a rapid rise in temperature (Figure 1). A distinct threshold rate of temperature rise was specified to identify the start of cooking events in each home. Most thresholds were in the ranges of 0.6 to 1 °C/min for cooktop burners and 0.6 to 2 °C/min for ovens. The end of a cooking event was designated as the time when the burner temperature started to drop, with most decays being between 0.2 and 0.5 °C/min. Selection of the threshold value for each home was done by visual inspection.

Figure 1: An Example of Full Range Hood Use During a Cooktop Event with Associated Particulate Matter Emissions.



Source: Lawrence Berkeley National Laboratory

Individual burner events that overlapped in time, or consecutive events that ended and started within 3 min of one another, were grouped into multi-burner cooking events. Each cooking event is defined by a start and stop time, burners used (CT for cooktop only, OV for oven only and CTOV for both), total minutes of CT burner use (for example, 2 CT burners used for 10 min each is 20 burner-min) and total minutes of all burner operation. This includes the estimated full duration of OV use, not accounting for cycling of the OV burner. In some analyses, the term “any CT” is used to refer to cooking events involving cooktop burners (that is, CT + CTOV).

Range Hood Use

Range hood usage was monitored at 1-min intervals using a logging anemometer (Digisense WD-20250-22) placed at the air inlet or using a motor on-off logger (Onset HOBO UX90-004) placed close to the motor. Residents were asked to record occupancy and activities throughout each day of monitoring using a daily log sheet. A participant from each home completed a survey that asked about household demographics, satisfaction with environmental conditions in the home, use of ventilation equipment, and other activities that can impact IAQ. The surveys asked how often range hoods were used during cooktop use (for houses) or any cooking events (for apartments). Data from the anemometers and motor on-off loggers were reviewed to identify and develop a data table of hood use events. Hood use was considered only if it overlapped in time with one or more cooking events; use that occurred independently of any cooking event was excluded from the analysis. In houses with OTRs, usage monitoring likely included incidences when the microwave was used to cook food and the fan was activated for that purpose, rather than for providing kitchen ventilation. The analysis only considered cooking events occurring during periods with valid range hood monitoring.

Fine Particulate Matter Event Identification

$PM_{2.5}$ emissions were identified by applying a machine learning approach called Random Forest (RF) to the time-resolved $PM_{2.5}$ concentration measured in the living room of each home, as described in detail elsewhere (Tang, Chan, and Sohn 2020). Briefly, the RF model was originally developed using a training dataset where the indoor and outdoor $PM_{2.5}$ concentrations were collected from 18 California low-income apartments (W. R. Chan et al. 2018). The model uses data features calculated from the indoor and outdoor $PM_{2.5}$ concentrations to identify indoor emission events. A large number of classification decision trees were generated to express the full possible sequences of features to characterize a data point. The predominant classification of all the decision trees becomes the final prediction of the RF model. In this study, the RF model was applied to 2-min running average $PM_{2.5}$ data for both houses and apartments.

The $PM_{2.5}$ emission events identified by the RF analysis were reviewed visually to correct any obvious errors in start and end times.

A $PM_{2.5}$ emission event was linked to cooking if it started during a cooking event and the $PM_{2.5}$ emission duration was no more than 5 min longer than the cooking duration. This window is applied to account for the uncertainty in PM emission event end times identified by the RF model, and also for the time lag between the start of an emission event and an increase in PM concentration measured by the photometer. If a cooking event overlapped with more than one emission event, all of the emission events were considered to be associated with the cooking event.

Analysis

The research team investigated the influence of cooking parameters, ventilation equipment, and household characteristics on the fraction of cooking events in each home that had coincident range hood use and/or the fraction of total events across all homes in each group—houses and apartments—that had range hood use during some or most of the duration of each cooking event. The investigated cooking parameters were cooktop or oven use, total minutes of burner use and whether there was an identifiable, substantial increase in $PM_{2.5}$ coincident with burner use; the latter was assumed to indicate a particle-generating cooking event. The studied ventilation equipment characteristics were conventional range hood or over the range microwave (OTR) and measured airflow and rated sound for highest and lowest settings. Home and household characteristics included floor area, number of occupants, occupant density, air exchange rate (total, per square meter, and per occupant), presence of senior or child someone with health condition that is impacted by air pollution, formal education, income, satisfaction with indoor air quality, satisfaction with air movement indoors, vacuum frequency, window opening frequency, and self-reported reasons for not using range hoods (forget, not need, ineffective, noisy).

Associations between range hood use and potential explanatory parameters were assessed in three different ways. Pearson's chi-square test or Fisher's exact test was used for categorical binary variables (for example, whether range hood used or not categorized by cooking type). Wilcoxon rank-sum tests were applied for continuous variables, such as burner minutes for cooking events, to assess if the distributions differed between groups of events differentiated by categorical variables, for example, in which range hoods were used or not used. An analysis of variance (ANOVA) test was applied to check relationships between two continuous variables, for example, range hood use rate in each home vs. floor area. Relationships are considered very likely when the *p*-value is <0.05 and likely when the *p*-value is between 0.05 and 0.1. For continuous variables such as cooking burner-min, Wilcoxon rank-sum tests were applied to assess if the distributions differed between groups of events differentiated by categorical variables (for example, in which range hoods were used or not used). Statistical analyses were performed using Stata version 15 (StataCorp, LLC, College Station, TX, USA).

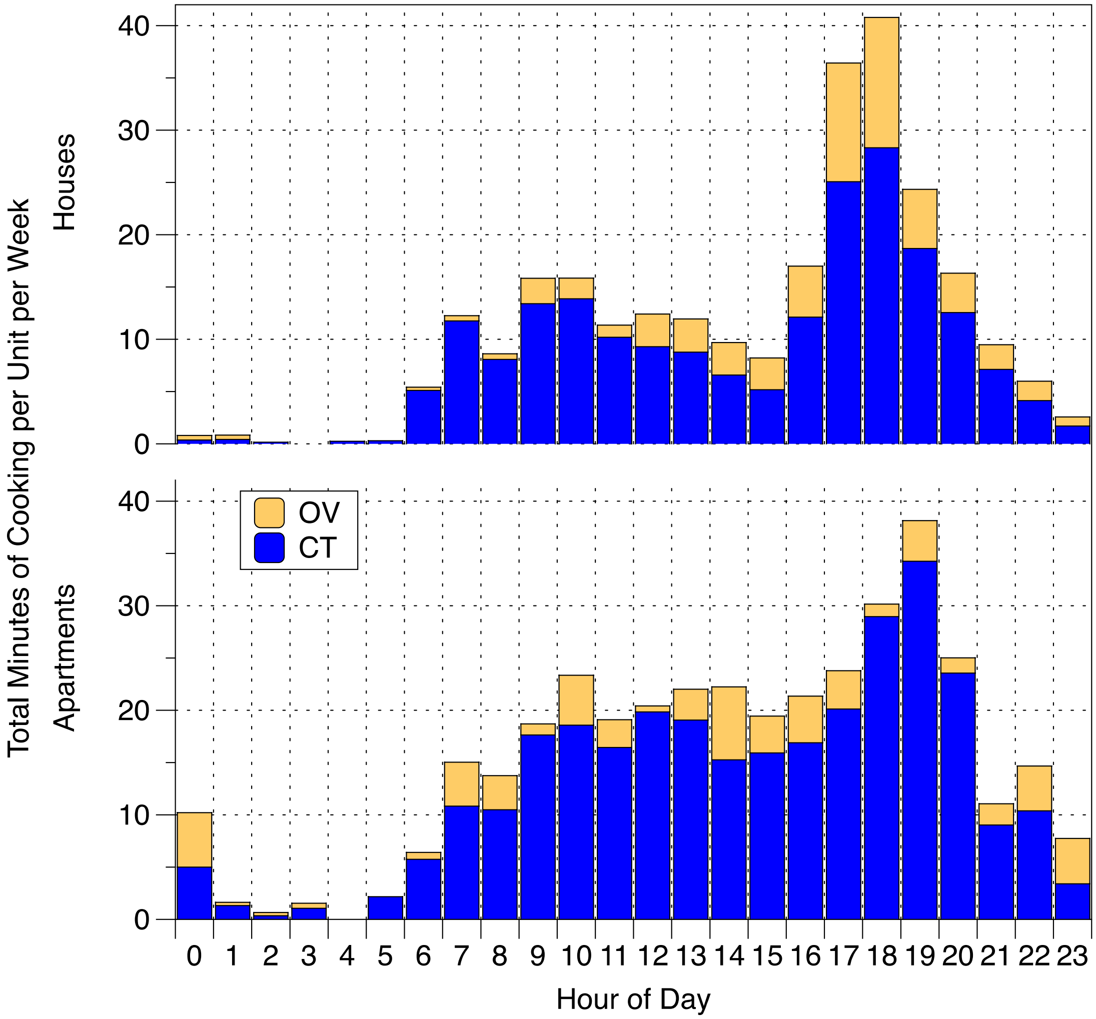
Results

Frequency of Cooking

Analysis of the iButton data found 607 cooking events in 57 single-family houses and 311 cooking events in 23 apartments. The distributions of total minutes of cooktop use and oven use per home per week at each hour of the day are shown in Figure 2 separately for houses and apartments. The mean and 10th–90th values of total cooking duration were 32 and 8–73 min for single-family houses and 40 and 8–56 min for apartments. In single family houses, the most cooking occurred during the late afternoon and evening (presumably around dinner) with a second mode during the morning, between 09:00 and 11:00. In apartments, cooking was more spread throughout the day with the peak occurring between 18:00 and 20:00.

Subsequent analyses excluded cooking events that occurred when range hood use was not monitored, events that occurred in apartments with a range hood operating continuously, and overnight oven use that was presumed to occur for heating. The remaining data included 784 cooking events, with 574 events in 54 houses and 210 events in 17 apartments.

Figure 2: Distribution of Total Minutes of Cooktop and Oven Use Per Home Per Week at Each Hour of the Day in Houses and Apartments



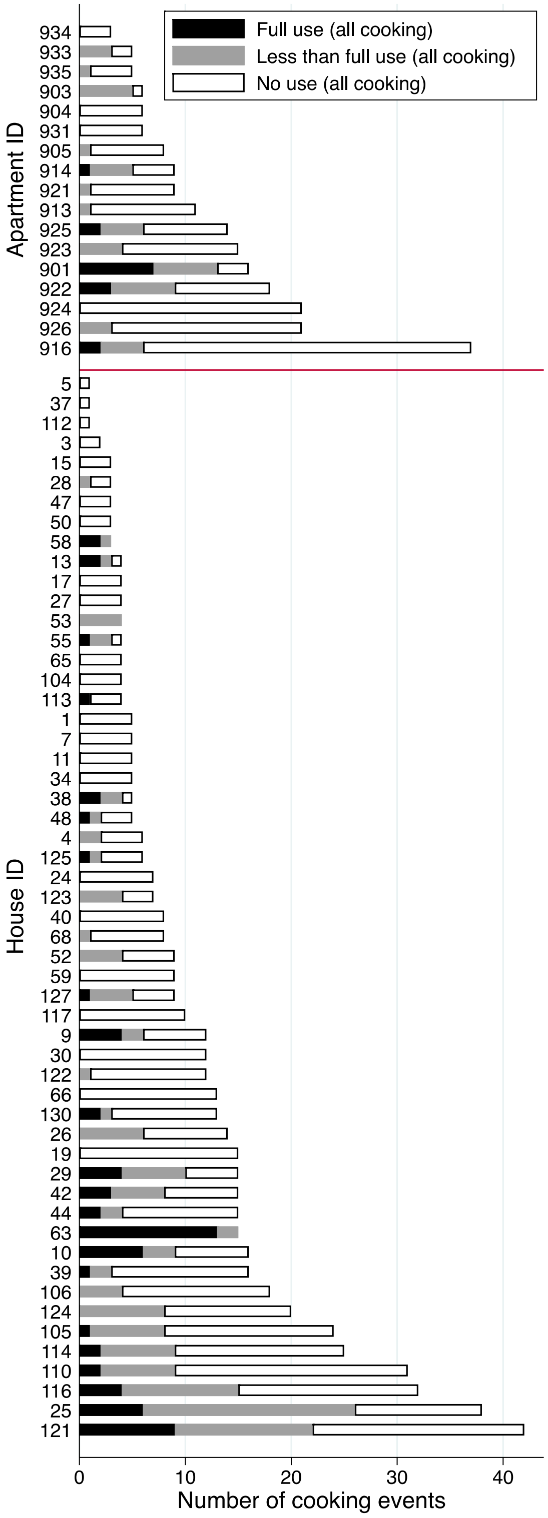
OV = Oven; CT = Cooktop

Source: Lawrence Berkeley National Laboratory

Fraction of Cooking Events with Range Hood Use by Home and Influencing Factors

Figure 3 shows the number of cooking events with no range hood use, any use, and full use in each house or apartment. On average, occupants in the apartments cooked slightly more meals (median = 9.0, mean = 12.4) than occupants in the houses (median = 7.5, mean = 10.6) during the weeklong monitoring period. About one-third (32 percent) of hood uses were considered full use, the remaining two-thirds of hood uses started with delays longer than 3 min and/or did not span 80 percent of the total cooking duration. Of 37 houses and 16 apartments with five or more cooking events, 49 percent of houses and 63 percent of apartments used the range hood for less than 30 percent of cooking events and only two of each type used the range hood during more than 70 percent of cooking events. The mean rate was indistinguishable in houses and apartments.

Figure 3: Range Hood Use for All Cooking Events by Home



Source: Lawrence Berkeley National Laboratory

There were no statistically significant associations between the fraction of cooking events with range hood use by home (henceforth, "rate") and any ventilation equipment or household characteristics with analysis limited to homes with five or more cooking events. Analyses examining relationships between equipment or home characteristics and the likelihood of a range hood being used across all the cooking events in all homes with data, found several significant associations. The most prominent factors were education and income level, with significantly higher rates of range hood use for cooking events in homes with higher income and education level. It is very important to note, however, that there were large and significant differences in education and of course income between the households in houses and the income-qualifying apartments. There also were statistically significant associations of lower range hood use when occupants were dissatisfied with air movement indoors ($p < 0.01$), open windows often (<0.01) and report that their range hood was ineffective ($p < 0.01$). In houses, range hood usage was likely lower when occupants said they sometimes do not use the range hood because it is not needed ($p < 0.01$) or self-assessed that their range hood was ineffective ($p = 0.02$).

Table 3 shows that residents in houses used their range hoods more frequently than residents in apartments when cooking with a cooktop ($p = 0.006$ for CT only and $p = 0.01$ for any CT). This difference may be connected to differences in range hood use by education and/or income level as noted previously. For example, residents in 46 out of 54 houses had bachelor degrees or higher, while only 2 out of 17 apartments had bachelor degrees or higher. Importantly, it is unclear which of the factors is driving higher rates of use, which could even be related to another factor that has not been quantified, for example, the potential for a homeowner to select a preferred design or model of range hood or more familiarity with the equipment from a longer period of occupancy.

Table 3: Range Hood Use by Cooking Type

Cooking Type	Cooking Events in Houses	Any Hood Use *n* (%)	Cooking Events in Apartments	Any Hood Use *n* (%)	*p*-Value [1]
CT only	487	182 (37%)	190	50 (26%)	0.006
OV only	48	12 (25%)	15	5 (33%)	0.53
CTOV	39	11 (25%)	5	3 (60%)	0.76
Total	574	205 (36%)	210	58 (28%)	0.03
p-value	0.09	Chi-square for CT only and OV only (houses)	0.56	Chi-square for CT only and OV only (apartments)	N/A

[1] Chi-square test for hood use comparing two home types: houses and apartments.

Source: Lawrence Berkeley National Laboratory

Effect of Range Hood and Oven Type

Unlike in the apartments, which all had a conventional range hood over a cooktop with gas oven underneath, configurations varied in single family houses. Among the 54 houses with valid cooking and range hood use data, some had a regular range hood ($n = 22$), while others had an OTR ($n = 32$). Some houses had ovens located underneath the range hood ($n = 32$), while others had separate ovens located off to a side ($n = 22$). Some houses had gas ovens, while others were electric (7 of 32 of the underneath ovens, and 21 of 22 the separate ovens were electric). Statistical tests were performed to see if these differences are associated with the frequency of range hood use. There was no discernible effect of range hood type in single family houses for cooking events that involved cooktop only, with range hoods being used for

39 percent of cooktop events and OTRs used for 36 percent of cooktop cooking events. For oven cooking, a range hood or OTR that was over the oven was likely ($p = 0.09$) to be used more frequently (7/18 = 36 percent) than a range hood that is not over the oven. (5/30 = 17 percent).

Moderate correlation was found between the rate of any range hood use and the number of total cooking events or cooktop uses in each house (Spearman coefficient of 0.36, $p < 0.01$ for total cooking events). However, no correlation was found between the rate of any range hood use and the number of any cooking burner events or of cooktop events in apartments (Spearman coefficient of 0.09, $p = 0.73$ for total cooking events).

Table 4 shows that range hood use was more frequent when cooktop burners were used during longer events. In houses, range hoods or OTRs were operated during 52 percent of events when cooktop burners were used for more than 20 burner-minutes, compared to 33 percent for 11–20 burner-minutes and 20 percent for 1–10 burner-minutes. Apartment residents also used range hoods slightly more frequently when the cooktop was used more than for 20 burner-minutes, but the association between hood use and cooktop use duration was not statistically significantly ($p = 0.45$). The esearch team also applied the two-sample Wilcoxon rank-sum test to the house data by sorting the cooktop use durations into two groups: "Hood used" and "Hood not used". The mean (± standard deviation or SD) cooktop use duration in houses was 35 (±34) minutes for the "Hood used" group, and the mean was 20 (±20) minutes for the "Hood not used" group. Cooktop use duration was significantly different between these two groups (p-value <0.01). Applying the same analysis to data from apartments provides cooktop use durations of 29 (±41) minutes for the "Hood used" group and 23 (±22) minutes for the "Hood not used" group, with $p = 0.38$ indicating that the two distributions are not likely different. For cooking events using ovens, no apparent relationship between hood use and oven use duration was found.

Table 4: Range Hood Use by Cooktop Use Duration

Cooktop Use (Burner-Minutes)	Cooking Events in Houses—CT Only	Any Hood Use *n* (%)	Cooking events in Apartments—CT Only	Any Hood Use *n* (%)
1–10	143	29 (20%)	60	14 (23%)
11–20	139	46 (33%)	53	12 (23%)
>20	205	107 (52%)	77	24 (31%)
p-value [1]	<0.01	-	0.45	-

[1] **Chi-square test for hood use comparing different cooktop use durations.**

Source: Lawrence Berkeley National Laboratory

Relationship of Actual Range Hood Use to Self-Reported Use

The research team compared actual range hood use and survey responses asking participants to self-report their range hood use habits in houses (Table 5) and apartments (Table 6). Note that the survey question and response options were somewhat different for the two studies. In the house study, participants were asked how frequently their range hood is used when cooking with a cooktop based on numerically-linked categories. In the apartment study, participants were asked about hood use during any cooking and given ordinal/categorical options. For consistency, the comparison considers only cooktop cooking (that is, "any CT"). In both houses and apartments, actual hood use was higher for participants that self-reported more frequent use, but actual use was much lower than self-reported use. For those reporting the most frequent range hood use—four or five out of five times in houses, or usually/always in apartments—actual hood use was only 45 percent and 36 percent, respectively. The difference is statistically significant among the houses ($p < 0.01$), and likely among apartments ($p = 0.10$).

Table 5: Range Hood Use by Self-Reported Use Habit in Houses

Survey Response [1]	Number of Houses	Cooking Events—Any CT	Any Hood Use *n* (%)	Cooking Events—All	Any Hood Use *n* (%)
Always/most of time (4–5 out of 5 times)	26	349	158 (45%)	371	166 (45%)
Sometimes (2–3 out of 5 times)	13	97	20 (21%)	109	22 (20%)
Rarely/never (0–1 out of 5 times)	13	70	11 (16%)	83	13 (16%)
I don't know	0	0	0	0	0
No response	2	10	4 (40%)	11	4 (36%)
p-value [2]	-	-	<0.01	-	<0.01

[1] Survey question: How often is a kitchen range hood or exhaust fan used when cooking with a cooktop?
[2] Chi-square test with 1-side Fisher exact value for hood use comparing different survey responses.

Source: Lawrence Berkeley National Laboratory

Table 6: Range Hood Use by Self-Reported Use Habit in Apartments

Survey Responses	Number of Apartments	Cooking Events—Any CT	Any Hood Use *n* (%)	Cooking Events—All	Any Hood Use *n* (%)
Usually or always	6	83	32 (39%)	92	33 (36%)
Sometimes/as needed	6	51	10 (20%)	57	14 (25%)
Rarely or never	0	0	0	0	0
I don't know	3	46	6 (13%)	46	6 (13%)
No response	2	15	5 (33%)	15	5 (33%)
p-value [2]	-	0.02	-	0.10	-

[1] Survey question: How often is the range hood or exhaust fan used when cooking? [2] Chi-square test with 1-side Fisher exact value for hood use comparing the within first three survey responses.

Source: Lawrence Berkeley National Laboratory

Fine Particulate Matter Emissions and Range Hood Use

There were 403 $PM_{2.5}$ emission events identified for houses and 281 for apartments. Emission events varied vastly by duration and intensity, but the central tendency and range of values were similar among the houses and the apartments. The median $PM_{2.5}$ emission duration was 16 min for the houses, and 14 min for the apartments. The 5th and 95th percentiles of $PM_{2.5}$ emission duration were 10 and 42 min for the houses, and 4 and 52 min for the apartments. The highest 5-min $PM_{2.5}$ concentration during emissions had a median value of 36 $\mu g/m^3$ for the houses, and 37 $\mu g/m^3$ for the apartments. The 5th and 95th percentiles of the highest 5-min $PM_{2.5}$ concentration were 9 and 310 $\mu g/m^3$ for the houses, and 9 and 250 $\mu g/m^3$ for the apartments. The research team notes the possibility that use of a range hood with high capture efficiency for particles theoretically could result in no substantial increase in $PM_{2.5}$ in the space and thus no identified event. Limited data on range hood effectiveness for particles generated during cooking suggest that high capture could result when cooking at low to medium heat on the back burner, but not when cooking at high heat on a front burner (Lunden, Delp, and Singer 2015, 201).

Roughly 25 percent of cooking events in houses and 20 percent in apartments were linked with $PM_{2.5}$ emissions (Table 7). In houses, a range hood was used for 58 percent of the cooking events with $PM_{2.5}$ emission, and this was substantially and statistically significantly ($p < 0.01$) higher than range hood use when there was no $PM_{2.5}$ emission detected (30 percent). In apartments, slightly higher use of range hoods when $PM_{2.5}$ accompanied cooking (34 percent compared to 26 percent) was not statistically significant ($p = 0.40$).

Table 7: Range Hood Use by Cooking Events with and without Fine Particulate Matter ($PM_{2.5}$) Emissions

$PM_{2.5}$ Emissions	Cooking Events in House	Any Hood Use *n* (%)	Cooking Events in Apartment	Any Hood Use *n* (%)
Yes	115	67 (58%)	41	14 (34%)
No	459	138 (30%)	169	44 (26%)
p-value [1]	-	<0.01	-	0.33

[1] **Chi-square test for hood use frequency comparing cooking events with and without PM emissions.**

Source: Lawrence Berkeley National Laboratory

Cooking events with associated $PM_{2.5}$ emissions were categorized into two groups based on the peak 5-min $PM_{2.5}$ concentration during emissions, and the association of this metric with range hood use. Higher peak $PM_{2.5}$ concentrations could result from events with higher mass emissions, similar emissions being emitted into smaller spaces (noting that apartments are systematically smaller than houses), and/or slower mixing within larger homes. In houses, range hood use did not vary with the peak 5-min $PM_{2.5}$ concentration. In apartments, however, range hood use was more frequent (56 percent) when the peak 5-min $PM_{2.5}$ concentration exceeded 50 $\mu g/m^3$, compared to only 28 percent when otherwise. But the differences were not statistically significant due to limited data. A possible reason for range hoods to be used less often in apartments when peak $PM_{2.5}$ concentrations are lower is that emissions must be much smaller for peak concentrations to remain low in the apartments, which have much smaller volumes compared with houses; the smaller emission sources may not be as noticeable to residents.

Limitations

A key limitation of the research team's study is that the sample was not randomly drawn from the population, so findings may not apply more broadly. The research team's analysis was based solely on households living in houses or apartments that were built or renovated in recent years. Relative to the general population of California, the households in the single, detached houses were skewed toward higher income and higher education, while the apartments were recruited within low-income communities. The sample was not recruited to represent the diversity of cooking practices or even the diversity of cultures within California or the US. In addition, all of the households included someone that volunteered to participate for a one-week indoor air quality study, indicating at least a possibility for greater interest and attentiveness to IAQ hazards and controls than occurs in the general population.

Another important limitation is the small sample size, which limits the discernibility of some potential predictors that correlate with range hood use. In most cases, the relationship between range hood use and a factor was analyzed independently, rather than considering all the different factors together. The research team is limited by the small dataset to explore how all these factors in aggregation impact range hood use in homes.

The methods used to identify the start and stop times of cooking and range hood use were imprecise; this could have caused some errors in characterizing full or partial range hood use. Despite the research team's best effort to visually inspect and correct the identification of cooking events, some ambiguity in the data remains. For example, it is difficult to estimate burner-minutes for cooking events that involved multiple burners. Future studies that can more precisely and certainly define cooking activities and link those to range hood use would advance understanding of how this residential IAQ control is used.

The linking of $PM_{2.5}$ emission events to temporally proximate cooking events was uncertain because the source of $PM_{2.5}$ may not be cooking related. The photometers used in the house and apartment studies were calibrated using a limited number of gravimetric filters that were collected. However, even after this calibration step, the adjusted $PM_{2.5}$ measurements may have missed some cooking emissions, such as if the emitted particles were predominantly too small in diameter for the photometer to measure. Future studies that confirm when PM is associated with cooking emissions would help in the understanding of how rationally people use their range hoods to control potentially hazardous contaminants.

Conclusions

The research team investigated range hood use for 784 cooking events in 71 homes including 54 single family houses and 17 low-income apartments constructed or renovated in recent years. Range hood use occurred more frequently with cooking in single family houses (36 percent) than in the apartments (28 percent). Range hood use by home generally increased with cooking frequency. In both houses and apartments, range hood use increased with cooktop use duration, but not with oven use duration. Participants who self-reported frequent use actually used their hoods more frequently; however, actual use was much lower than self-reported, with only 45 percent and 36 percent actual range hood use in houses and apartments where occupants self-reported use of always, usually, or most of the time. Residents in single family houses used range hoods more often when cooking events generated any level of $PM_{2.5}$. In apartments, residents used the range hood more often only if high concentrations of particles were generated during cooking.

A better understanding of how range hoods are currently used in homes will help inform the potential benefits of adding sensing for automatic operation and improving awareness that range hoods should be used to reduce the population health burden from cooking emissions. The findings from this analysis are useful bases for future studies that aim to measure the impact of range hood use in reducing occupant exposure to indoor air pollutants in their homes.

CHAPTER 4: Performance of Combined Over-the-Range Microwave and Exhaust Devices

Objective and Overview

The original objective of this task was to assess whether microwave exhaust fans (OTRs) which were at the time not certified to meet the performance specifications in the code, could provide equivalent protection to range hoods that are minimally compliant with current code. After the project was approved and initiated, certified airflow and sound ratings were published for numerous OTRs via the HVI catalog. The objective was revised to focus on the relative performance of OTRs and conventional range hoods of similar cost, with a focus on capture efficiency.

The task was also expanded to include an investigation of the bias in OTR airflows reported from the HENGH field study. The research team selected OTR models that were seen in homes in the recent HENGH study and from the HVI product directory. The research team conducted the following measurements:

- Measure airflows of OTRs installed in the research team's research facility with a fixed duct configuration that is a reasonable surrogate for many homes;
- Validate a new method for measuring airflows for OTRs with multiple air inlets;
- Measure capture efficiency (CE) and sound of OTRs installed as above;
- Compare CE vs. airflow relationship of OTRs to standard range hoods within similar cost range;
- Estimate bias of the method used to measure airflow in the HENGH field study.

The details of this study are reported in a technical report (H. Zhao et al. 2020) that is available to the public via the publications database maintained by the Energy Technologies Area of Lawrence Berkeley National Laboratory (https://eta.lbl.gov/publications).

Background Relevant to Range Hood Performance

Over-the-range microwave range hoods are popular for their space saving utility and are often installed in new homes. In 2015, LBNL conducted an online survey of residents of California single-family homes built in 2002 or later and found that roughly half of the respondents that provided information on their kitchen ventilation had OTRs, with the other half having traditional range hoods (Appendix A of (W. R. Chan et al. 2019)). The vast majority of homes for which data were reported were built before the California building code started to require kitchen exhaust ventilation; yet roughly 90 percent of the range hoods and 80 percent of the OTRs were reported to vent to the outdoors. In the follow-up field study of ventilation and indoor air quality in 70 single, detached homes constructed in California since 2011 (the "HENGH" study) 38 of the homes had venting OTRs and 32 had venting range hoods (W. R. Chan et al. 2019).

When this project was initiated there were very few published data about OTR airflows. There were no OTRs listed in the HVI category and thus none certified to meet ASHRAE/California standards). In August 2019, the HVI catalog had performance data for 219 unique model numbers, which included multiple color/finish variations of 57 OTR models. And the listed performance data suggest that these could represent as few as 9 distinct models of hardware, each marketed under several brand names. More information about this analysis is presented later in the chapter.

The performance metric that most directly addresses the effectiveness of a range hood (or OTR) at protecting indoor air quality is capture efficiency (CE). LBNL has conducted several studies of range hood and OTR CE in the laboratory and in the field, using varied test methods.

Singer et al. (B. C. Singer et al. 2012) used a dynamic CO_2 mass balance method that involved heating of pots of water on a gas cooktop. CO_2 concentration was measured in the exhaust duct and combined with the measured airflow to calculate a mass flow. The CO_2 mass emission rate from natural gas combustion was calculated based on the firing rate of the burners and consideration of the fuel composition. Capture efficiency was measured and reported for 11 range hoods, 2 OTRs and 2 downdraft systems installed in occupied homes. Many tests were conducted for each kitchen exhaust device, evaluating the effect of varied burner selection and varied airflow setting. The source locations were one front burner, one back burner, front and back burners simultaneously, and the oven. Temporally resolved CE was calculated using time-series measurements of airflow (Q, m^3/min), the CO_2 concentration differences between the room background and the range hood exhaust (mL/m^3), and the CO_2 emission rate (E, mL/min), as shown in Equation 4.1 below:

$$CE = Q * (C_v - C_0) * 10^6 / E \tag{4.1}$$

The source of the CO_2 was the natural gas burners on the cooktop. The CO_2 emission rate was calculated from stoichiometry, assuming complete combustion and the measured gas fuel flow rate (based on information about the molar fraction of carbon in the fuel). Results indicate that CE varied by hood geometry, higher airflow generally led to higher CE, and the CE was much higher for the back burner.

Delp and Singer (Delp and Singer 2012, 2012) conducted laboratory tests for 6 range hoods and one OTR using the same approach, with CO_2 from gas burners as the tracer. That study showed very similar results to the field study, with CE values ranging from 17 percent–100 percent with a strong dependency on airflow and burner, pot, and range hood geometries.

Walker et al. (Walker et al. 2016) and Kim et al. (Kim, Walker, and Delp 2018) describe development of a steady-state CE test method in a controlled chamber. Instead of using gas burners with boiling pots of water as a source, a standardized tracer gas emitter was used to deliberately emit CO_2 over the heated surface. Steady-state CO_2 concentrations were measured in the chamber (C_c), in the hood exhaust stream (C_e), and at the air inlet to the chamber (C_i). The capture efficiency was calculated using Equation 4.2. The developed method was adopted as ASTM Standard E-3087-2018.

$$CE = (C_e - C_c) / (C_e - C_i) \tag{4.2}$$

In another field study, Singer et al. (B. C. Singer, Pass, et al. 2017) developed and applied a ratio test method that also used CO_2 emitted from burners with boiling pots of water as a tracer. The approach compared the flow of CO_2 through the hood under the normal operating condition to the flow of CO_2 when a foil curtain was used to extend the hood over the cooktop to ensure perfect or nearly perfect capture. This approach assumes no change in airflow between the conditions, meaning the CO_2 mass flow changes proportionally with the CO_2 concentration. CE is calculated using CO_2 concentrations measured under the normal operating condition (C_N) and with the hood extended to create nearly perfect capture conditions (C_{100}), and background concentrations with the cooking burners off (C_0), as shown in Equation 4.3.

$$CE = \frac{(C_N - C_0)}{(C_{100} - C_0)} \quad (4.3)$$

Using a dynamic room-based method, Lunden et al. (Lunden, Delp, and Singer 2015) determined the CE for particles produced during cooking. Two cooking procedures - pan-frying a burger and stir-frying string beans - were conducted in a ventilated test room. Particle concentrations were measured at the room exhaust with and without the range hood operating ($C_{\text{room-with hood}}$; $C_{\text{room-no hood}}$). Background concentrations (C_{bg}) were measured and CE was calculated using Equation 4.4. That study also reported CE calculated with the CO_2 mass balanced method, which was conducted at the same time. Results showed lower CE values for PM that for CO_2.

$$CE = 1 - \frac{(C_{room-with\,hood} - C_{bg})}{(C_{room-no\,hood} - C_{bg})} \quad (4.4)$$

The studies cited above reported capture efficiency for only 7 OTRs.

Approach

Over the Counter Microwaves Range Hood Selection

Six OTR microwave range hoods were selected and tested in this study. Models were selected from among OTRs seen in the HENGH field study and from products identified in the HVI Certified Home Ventilating Products Directory.

The research team's search of the microwave subcategory of the kitchen ventilation product category in the HVI catalog, conducted in August 2019, found 861 records of test results for 219 models. All were listed under the same brand owner, under 5 brand names. The research team sorted all 219 models by model number, blower capacity, speed settings, air flow and sound level. This sorting identified what appeared to be 57 unique models, each with variants representing different colors or finishes. The 57 models were grouped by their performance specifications. The grouping identified 9 sets of performance specifications, suggesting multiple models using the same hardware. From this list, the research team selected three OTR models that were observed in HENGH homes, as indicated in Table 8. For one of the models, the precise model that had been observed in HENGH homes (ending in "AS") was no longer available, so the research team procured one with the same base model number but a different ending code ("HB"), incorrectly thinking that the difference was aesthetic. In fact, the tested unit had a larger blower (rated at 300 cfm) compared with the model observed in HENGH homes (blower rated at 220 cfm).

The research team also selected 3 non-rated OTRs observed in many homes visited in the HENGH field study, as shown in Table 8: Comparison of Over the Counter Models Tested with Models in HENGH Study . These included two GE models and one Frigidaire model. By the time of the research team's lab study, the Frigidaire model had been discontinued by the manufacturer and was not generally available. The research team procured and tested the closest model that we could find, while acknowledging that the model the research team tested had a nominal 220 cfm blower whereas the model seen in the HENGH field study had a nominal 300 cfm blower.

Table 8: Comparison of Over the Counter Models Tested with Models in HENGH Study

Brand	Product Series	Number in HENGH homes	Available from retailers in July 2019	Models tested in lab	HVI certificated in July 2019
Whirlpool	WMH31017AS	4	Yes [a]	WMH31017HB	Yes
Whirlpool	WMH53520 series	3	Yes	WMH53520CB	Yes
Whirlpool	WMH32519 series	1	Yes	WMH32519HV-4	Yes
GE	JVM3160 series	4	Yes	JVM3160RF5SS	No
GE	JVM7195 series	12	Yes	JVM7195SK3SS	No
Frigidaire	FFMVLS series	7	No [b]	FFMV1645TS	No
Sub-total [c]	-	31	-	-	-

[a] The model tested in the lab had a different blower than the models observed in the HENGH study; see text for details.

[b] This model was discontinued by the manufacturer before the research team's laboratory study had begun. The research team purchased this unit from a retailer who had one remaining in stock.

[c] These models represent 31 of the 38 OTRs found in HENGH homes.

Source: Lawrence Berkeley National Laboratory

Table 9 summarizes characteristics of the six OTRs that were selected and tested. Since OTR prices vary by exterior color and finish, for comparison purposes the research team provided pricing for the basic version with black exterior. The prices shown in the table were calculated as the average of regular prices (excluding special offers) listed online by four major retailers in August 2019: The Home Depot, BestBuy, Lowes and AJ Madison. The research team also tested two standard under-cabinet range hoods with similar advertised airflow ranges as the OTRs tested in this study. The purpose was to confirm the consistency of the research team's testing with prior published work by testing standard range hoods that are similar to models tested previously. The selected range hoods satisfied these criteria: 1) listed in the HVI catalog; 2) advertised airflow and sound level met BEES requirements for residential kitchen ventilation (airflow greater than 100 cfm and sound level less than 3 sone); 3) available for purchase in July 2019; and 4) priced similarly to OTRs when accounting for OTRs also providing the service of a microwave oven (with approximate value of $75-100). Specification of the two selected range hoods are also summarized in Table 9. The codes in Table 9 are used to identify range hoods throughout the remainder of the report.

Table 9: Over the Counter and Standard Range Hoods Tested

Brand	Model	Code	Type	Blower (CFM)	Price	HVI flow HS/WS [a] (CFM)	HVI sound HS/WS [a] (sone)
Whirlpool	WMH31017HB	WH1	OTR	300	$235	210/140	5/2
Whirlpool	WMH53520CB	WH2	OTR	400	$315	290/110	7/1.5
Whirlpool	WMH32519HV-4	WH3	OTR	300	$291	210/140	5/2
GE	JVM3160RF5SS	GE1	OTR	300	$204	N/A	N/A
GE	JVM7195SK3SS	GE2	OTR	400	$383	N/A	N/A
Frigidaire	FFMV1645TS	Frigidaire 1	OTR	220	$239	N/A	N/A
Air King	ESD1Q1303	RH1	RH	270	$227	270/150	4/1.5
Broan	BKSA130SS	RH2	RH	250	$156	230/140	5/1.5

[a] **Airflows and sound levels for vertical discharge.**

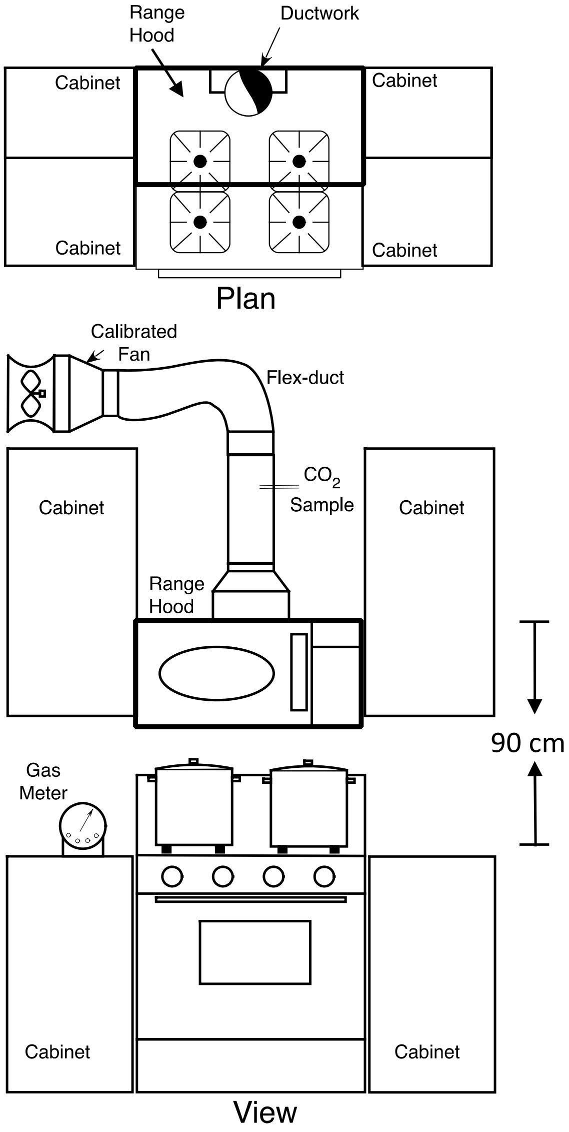
Source: Lawrence Berkeley National Laboratory

Experimental Setup

The experiment was set up in the FLEXLAB facility at LBNL (https://flexlab.lbl.gov/). The experimental room within the cell measured 7.6 m long by 6 m wide with a drop ceiling at height of 2.7 m, providing a volume of 123 m^3. A simulated residential kitchen area was set up in front of set-back windows that occupied the top half of one of the 6 m wide walls. A plywood wall measuring 2.4 m by 2.4 m was installed in the horizontal middle of the FLEXLAB window-wall to provide a mounting surface for the simulated kitchen area. The simulated kitchen included a 76 cm wide gas cooking range, boxes to simulate floor and wall cabinets, and vertically adjustable brackets to allow mounting of OTRs or range hoods at varied heights above the cooktop. OTRs and range hoods were mounted between drywall boxes installed to simulate wall cabinets and a cooking range was installed between drywall boxes topped with steel sheeting to simulate side cabinets and countertops. During each test, a piece of 76-cm wide and 15-cm high cardboard was attached above the microwave range hoods between the two drywall boxes to mimic the cabinet typically installed above the microwaves.

A schematic of the experimental set up is shown in Figure 4 below. The range hoods were connected to a 30-cm long section of 15-cm diameter smooth galvanized ducting via a 22-cm long rectangular to round duct transition. Above this section was a 90-degree duct elbow to vent outdoors through a wall vent cap outside. The estimated system curve provides a static pressure of about 60 Pa at 250 cfm and 20 Pa at 100 cfm. The OTRs were mounted with their tops 90 cm above the cooktop. The mounting heights of OTRs and range hoods in this study are consistent with the most common mounting heights found in HENGH study homes; but they are higher than manufacturer-recommended heights.

Figure 4: Experiment Setup



Source: Lawrence Berkeley National Laboratory

The cooktop had one nominal 12.7 MJ/h (12 000 BTU/h) burner at the front right position and three nominal 10.0 MJ/h (9500 BTU/h) burners. The range was supplied with 99.97 percent methane from certified cylinders (Airgas). Fuel flow was measured using a mass flow meter (Model MLD-20SLPM-D/5M, ALICAT), factory calibrated for methane with an accuracy of 1 percent. Flow was reported at a reference condition of 1 atm and 25°C. Fuel flow was controlled using the burner adjustment knobs on the appliance.

The test room was connected to an adjunct space which is directly connected to outdoor air though an exterior door. The door was slightly open during each test to maintain the pressure in the adjunct space equal to outside. Air continuously entered the test room through an entrance covered by transparent film curtains to maintain the pressure balance in the test room while operating the exhaust hoods. Other than the OTR or range hood, there were no drivers of airflow in the vicinity of the range that would have influenced the plume from the cooktop.

Over the Counter Performance Test Procedures

Exhaust air flow from the hoods and OTRs was measured using the balanced-pressure flow hood method described by Walker et al. (Walker et al. 2001). The balanced-pressure flow hood method can measure airflow at the inlet or outlet of any ventilation fan, provided that a proper transition piece is in place. With the objectives of ensuring accurate test results and verifying the more complicated measurements at the inlet, the research team conducted airflow testing for each device at both the inlet and outlet. The key challenge of applying the balanced pressure method at the inlet is to construct a customized transition box to create the neutral pressure volume. It is particularly challenging to construct a suitable transition to measure OTR inlet airflows because the OTRs have multiple inlets. The research team thus designed and fabricated a customized transition that combines separate pieces to cover the bottom and top inlets, as shown in the left image of Figure 5. Airflow was measured by connecting the Duct Blaster fan to the bottom of the transition, as shown in the right half of Figure 5, and adjusting the fan to achieve neutral pressure inside the transition, as described above.

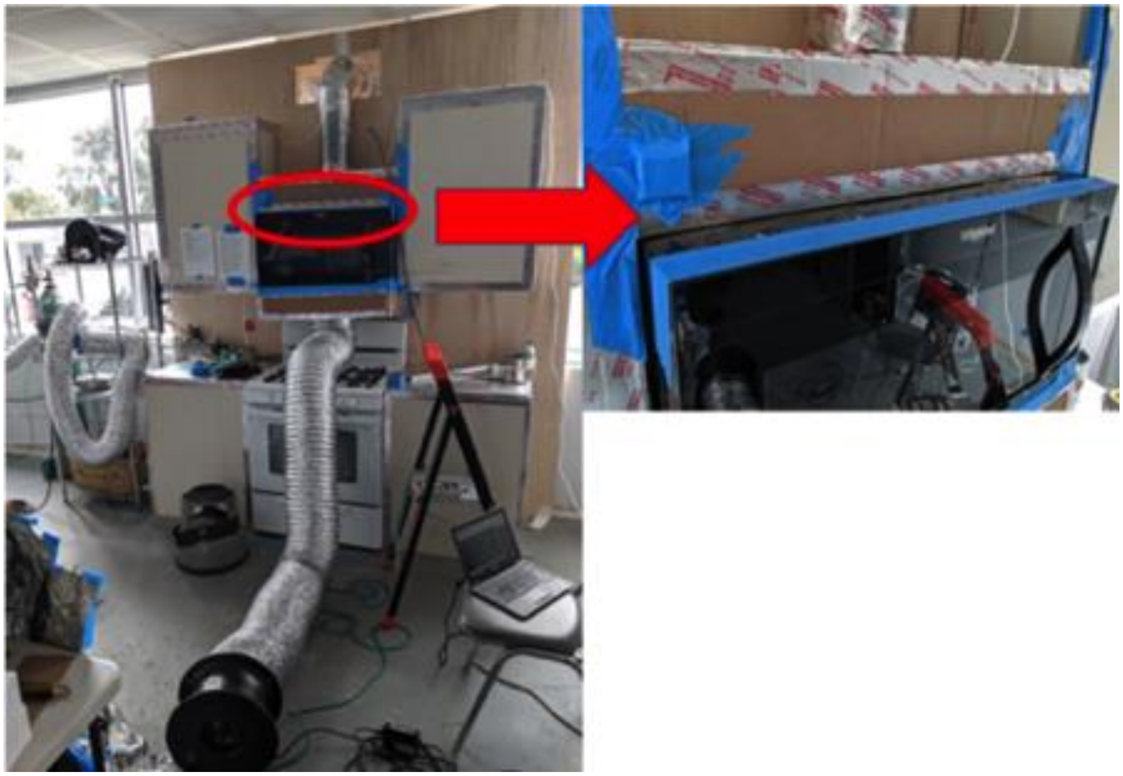
Figure 5: Configuration to measure total airflow into OTR at Inlets

Source: Lawrence Berkeley National Laboratory

Another objective of the airflow testing was to determine the bias that results when using the test method employed for OTRs in the recent HENGH field study in new California homes. In the HENGH study, the field teams blocked the top inlets to OTRs using tape and mounted a transition to cover only the bottom air inlets, as shown in Figure 6. (This approach was used because it enabled the use of similar transitions for common range hoods and OTRs.) The bias investigation was done out of concern that the tape over the top inlets in the OTR field method can cause flow restriction that reduces overall airflow through the blower.

Each of the OTRs and range hoods was tested for airflow at each available setting.

Figure 6: Example of Airflow Measurement at Inside with Top Inlet Taped



Source: Lawrence Berkeley National Laboratory

Sound Level

OTR and range hood sound levels were measured on an iPhone6 using the Real Time Analyzer tool of the Audio Tools app (version 8.9.X from Studio Six Digital) 2. The Real Time Analyzer records sound pressure (in decibels, dB) as a function of frequency. The sound pressure distribution was measured for background conditions (range hood off) and for each available range hood speed when the test room was in an otherwise quiescent condition. A-weighted total sound pressure (dBA) reported by the app was recorded and the research team, applied the *sound pressure weighting procedure* described in HVI Publication 915 to calculate a sone value. One objective was to assess how this widely accessible technique compared with certified data from the HVI test procedure, which requires testing of devices in an anechoic chamber and using laboratory-grade acoustic equipment. Measurements of dB(A) were also made using a digital sound meter (Extech 407736, Waltham, MA, USA) placed 0.5 m in front of the hood, level with the hood bottom opening and horizontally on center.

Capture Efficiency

Capture efficiency was determined using the mass balance method described in Equation 4.1. For this calculation, Q is volumetric airflow rate through the hood (in liters per minute), which is measured from the outside; C_V is the CO_2 concentration measured in exhaust duct above the range hood (ppm); C_0 is the CO_2 background concentration in the room, interpolated from CO_2 in duct before and after burner use. E is the CO_2 emission rate from the burner (L CO_2/min), described in Equation 5 below:

$$E = Q_{fuel} * N \tag{4.5}$$

In Equation 4.5, Q_{fuel} is fuel flow rate in liters per minute (lpm) and N is the molar fraction of carbon in the fuel (mol C per mol fuel, equal to 1 for pure methane). Carbon dioxide concentrations were measured in the exhaust duct at a point that was approximately 3 duct diameters downstream of the hood. Measurements were made with an EGM-4 infrared analyzer (ppsystems.com) The logging interval was 1.6 s. The analyzer has a rated accuracy of better than 1 percent of the span concentration over the calibrated range. The span calibration was checked with a verified standard mixture of CO_2 gas.

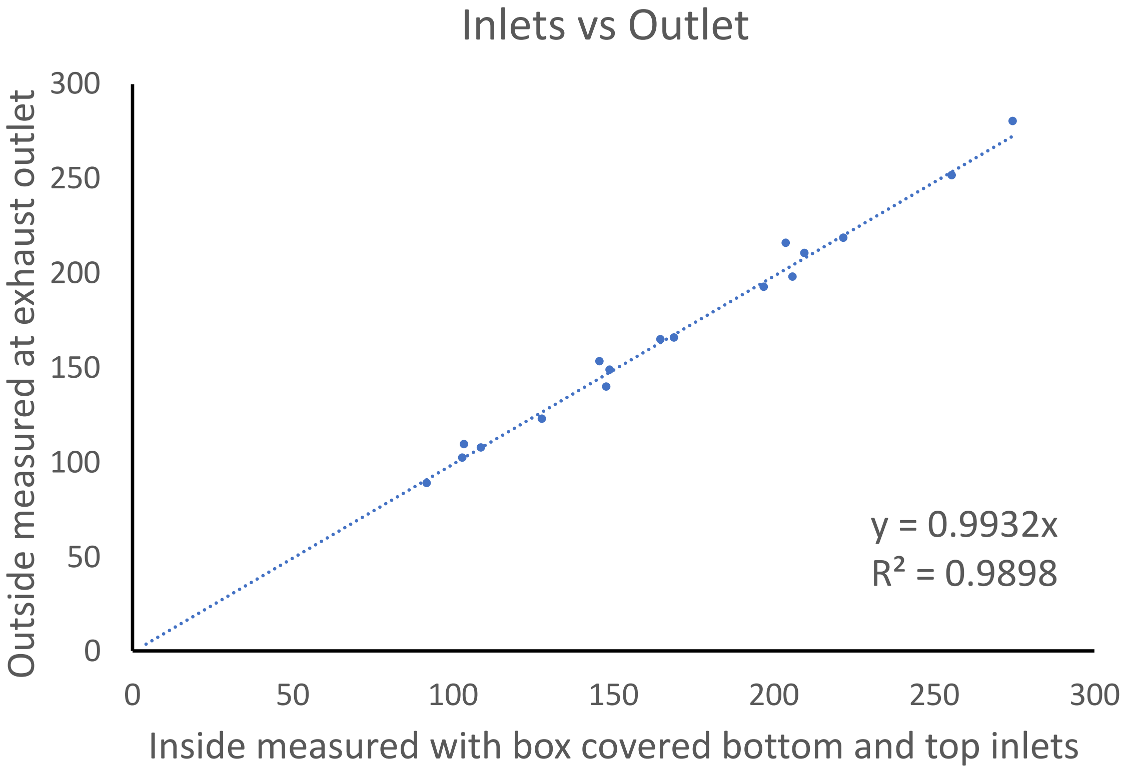
Three burner configurations were used: 1) both front burners, 2) both back burners and 3) one front burner and one back burner (using the nominal 9500 BTU/h front burner). Covered 5L stainless steel pots filled with approximately 3 L of water were placed on the cooktop burners to simulate cooking. After the pots were placed on the stovetop, the burners were ignited and operated for ~3 min and then turned off. The researcher moved slowly away from the range after placing the pot of water to minimize activity-based air currents that can affect CE. This approach will be referred to as the pot of water CE test. Fuel flow rates were 9.5±0.2 lpm, 8.5±0.1 lpm and 8.6±0.3 lpm for the two front burners, two back burners and one front and one back burners, respectively.

Results

Comparison of Over the Counter airflow measured at outlet and inlets

The results of OTR airflows measured using the balanced-pressure flow method with transition boxes on the outlet or covering both the top and bottom inlets are shown in Table 5 of (H. Zhao et al. 2020), which also presents the ratios of the flows measured at the inlets to flows measured at the outlets. The result shows that the inlet and outlet airflow measurements match within 5 percent for all of the tested devices and speed settings. A plot of inlet versus outlet airflow measurements is shown in Figure 7; it shows that the two approaches provided highly correlated results with a linear slope of 0.99 and a root-mean-square error of 5.6. The average (±SD) difference between airflows measured at outlets and those measured at inlets is 2.8 percent±1.9 percent. The approach of measuring from the inside with a transition that covers both the top and bottom inlets is equivalent to measuring the flow at the outlet.

Figure 7: Airflow Measured at Over the Counter Inlets versus Outlet



Each data point is a flow setting on one of the 6 OTRs tested.

Source: Lawrence Berkeley National Laboratory

Airflows of Over the Counter and Range Hoods

Table 10 summarizes the airflows measured at each speed setting of the 6 OTRs and 2 range hoods, using the measurement at the outlet. The minimum airflow requirement of ASHRAE 62.2 for kitchen ventilation (100 cfm) was met at the lowest settings of most of the OTRs and both of the range hoods; for WH2, the 100 cfm requirement was met at the second lowest setting. The highest airflows of two OTRs (WH2 and GE2) and one regular range hood (RH1) met the HVI recommended exhaust airflow level for standard 30-inch wide range (250 cfm). The highest airflows were 165 to 268 cfm.

The airflows measured in the research team's study were all within 17 percent of the values reported by HVI, as shown in Table 10. Of the 10 data points (2 settings each for 5 devices) available for comparison, in 3 cases the values measured in the research team's lab were <90 percent of those reported by HVI and in one case the research team's measurement was >110 percent of the HVI value. The agreement is expected since the measurement configuration in FLEXLAB had modest airflow resistance.

Table 10: Measured Airflows (cfm) of 6 Over the Counter and 2 Range Hoods

Device ID	Highest	Med-high	Med-low	Lowest	HVI HS [a]	HVI WS [a]
WH1	210			149	210	140
WH2	256	206	148	92	290	110
WH3	197	169		128	210	140
GE1	222			109		
GE2	275	204	146	104		
Frigidaire 1	165			103		
RH1	268	253		176	270	150
RH2	208			120	230	140

[a] Listed HVI airflows at high speed (HS) and working speed (WS) values are for vertical discharge.

Source: Lawrence Berkeley National Laboratory

Results comparing airflow to the cost for each range hood or incremental cost for the OTR above the cost of a similar microwave and sound measurements are provided in the LBNL report (H. Zhao et al. 2020).

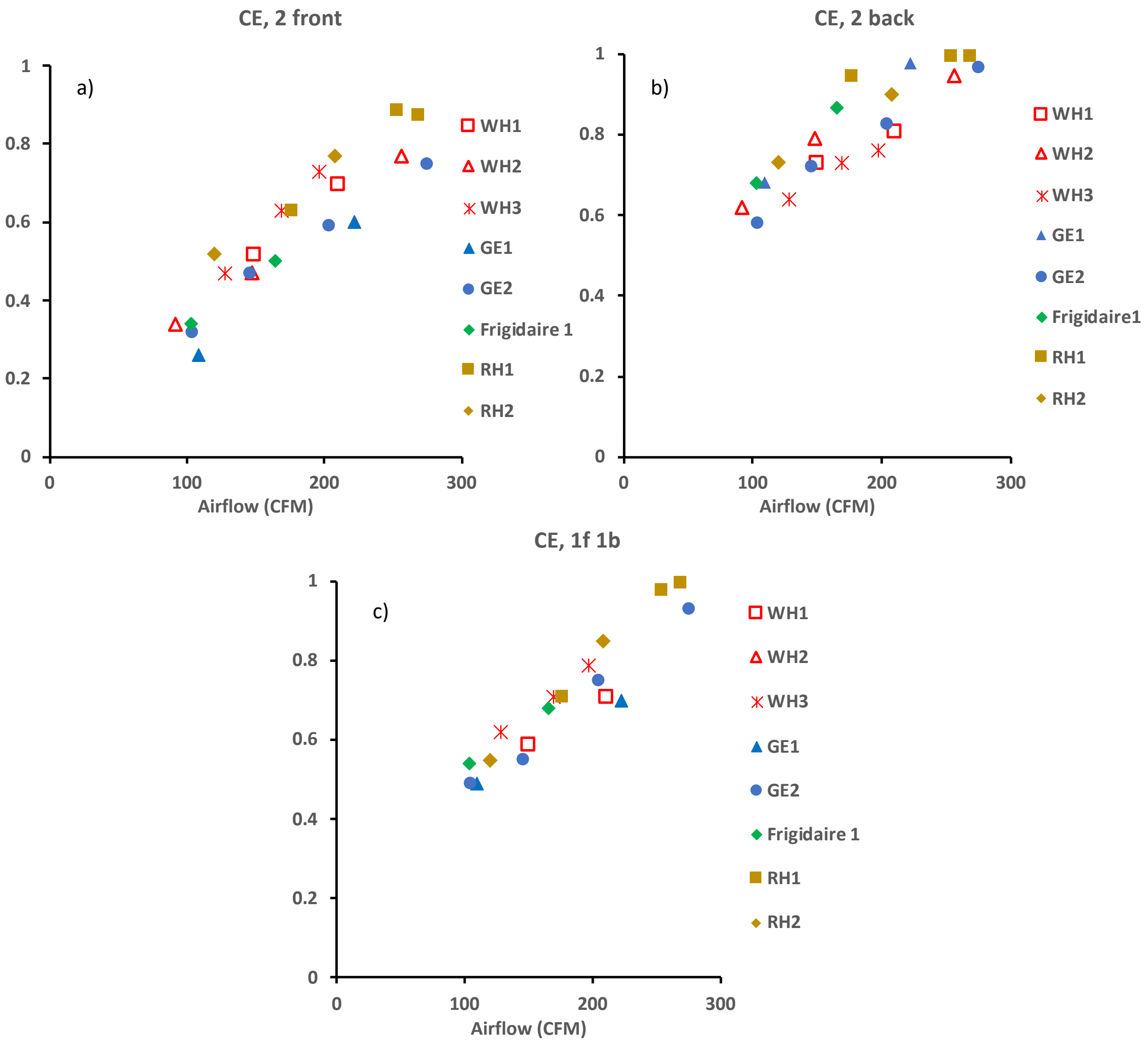
Evaluation of Airflow Measurements in HENGH Study

The LBNL report provides detailed results comparing airflows measured for OTRs at the exhaust outlet, which is taken as the most accurate, and using the modified balanced-pressure flow method employed in the HENGH field study, which restricted the airflow through the top inlets. Airflows measured using the modified field method were substantially lower than those measured at the exhaust outlet, with the ratio varying by OTR model over the range of 0.72 to 0.96 (means by model, across multiple speeds). The mean ± standard deviation of the error of the modified method was 13 percent±8 percent. This reveals that the research team underestimated airflows by approximately 13 percent overall for OTRs tested in the HENGH study. The LBNL report additionally presents a discussion of how the results from this testing were used to adjust the airflows measured in the HENGH field study. The adjusted values are included in the published dataset for the HENGH study (W. Chan et al. 2020).

Measured Capture Efficiency of Over the Counter and Regular Range Hoods

The results of capture efficiency testing in this study for OTRs and range hoods as a function of their measured airflows are shown in Figure 8. Panels a, b, and c of Figure 8 show CE measured with 2 front burners, 2 back burners, and 1 front + 1 back burner, respectively. The measured CEs generally increased with airflow. Capture efficiency was much higher when using the back burners, above 90 percent when airflow was roughly 250 cfm, 75-90 percent when airflow was around 200 cfm, and roughly 60 percent at 100 cfm airflow. Capture efficiency was much lower when cooking on front burners, approximately 75-85 percent with airflow of roughly 250 cfm, 60-75 percent at 200 cfm airflow and, very importantly, <35 percent at 100 cfm airflow. Results for CE testing with one front and one back burner generally appear to be in the middle of the results obtained with use of two front or two back burners. The relationship between airflow and CE for OTR models listed in the HVI directory (red markers) do not appear to be very different with those not certified by HVI (blue and green markers). Additionally, the measured CEs of the two range hoods (brown markers) are not significantly different than those of OTRs at similar airflow and burner configuration.

Figure 8: Capture Efficiency Related to Airflow for Over the Counter and Range Hoods in this Study



Capture efficiency as a function of airflow measured for OTRs and range hoods with a) two front burners b) two back burners and c) one front and one back burners. HVI listed OTR models are marked red and regular range hoods are marked brown.

Source: Lawrence Berkeley National Laboratory

The LBNL report presents a discussion of how these new measurements relate to previously published results for OTRs and also presents a comparison of CE vs. airflow for OTRs versus conventional range hoods based on all the available data. The data show generally similar performance for OTRs and range hoods; CEs of both OTRs and range hoods generally increase with airflow and follow similar trends for front and for back burners. At the same airflows, CEs are higher and more consistent across devices for back burners than for front burners. For front burners, roughly 250-300 cfm is needed to reliably get to above 60 percent CE, whereas

60 percent CE appears to be achieved on back burners at less than 150 cfm for most devices (excluding a few outliers). One apparent difference between OTRs and range hoods is that range hoods appear to have more variable performance for front burners. The more consistent CEs of OTRs on front burners may result from greater consistency in their geometry including the inlets above the door, which is more important for front burners. Range hoods vary a lot more in the degree to which they capture emissions from front burners, based substantially on varied geometries of the hood relative to the cooktop burners. The overall finding here is that OTRs appear to provide similar capture efficiency as range hoods at the same airflow.

Conclusions

Over the Counter Airflows

In this study, the research team selected six over-the-range microwave range hood combinations (OTRs) and two standard under-cabinet range hoods based on listings in the HVI catalog and devices observed in the HENGH study. The tested their airflows and capture efficiency in an installation with downstream ducting that provided similar flow resistance to HVI standard testing, up to about 250 cfm. Three different approaches were utilized to measure airflows, including measurements at the outlet of the exhaust duct, measurements that capture airflow into both of the main inlets, and a protocol that was used in the recent HENGH field study that involved taping over the top vents of the OTRs and measuring only the airflow entering at the bottom. Airflows measured using these approaches were compared to evaluate consistency and bias. Comparisons also were made between OTRs and range hoods and between models with and without HVI cortication. These assessments provide the following results:

1. Airflows measured with a transition that covered both the top and bottom inlets of an OTR match those measured at the outlet.
2. The method used in the HENGH field study – in which the top inlet was taped and airflow was measured going into the bottom inlet - underestimated OTR airflows, presumably by changing flow dynamics inside the hood. Correction factors were determined for the 6 hoods and used to correct data for 20 OTRs in the HENGH dataset.
3. Airflows of OTRs were similar to range hoods of similar cost, when an adjustment is made for the functionality of the microwave (which adds cost).
4. Airflows of OTRs not listed in the HVI catalog were similar to those that were listed and met the airflow requirements of ASHRAE 62.2.

Over the Counter Capture Efficiency

The capture efficiency of six OTR microwave range hoods and two standard under-cabinet range hoods were also tested using a CO_2 mass balance method with boiling pots of water. Three different burner configurations were tested including 2 front burners, 2 back burners and 1 front and 1 back burner. The results were compared to previous studies on OTR and range hood CE. These tests support the following findings:

1. OTR capture efficiency generally increases with airflow, and the trend was consistent with CEs reported for OTRs in previous lab and field studies using the same method.

2. OTRs and standard range hoods both have much lower CEs when emissions occur on front vs. back burners and CE is a function of airflow for both types of exhaust devices, and for both front and back burners.
3. The central relationship of CE to airflow is similar for OTRs and range hoods for both front and back burners, but CEs for range hoods as a group were much more variable than CEs of OTRs when emission occur on the front burners.
4. Capture efficiency depends greatly on the specific conditions of the test method. Capture efficiency was much lower for particles from cooking.

Looking Ahead

As this report is being finalized, HVI appears very close to completing all necessary preparations to certify capture efficiency test results based on a steady-state chamber method developed from ASTM-E3087-18. Data from certified CE test results may soon provide a much more expansive record of OTR and range hood capture efficiency performance than the limited data reported in this document.

CHAPTER 5: Pollutant Exposure Simulations to Inform Capture Efficiency Standards

Objective and Overview

The objective of this task was to inform consideration of changes to the BEES to specify a required level of range hood capture efficiency, rather than only focusing on airflow and sound requirements. This chapter describes and presents results of simulations conducted for the purpose of determining a capture efficiency (CE) that will keep combustion and cooking-generated air pollutants from reaching unhealthful levels as long as the range hood is used.

The use of capture efficiency as the performance metric would enable kitchen ventilation solutions that do not rely solely on high airflows that increase energy use – both for the fan power and to condition the additional air brought into the home to make up for the higher airflows. Currently, there are limited CE data available. However, with the recently established ASTM E3087 standard test method and the development by HVI of a testing and certification process, it is expected that extensive CE performance data will soon be more readily available.

The research team's analysis sought to determine the capture efficiency needed to control NO_2 emitted from natural gas cooking burners and $PM_{2.5}$ emitted during cooking regardless of the cooking fuel used, that is assuming that the same PM would be produced by the meals considered whether they were cooked with gas, propane or electric burners.

A detailed description of the methods, input data and preliminary results from the simulation analyses conducted for this task are reported in a technical report (W. R. Chan et al. 2020) that is available to the public via the publications database maintained by the Energy Technologies Area of Lawrence Berkeley National Laboratory (https://eta.lbl.gov/publications). Modifications to the analysis procedure and updated results are presented in a technical memorandum that was submitted to the Energy Commission on October 27, 2020.

Approach

The indoor air quality implications of varied range hood performance levels were assessed using computer simulations of pollutant emissions and removal processes to determine time series of concentrations in homes with cooking. The simulation framework considers emissions from cooking and entry of pollutants with outdoor air, and accounts for removal by kitchen ventilation, continuous dwelling unit ventilation and deposition to surfaces. The simulations assumed that range hoods are used at least for the duration of all cooking events. Simulations were conducted in a "Monte Carlo" fashion in which key input parameters were selected from distributions at the start of the time series calculation for each individual home. Input parameters included home size and number of bedrooms (which were used in the assignment of the code-required dwelling unit ventilation rate), outdoor air pollutant levels, and deposition rates. Details about the simulation model and parameter distributions are provided in the following paragraphs and sub-sections.

In consideration of findings from prior work and an assessment of the air pollutants that are most likely to exceed guidelines, the analysis focused on short-term nitrogen dioxide (NO_2), which is emitted at substantial rates by gas burners, and fine particulate matter ($PM_{2.5}$), which is emitted at substantial rates during food preparation by frying, grilling and broiling. Electric coil burners can also emit NO_2 but the rates are much lower than from gas burners (Dennekamp et al. 2001; Fortmann, Kariher, and Clayton 2001); NO_2 from electric burners is thus not considered. (Induction burners are even cleaner, as they should have no NO_X emissions since they none of the equipment reaches the high temperature needed to break the molecular nitrogen bonds and limited data suggest they also have much lower ultrafine particle emissions compared to gas or electric resistance burners.) The analysis did not explicitly consider whether $PM_{2.5}$ is emitted only from cooking with appliances that combine cooktops and ovens under the range hood, or if some of the $PM_{2.5}$ is emitted from ovens that are separate or other cooking appliances such as toasters, toaster-ovens, and countertop electric grills. However, since a single range hood capture efficiency (CE) is assumed in each set of simulation runs, the analysis implicitly assumes that all emissions occur from cooking appliance situated under the range hood. Since this is not the case for most countertop appliances (for example toasters, toaster ovens, electric grills, etc.) or from ovens that are not integrated with the cooktops in range units, this analysis applies only to cooking on cooktops and range ovens. The analysis also does not explicitly consider ultrafine particles – which are emitted by gas and electric burners and during cooking – or potentially irritating or hazardous organic gases emitted during cooking, for example acrolein. The analysis of highest 1-h NO_2 concentrations considers cooking of a single meal suitable for 3-4 persons. The analysis of 24-h $PM_{2.5}$ considers cooking three meals that all emit substantial, though not extreme quantities of $PM_{2.5}$, in a single 24-h period.

Sets of simulations – in which input parameter values were selected from specified distributions to represent conditions across California new homes - were run for several discrete levels of CE. For each CE level, the output of the simulation set was an estimate of the fraction of California new homes that would exceed the following health-based air pollutant guidelines under the conditions modeled.

- NO_2: 1-hour maximum of 100 ppb (California Air Resources Board 2016)
- $PM_{2.5}$: 24-hour average of 25 ug/m^3 (World Health Organization 2006) and 35 ug/m^3 (US Environmental Protection Agency 2012)

The analysis examined new, single family detached, single family attached, and multi-family homes. It was assumed that each home is ventilated precisely at the rate required in California's Building Energy Efficiency Standards, Part 6 of the Title 24 building code. Each home type was assigned a distinct floor area distribution and breakdown of natural gas or electric cooking fuel. For homes that use natural gas cooking fuel, NO_2 concentrations were simulated for 4 h from the start of cooking and the maximum 1-h average NO_2 concentration was calculated. $PM_{2.5}$ concentrations were modeled for 24 h with emissions from the cooking of breakfast, lunch, and dinner. The same $PM_{2.5}$ emission rates were assumed for both natural gas and electric range use. Outdoor NO_2 and $PM_{2.5}$ concentrations were sampled from distributions developed from ambient monitoring data. Distributions for $PM_{2.5}$ and NO_2 penetration factors, deposition rates and emission rates were determined from values reported in the literature.

The assumptions for the Monte Carlo simulation were as follows: that operation of the range hood reduces the cooking or burner pollutant emissions by the specified CE rate; that air in the house is at all times perfectly mixed (and emissions are instantaneously mixed into the full volume of the home); range hood operation both removes cooking and burner pollutants directly by plume capture and also by providing additional dwelling unit ventilation; and the same pollutant emissions (essentially meaning the same meals) are cooked in each residence, irrespective of size and occupancy.

Mass Balance Model

The following mass balance equation was used to simulate indoor NO_2 and $PM_{2.5}$ concentrations resulted from cooking:

$$\frac{dC}{dt} = P\left(\frac{Q}{V} + \frac{Q_{RH}}{V}\right)C_o + (1 - CE)\frac{E}{V} - \left(\frac{Q}{V} + \frac{Q_{RH}}{V} + k_d\right)C \qquad (5.1)$$

The indoor concentration was calculated at 1 min resolution (Δt = 1-min) using Equation 5.2:

$$C_t = C_{t-1}e^{-k\Delta t} + \left[P\left(\frac{Q}{V} + \frac{Q_{RH}}{V}\right)C_o + (1 - CE)\frac{E}{V}\right]\frac{1-e^{-k\Delta t}}{k} \qquad (5.2)$$

where $k = \frac{Q}{V} + \frac{Q_{RH}}{V} + k_d$. $\frac{Q_{RH}}{V}$ is the range hood airflow rate normalized by the house volume and is applied for the full duration of all cooking events and for an additional 10 minutes during some simulations. When the range hood is not in use, $Q_{RH} = 0$.

The initial indoor concentration was calculated using Equation 5.3:

$$C_{t=0} = \frac{P\left(\frac{Q}{V}\right)C_o}{\frac{Q}{V}+k_d} \qquad (5.3)$$

All inputs are defined in the table below. Since the number of combinations is large (~12 million), each of the parameters were randomly sampled with replacement for a total of 50,000 simulations. Each home simulation returns the maximum 1-hr concentration (rolling mean) for NO_2, and the daily average concentration for $PM_{2.5}$. Selected model runs were performed using 100,000 simulations to confirm that 50,000 simulations are adequate for predicting the percentage of homes exceeding a certain health guideline.

Table 11: Model Input Parameters

Variable	Units	Description
C	g/m^3	Indoor concentration
C_o	g/m^3	Outdoor concentration
V	m^3	Volume of home, calculated from floor area and an assumed ceiling height of 2.5 m
P	-	Penetration efficiency
k_d	1/h	Deposition rate
Q	m^3/h	Ventilation rate
Q_{RH}	m^3/h	Range hood airflow rate
CE	-	Range hood capture efficiency
E	g/h	Emission rate

Source: Lawrence Berkeley National Laboratory

Details about the parameter distributions used for home sizes and air exchange rates are provided in the LBNL report.

Nitrogen Dioxide and Fine Particulate Matter Model Parameters

The analysis for NO_2 was based on the burner use and fuel consumption measured by LBNL for a meal of pasta with meat sauce, blanched broccoli and garlic bread (unpublished data). The meal has a total of 82 minutes of burner operation. The average fuel use per minute of burner operation is 7 kBTU/h. In the simulations, the meal was simplified as 4 burners operating for 21 minutes with a constant emission rate of 7 kBTU/h per burner or 28 kBTU/h total. Additional details are provided in the LBNL report.

$PM_{2.5}$ concentrations were modeled over a 24-hour period during which three meals were cooked and all three had substantial $PM_{2.5}$ emissions. The modeled mass of $PM_{2.5}$ emitted per meal is as follows:

- Breakfast: bacon, eggs and hash browns, 19 min, 100 mg;
- Lunch: stir-fry of chicken and vegetables, 17 min, 50 mg;
- Dinner: pasta Bolognese, 20 min, 50 mg.

These emitted mass and cooking duration values were adapted from data on scripted meals. Breakfast is based on unpublished measurements made at LBNL that estimated emissions from frying of bacon, eggs, and hash browns to be roughly 85 mg; these were rounded up to 100 mg. O'Leary et al. (O'Leary et al. 2019) reported average emissions of 53.4 and 53.2 mg of $PM_{2.5}$ for the meals noted; these were rounded to 50 mg/meal. The 100 and 50 mg/meal emission factors are roughly at the 80th and 50th percentiles of published emission rates for meals producing $PM_{2.5}$, as described in the LBNL report.

As another check, the research team considered the distribution of cooking event emissions determined from analysis of time-resolved $PM_{2.5}$ concentrations in 18 California apartments (W. R. Chan et al. 2018); that study identified 836 emission events from 224 days of monitoring data. While the emission events included all indoor sources, many of them were likely cooking related. The analysis found that the mass emitted per event in the 18 California apartments ranged from 1 to 154 mg, with a mean value of 30 mg and a median of 12 mg. The 100 mg (breakfast) and 50 mg (lunch and dinner) modeled roughly correspond to the 90th and 80th percentile of the emitted mass per event estimated by Chan et al.

Loss of NO_2 by deposition (k_d), as shown in Equation 5.1, can have a large impact on modeled concentrations. In a prior study in which LBNL estimated exposures to NO_2 from natural gas cooking burners, NO_2 first-order deposition rates were modeled as being either 0.5/h or 1.05/h (Logue et al. 2014). These span the range of values between 0.11 and 1.4/h reported in literature for furnished residences (Nazaroff, Gadgil, and Weschler 1993; Spengler et al. 1994; Spicer et al. 1993; Yang, Lee, and Chung 2004). Differences in NO_2 deposition rate can be partly explained by humidity effects and variations in indoor surface characteristics. For the current analysis, the research team put more emphasis on studies by Zhou et al. (Zhou et al. 2018) in a single-family NY house, and work by Francisco et al. (Francisco, Gordon, and Rose 2010) and Gordon et al. (Gordon, Francisco, and Rose 2008) in 17 Illinois homes. Those studies both report a central estimate of 0.75/h for the NO_2 deposition rate. In light of these data, the research team modeled NO_2 deposition rate using a triangular distribution with mode of 0.75/h, minimum of 0.5/h, and maximum of 1.0/h.

The $PM_{2.5}$ deposition rate was modeled using a triangular distribution with mode of 0.6/h, minimum of 0.3/h, and maximum of 1.2/h. This is based on results reported by Wallace et al. (L. Wallace et al. 2013), who analyzed $PM_{2.5}$ time series in 58 Canadian homes during winter. The measured median AER of the sample was 0.34/h, which is similar to the AER for new California homes that are mechanically ventilated per Title 24. And Canadian homes are expected to have similar $PM_{2.5}$ deposition as California homes owing to the homes being of similar construction and with similar materials and furnishings. Wallace et al. reported median and interquartile deposition rates of 0.60/h and 0.34–1.19/h.

The research team modeled the $PM_{2.5}$ penetration factor as a uniform distribution ranging from 0.4 to 0.6. This range, which is at the lower end of penetration factors reported in the literature, was selected because the exhaust mechanical ventilation systems which are common in new California homes cause outside air to enter through the building envelope, which results in substantial particle removal. A recent study of ventilation and filtration systems that was conducted in a typically airtight (5 air changes per hour at 50 Pascal indoor-outdoor pressure difference), 2006-built home in Sacramento reported estimates of penetration factors of 0.4–0.5 for particles between 0.3 and 2.5 μm when the house used exhaust ventilation (B. C. Singer, Delp, et al. 2017). The LBNL report includes a discussion of penetration factors reported in other studies.

Outdoor Air Quality Data

Aggregated $PM_{2.5}$ and NO_2 outdoor data from the Air Quality Monitoring Information System (AQMIS) was used to provide ambient concentrations of these two pollutants when running the simulations. Hourly outdoor data for NO_2 (ppb) for the years 2016–2018 were downloaded from the AQMIS website. Data was extracted for 15 of the largest counties in California where approximately 83 percent of the state population reside. Data were obtained for 43 monitoring sites with NO_2 outdoor data. Because NO_2 concentrations tend to be higher in the winter months, November to January data were used to characterize the outdoor NO_2 concentrations.

Outdoor NO_2 concentrations were approximated using a cropped normal distribution, with mean of 12 ppb, standard deviation of 18 ppb, and minimum and maximum of the simplified distribution corresponding to the 5th and 95th percentiles of the actual distribution, that is, 3 ppb and 44 ppb. Additional details are provided in the LBNL report.

Distributions of 24-h average outdoor $PM_{2.5}$ ($\mu g/m^3$) were developed from data downloaded from the California Air Resources Board AQMIS website. Three years of data (2016 to 2018) were downloaded for 15 of the largest counties in California, with 35 monitoring sites in populated areas. Daily average $PM_{2.5}$ concentrations follow lognormal distributions with GM of 8.9 $\mu g/m^3$ and GSD of 2.1. Values of outdoor $PM_{2.5}$ were cropped to limit values between 3 and 25 $\mu g/m^3$, roughly corresponding to 5th and 95th percentiles of the AQMIS data. Additional details are provided in the LBNL report.

Modifications to Analysis Subsequent to Published Lawrence Berkeley National Laboratory Report

The initial simulation results considered variations in capture efficiency and airflow independently. Additional simulations were conducted to assess performance when CE and airflow are linked. A second enhancement was consideration of higher acute NO_2 exposures for the cook, who is in the kitchen area during and shortly after the burners are used for meal preparation. The enhanced model accounts for higher NO_2 in the kitchen when calculating the peak 1-h NO_2 concentration. A proximity factor of 2 was applied to the indoor-generated NO_2 from cooking to account for higher concentrations of the burner-emitted pollutant in the kitchen during and shortly after cooking. In other words, it is assumed that the concentration of NO_2 emitted from the burner is twice as high in the kitchen as it is generally mixed throughout the house. The same proximity factor was used in the research team's previous work (Logue et al. 2014).

Relationship between Capture Efficiency and Range Hood Airflow

The relationship between range hood airflow and capture efficiency (CE) depends on hood design, whether front or back burners are used and the cooking procedure (Logue et al. 2015; B. C. Singer et al. 2012).

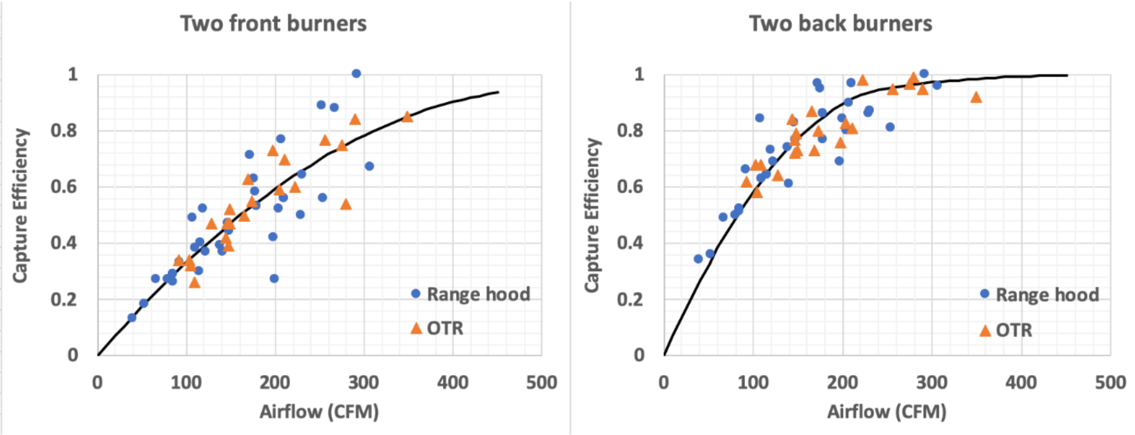
Figure 9 shows the relationship determined from LBNL studies (Delp and Singer 2012; B. C. Singer et al. 2012; Lunden, Delp, and Singer 2015; H. Zhao et al. 2020) conducted by placing 5L capacity pots, each filled with 4L of water, on either the front or back burners of gas cooktops. The CE was calculated using measurements of airflow, the CO_2 concentration differences between the room and the range hood exhaust, and the CO_2 emission rate, as described in detail in the cited papers. The CO_2 emission rate was determined by measuring the gas fuel flow rate and calculated from stoichiometry assuming complete combustion.

Figure 9 shows that higher airflow generally translates to higher CE, and CE is higher when using two back burners compared to two front burners. In this analysis, the relationship between capture efficiency and range hood airflow was assumed to follow the one fitted for front burners in the left panel of Figure 9. Since this test procedure measured CE using CO_2, a combustion pollutant, the research team assumes it is representative for NO_2.

An alternative method to measuring CE was described by Kim et al. (Kim, Walker, and Delp 2018). That method was developed to be a precisely-repeatable, standard test method and used a steady-state approach, where CO_2 is injected using heated emitters, rather than relying on CO_2 generated from gas combustion (ASTM 2018). The method specifies emitters which release CO_2 from both the middle, to represent cooking emissions, and the outer circumference to represent gas or electric burner emissions. Figure 10 presents CE data reported by Kim et al. (as green triangles) using the method that was proposed to ASTM and closely reflecting the final approved method. Meleika and Pate (Meleika and Pate 2020) tested five range hoods using the approved ASTM method, but with burner and hood installations that differed somewhat from those used in the experiments of Kim et al. Specifically, Meleika and Pate had emitters placed on top of hot plates on a countertop surface simulating the cooktop base; whereas Kim et al. placed emitters onto heating coils that were at the level of cooktop base. Since the distance between the top of the emitter and range hood was similar in the two studies, in the Melieka and Pate configuration, the range hood was higher relative to the simulated side cabinets, effectively creating partial side panels. Melieka and Pate conducted testing at emitter temperatures of 160C, 130C and 200C.

Figure 10 shows the capture efficiency results presented by Meleika and Pate (orange diamonds) as a function of airflow at all three cooktop temperatures.

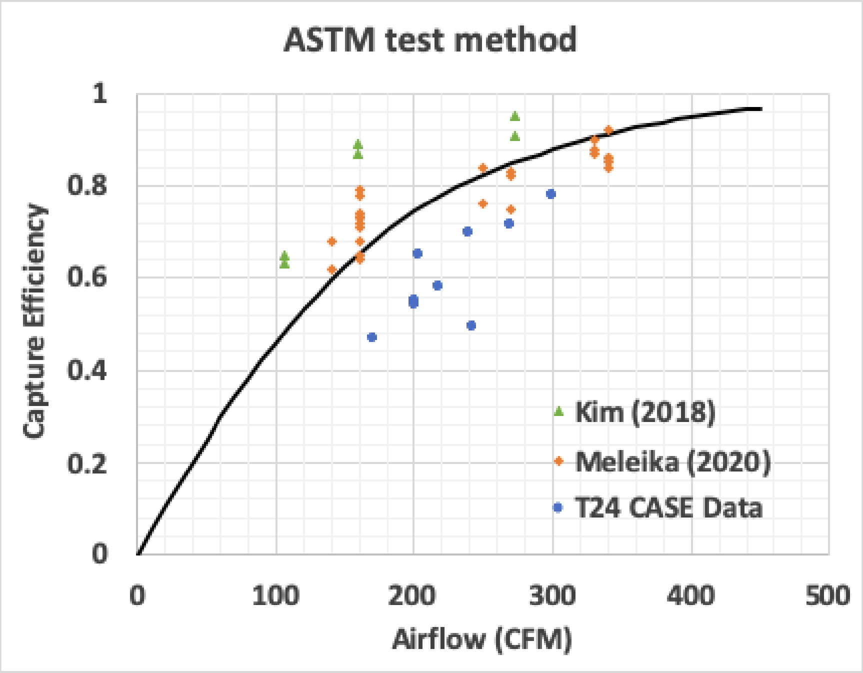
Figure 9: Capture Efficiency and Range Hood Airflow from Past Lawrence Berkeley National Laboratory Studies



Using a transient method by placing either two pots at the front (left panel) or back (right panel) burners. OTR = over-the-range microwave

Source: Lawrence Berkeley National Laboratory

Figure 10: Capture Efficiency and Range Hood Airflow Determined Following the ASTM Test Method



Source: Lawrence Berkeley National Laboratory

Additional testing of capture efficiency and range hood airflow was conducted for Title 24 CASE 2022 cycle using yet another configuration of emitters and range hood placement in relation to the counter and side cabinets These data are the blue circles in Figure 10. Photos of the experimental set-up in the CASE report show that the CO_2 emitters were set into the countertop with their tops at counter level, rather than placed on top of heat plates as the photos shown in Meleika and Pate. These experimental differences may explain why the Title 24 CASE data show lower capture efficiency at a given range hood airflow rate than other tests following the ASTM procedure.

Overall, the ASTM method with CO_2 emitted from both the middle and the outer edge of the emitters shows higher capture efficiency at a given range hood airflow compared to the transient method where natural gas burners were used as the CO_2 source. The ASTM test method is designed to determine the capture of all cooking contaminants from both the source of heat (natural gas or electric coils) and emitted from the cooking process. The data shown in Figure 9 are specifically from emissions of natural gas burners and thus should be considered as specifically more relevant to NO_2 from gas combustion. In this analysis, the relationship between capture efficiency and range hood airflow rate is modeled following the curve drawn using the ASTM method for $PM_{2.5}$. For natural gas burner emissions, such as NO_2, the relationship between capture efficiency and range hood airflow is modeled using the curve drawn using "two front burners" in Figure 9.

Results

Table 12 shows the calculated percentage of simulated homes with a 24-h averaged $PM_{2.5}$ of 25 ug/m^3 or higher resulting from cooking three meals that each have substantial $PM_{2.5}$ emissions in a single day and with the range hood used for each meal. For this analysis the research team used pairs of CE and airflow determined with an ASTM test and the model also considers $PM_{2.5}$ coming from outside. The range hood was assumed to reduce emissions into the well-mixed home air volume base on the capture efficiency value used in the simulation. All homes (single-family detached, single-family attached, and multi-family units) were modeled as having base, dwelling unit mechanical ventilation just meeting the requirement of the state's Building Energy Efficiency Standards, with additional airflow from the range hood throughout the assumed cooking duration for each meal. A capture efficiency of 0.50 (50 percent removal of $PM_{2.5}$ generated at the cooktop) is sufficient to maintain indoor $PM_{2.5}$ below the limit value in virtually all homes (>99 percent) that are larger than 1,000 ft^2. Homes smaller than 1,000 ft^2 would require higher capture efficiencies (0.55 and 0.65) to meet the 25 µg/m^3 limit.

Table 12: Percent of Homes exceeding $PM_{2.5}$ 24-h Threshold Value for Range Hoods with ASTM Capture Efficiency and Modelled Airflow Rate as Drawn in Figure 10

ASTM Capture Efficiency	Modeled Flow Rate (cfm)	All homes	Floor area <750 ft^2	Floor area 750 - 1,000 ft^2	Floor area 1,000 - 1,500 ft^2	Floor area >1,500 ft^2
0	0	55%	100%	100%	76%	8%
0.50	110	7%	39%	4%	0.3%	0
0.55	130	3%	18%	0.7%	0	0
0.60	140	1%	7%	0.2%	0	0
0.65	160	0.2%	1%	0	0	0
0.70	180	0.01%	0.06%	0	0	0

Source: Lawrence Berkeley National Laboratory

Higher capture efficiencies are needed to maintain the maximum 1-h NO_2 below the 100-ppb threshold value (Table 13). In this analysis, the home is assumed well-mixed, but a proximity factor of 2 was applied to the NO_2 emitted by the gas burners to account for higher NO_2 in the kitchen when calculating the maximum 1-h concentration. (The factor of 2 for proximity to the emission source is assumed only for the NO_2 emitted from the gas burner, and not applied to NO_2 entering from outdoors.) The highest 1-h NO_2 was modeled with outdoor NO_2 data from late afternoon and evening hours because dinner is typically the largest meal in California households, and the one most likely to have extensive burner use. A CE of 0.55 is sufficient to maintain the indoor NO_2 below the 1-h threshold value in virtually all homes (>99 percent) larger than 1,500 ft^2. Homes smaller than 1,500 ft^2 would need higher burner emission capture efficiencies (0.70 to 0.75) to meet this threshold value.

Table 13: Percent of Homes with 1h NO_2 Exceeding the Threshold Value for Range Hoods with the Same Capture Efficiency but Higher Flow Rates as Shown in Figure 9 for "two front burners"

Capture Efficiency	Modeled Flow Rate (cfm)	All Homes	All Gas Homes	Gas, floor area <750 ft^2	Gas, floor area 750 - 1,000 ft^2	Gas, floor area 1,000-1,500 ft^2	Gas, floor area >1,500 ft^2
0	0	49%	84%	100%	100%	100%	70%
0.50	160	19%	33%	95%	75%	47%	4%
0.55	180	14%	24%	85%	57%	30%	1%
0.60	200	9%	16%	66%	38%	16%	0.1%
0.65	225	5%	8%	42%	18%	3%	0%
0.70	250	1%	2%	18%	2%	0%	0%
0.75	280	0.09%	0.2%	1%	0%	0%	0%
0.80	310	0%	0%	0%	0%	0%	0%
0.85	350	0%	0%	0%	0%	0%	0%

Source: Lawrence Berkeley National Laboratory

The research team notes that the simulations for NO_2 control used range hood airflows determined from testing with combustion burner pollutants from front burners (Figure 9), and this testing found that higher airflows are needed to achieve a given CE compared to testing with the ASTM method (Figure 10).

These higher airflows added substantially to the general ventilation when range hoods were simulated to operate in the smallest housing units, especially those smaller than1,000 ft^2. The research team also note that the relationship used to model the CE vs. airflow relationship for combustion burner pollutants is through the middle of the available data. For example, in Figure 9, a burner emission capture efficiency of 0.55 was measured for range hoods with airflows ranging from approximately 140 to 260 cfm. The research team picked a middle value, of 180 cfm, even though 180 cfm does not guarantee a burner emission capture efficiency of 0.55. The research team believes this is justified because some cooking will naturally occur on back burners, and users also have the option of using back burners preferentially for better performance, when air quality is a concern. Any cooking that is done on the back burner will have much higher CE for combustion pollutants. A meal that includes some front burner and some back burner cooking will have an overall CE better than the conservative, front-burner relationship used in the modeling for NO_2.

To enable flexibility in selecting a suitable range hood for a home of a given size, the research team notes that the airflow determined in the above analysis can be translated to a CE value determined by the ASTM standard test for CE. This translation is uncertain because the ASTM test was not designed to measure performance specifically and only for pollutants generated by gas burners. As a conservative approach to provide equivalent protection, the research team used the curve shown in Figure 10 to find the ASTM CE that corresponds to each airflow highlighted in Table 13.

Using this approach and the fitted line shown in Figure 10, the research team determined that a range hood moving 180 cfm should have a corresponding ASTM CE of at least 0.70. Following this logic, homes that are between 1,000 and 1,500 ft^2 would need a range hood with a measured airflow rate of either 250 cfm or an ASTM CE of 0.80 to maintain 1-h NO_2 below the threshold value. For homes less than 1,000 ft^2, either a measured range hood airflow rate of 280 cfm or an ASTM CE of 0.85 is needed.

Conclusions

Table 14 presents the ASTM capture efficiency or rated range hood airflows needed to avoid exceeding the World Health Organization 24-h $PM_{2.5}$ guideline level when cooking three meals in a day that all emit substantial quantities of particles and Table 15 shows the CE or airflows to avoid exceeding and NAAQS 1-h NO_2 threshold value when cooking a full meal with a gas cooktop and oven. In short, it is possible to provide kitchen exhaust ventilation that, when used routinely, will allow cooking to occur safely in homes of all sizes, with either electric or gas burners, and considering both acute and chronic exposures to cooking-related air pollutants that have established health-based guideline or benchmark levels.

Table 14: Summary of ASTM Capture Efficiency or Range Hood Airflows Needed to Meet 24-h Fine Particulate Matter Threshold Value

Floor Area (ft^2)	ASTM Capture Efficiency	Airflow as installed (cfm)
>1,500 ft^2	0.50	110
1,000 - 1,500 ft^2	0.50	110
750 - 1,000 ft^2	0.55	130
<750 ft^2	0.65	160

Source: Lawrence Berkeley National Laboratory

Table 15: Summary of ASTM Capture Efficiency or Range Hood Airflows Needed to Meet 1-h Nitrogen Dioxide Threshold Value of 100 Parts per Billion

Floor Area	ASTM Capture Efficiency	Airflow as installed
>1,500 ft^2	0.70	180
1,000 - 1,500 ft^2	0.80	250
750 - 1,000 ft^2	0.85	280
<750 ft^2	0.85	280

Source: Lawrence Berkeley National Laboratory

CHAPTER 6: Technology/Knowledge/Market Transfer Activities

Technical Support for California's Building Energy Efficiency Standards

Direct Technical Support to Codes and Standards Enhancement and California energy Commission Standards Teams

The project team worked closely over many months to ensure that results from this project could be used to provide a scientific basis for the reconsideration of kitchen ventilation requirements for the 2022 California Building Energy Efficiency Standards. The research team worked first with the Codes and Standards Enhancement (CASE) team to share the research team's technical results, identify gaps that could be addressed by supplemental research supported through the CASE process and develop options for improving kitchen ventilation and other mechanical ventilation options to meaningfully improve safety for Californians with regulations that were also conscious of costs to builders and homebuyers. The research team helped the CASE team develop a plan for new data collection related to capture efficiency using the new ASTM test method, and to identify a suitable contractor to conduct the work. The research team subsequently worked with the Building Codes & Standards team of the Energy Commission to refine proposals and contributed a presentation and technical support at a Workshop on Indoor Cooking and Air Quality that was convened by CEC on September 30, 2020. Following that meeting, the research team provided formal comments (dated 16-October-2020) to address questions related to modeling conducted by UCLA to estimate exposures to natural gas cooking burners.

Finally, in response to several technical questions and uncertainties that arose about the simulation analysis that the research team had already completed for Task 4 of the project, the research team conducted additional simulations and provided results to the Commission in a technical memorandum (dated 27-Oct-2020), which was entered into the official state docket (19-BSTD-03).

Briefings to California Stakeholders

In parallel to the research team's work with the CASE and Energy Commission Standard teams, the research team's project team responded to numerous inquiries, shared draft and final technical reports and provided briefings to stakeholder organizations and individuals who reached out to us to better understand the risks of cooking and gas burner pollutants and the efficacy of kitchen ventilation as a solution. Among others, the research team had interactions with the following groups: Redwood Energy (builder), Rocky Mountain Institute, the Sierra Club, the Association for Home Appliance Manufacturers and the Home Ventilating Institute.

Technical Support for Other Codes and Standards Related to Kitchen Ventilation

Using match funding provided by the U.S. Department of Energy's Building America Program, within the Building Technologies Office, members of the research team's project team contributed technical support to codes and standards efforts that are intertwined and help California's efforts to improve building energy performance and safety through the BEES.

- Leadership and technical contributions to the ASHRAE Standard 62.2 Ventilation and Indoor Air Quality for Residential Buildings.
- Technical assistance to HVI to develop a capture efficiency testing program.
- Technical assistance to AHAM to develop a testing program for range hood airflow and sound.
- Technical consulting to AHAM to support their consideration of developing a new test method for capture efficiency.
- Technical support to the laboratory at Texas A&M that will do much if not all of the testing for CE for HVI.

Technical support to other researchers studying air pollutant emissions and exposures in California homes.

- Provided input to UCLA team led by Prof. Yifang Zhu that conducted simulations to assess indoor exposures to pollutants from gas burners: pre-publication support and post-publication comments.
- Provided technical support to a team at Stanford University that was measuring methane emission rates from residential appliances and added measurements of NOX including NO2 using methods suggested by LBNL and equipment loaned by LBNL.

Technical Papers and Reports and Presentations at Scientific Conferences

The results of this project have been provided for societal benefit through several mechanisms. The primary mechanism has been the publication of technical reports and datasets, focusing on peer-reviewed journal papers, datasets and conference papers. To advance the availability of information to the public; two final task reports were published and made publicly available as LBNL reports. The outcomes of these tasks also were presented as recorded, online oral presentations at the Indoor Air 2020 conference and summarized in papers or extended abstracts published in the conference proceedings.

The following sections list the published archival papers, reports, presentations and datasets resulting from this project.

Journal Papers

- Tang H, Chan WR, Sohn MD. 2020. Automating the interpretation of PM2.5 time-resolved measurements using a data-driven approach. *Indoor Air.* Published 28-Dec-2020. [Journal Link]
- Zhao H, Chan WR, Cohn S, Delp WW, Walker IS, Singer BC. 2020. Indoor air quality in new and renovated low-income apartments with mechanical ventilation and natural gas cooking in California. *Indoor Air.* Published online 18-Oct-2020. [Journal Link]
- Zhao H, Chan WR, Singer BC, Delp WW, Tang H, Walker IS. 2020. Factors impacting range hood use in California houses and low-income apartments. *International Journal of Environmental Research in Public Health.* [Accessible Journal Link]

Lawrence Berkeley National Laboratory Reports

- Chan WR, Kumar S, Johnson AL, Singer BC. 2020. Simulations of short-term exposure to NO2 and PM2.5 to inform capture efficiency standards. Lawrence Berkeley National Laboratory, Berkeley, CA. LBNL-2001332.
- Zhao H, Delp WW, Chan WR, Walker IS, Singer BC. 2020. Measured Performance of Over the Range Microwave Range Hoods. Lawrence Berkeley National Laboratory, Berkeley, CA. LBNL-2001351.

Published Datasets

- Chan WR, Tang H, Sohn MD. 2020. Automating the interpretation of PM2.5 time-resolved measurements using a data-driven approach, Dryad, Dataset, https://doi.org/10.7941/D1HG9J
- Zhao H, Chan WR, Cohn S, Delp WW, Walker IS, Singer BC. 2020., Data from: Indoor air quality in new and renovated low-income apartments with mechanical ventilation and natural gas cooking in California, Dryad, Dataset, https://doi.org/10.7941/D1T050

Conference Papers

- Kumar S, Johnson A. Chan WR, Singer BC. 2020. Analysis to inform a range hood capture efficiency standard for California new homes. *Indoor Air 2020: The 16th International Conference on Indoor Air Quality and Climate.* Seoul, Korea, Nov 1-5. *2-page extended abstract.*
- Zhao H, Tang H, Chan WR, Singer BC, Sohn MD. 2020. Contribution of indoor $PM_{2.5}$ from cooking using field data collected from new California homes. *Indoor Air 2020: The 16th International Conference on Indoor Air Quality and Climate.* Seoul, Korea, Nov 1-5*.*
- Zhao H, Singer BC, Delp WW, Chan WR, Walker IS. 2020. Performance of over-the-range microwave exhaust fans compared to range hoods. 2020. *Indoor Air 2020: The 16th International Conference on Indoor Air Quality and Climate.* Seoul, Korea, Nov 1-5.

Presentations at Indoor Air 2020

- Requirements for Kitchen Ventilation in High Performance Homes (Symposium organized by Singer BC)

- Contribution of indoor $PM_{2.5}$ from cooking using field data collected from new California homes. (Presenter: Zhao H. Co-authors: Tang H, Chan WR, Singer BC, Sohn MD. 2020
- Analysis to inform a range hood capture efficiency standard for California new homes. (Presenter: Kumar S. Co-authors: Johnson A, Chan WR, Singer BC)
- Performance of over-the-range microwave exhaust fans compared to range hoods. (Presenter: Zhao H. Co-authors: Singer BC, Delp WW, Chan WR, Walker IS).

CHAPTER 7: Conclusions/Recommendations

Conclusions

The following conclusions derive from the technical task summaries presented in chapters 2-5.

Based on a very limited sample of 23 low-income apartments at four sites throughout California, the research team's field study of multiunit buildings for income-qualifying Californians found the following:

- Mechanical ventilation systems in a substantial fraction of apartments may have operational deficiencies that impact their performance. These ventilation deficiencies likely translate to higher concentrations of air pollutants whose main source is indoor emission, compared to those that would occur with operation of ventilation meeting the state building code.
- In comparison to a group of single-detached houses with code-required mechanical ventilation that were examined in a recent study, the apartments much more commonly had dwelling unit ventilation equipment operating but airflows were generally much lower relative to equipment ratings compared to equipment found in houses.
- Measurements of $PM_{2.5}$ and NO_2 during a week of monitoring in apartments and houses suggest that in a substantial minority of homes, concentrations may exceed health-based limits set by the U.S. EPA and California EPA for ambient air quality or by the WHO for personal exposure. Formaldehyde concentrations were lower in apartments than in houses; but still routinely above the chronic reference exposures levels set by the California EPA.
- Data collected in the apartments affirm prior research showing that use of gas cooking burners produces high short-term and weekly time-averaged NO_2. While concentrations of $PM_{2.5}$ were similar in apartments and houses with similar levels of cooking, NO_2 was much higher in the apartments.

The research team's investigation of range hood use for 784 cooking events in 71 homes including 54 single family houses and 17 low-income apartments found the following:

- Range hoods were used more frequently in single family houses (36 percent) than in the apartments (28 percent).
- Range hood use by home generally increased with cooking frequency.
- In both houses and apartments, range hood use increased with cooktop use duration, but not with oven use duration.
- Participants who self-reported frequent use actually used their hoods more frequently; however, actual use was much lower than self-reported, with range hoods being used only 45 percent and 36 percent of the time in houses and apartments where occupants self-reported use of range hoods always, usually, or most of the time.

- Residents in single family houses used range hoods more often when cooking events generated any level of $PM_{2.5}$. In apartments, residents used the range hood more often only if high concentrations of particles were generated during cooking.

The research team's investigation of the performance of over the range microwave range hoods, commonly called "OTRs" had the following findings.

- Airflows measured with a transition that covered both the top and bottom inlets of an OTR match those measured at the outlet; this supports the use of this method for field studies and potentially also for code enforcement.
- The airflow measurement method used in the HENGH field study – in which the top inlet was taped and airflow was measured going into the bottom inlet - underestimated OTR airflows, presumably by changing flow dynamics inside the hood. Correction factors were determined for the 6 hoods and used to correct data for 20 OTRs in the HENGH dataset.
- Airflows of OTRs were similar to range hoods of similar cost, when an adjustment is made for the functionality of the microwave (which adds cost).
- Airflows of OTRs not listed in the HVI catalog were similar to those that were listed and met the airflow requirements of ASHRAE 62.2.
- OTR capture efficiency generally increases with airflow, and the trend was consistent with CEs reported for OTRs in previous lab and field studies using the same method.
- OTRs and standard range hoods both have much lower CEs when emissions occur on front versus back burners and CE is a function of airflow for both types of exhaust devices, and for both front and back burners.
- The central relationship of CE to airflow is similar for OTRs and range hoods for both front and back burners, but CEs for range hoods as a group were much more variable than CEs of OTRs when emission occur on the front burners.
- Capture efficiency depends greatly on the specific conditions of the test method. Capture efficiency was much lower for particles from cooking.

The research team's simulation-based study of NO_2 and $PM_{2.5}$ concentrations resulting from cooking in California new homes while using range hoods with varied performance levels, found the following:

- It is possible to provide kitchen exhaust ventilation that, when used routinely, will allow cooking to occur safely in homes of all sizes, with either electric or gas burners, and considering both acute and chronic exposures to cooking-related air pollutants that have established health-based guideline or benchmark levels.
- To maintain low risk (<1 percent) of exceeding the health-based threshold of 100 ppb averaged over one hour in homes with gas burners, range hoods should have the following performance:
    - For homes >1,500 ft^2 a capture efficiency measured by the ASTM test method of 70 percent or a confirmed (verified or certified) airflow of 180 cfm.
    - For homes 1,000-1,500 ft^2, a CE of 80 percent or an airflow of 250 cfm.
    - For homes <1,000 ft^2, a CE of 85 percent or an airflow of 280 cfm.

- To maintain low risk (<1 percent) of exceeding the health-based threshold of 25 μg / m^3 $PM_{2.5}$ averaged over 24 hours, every home should have a range hood that minimally meets the following specifications:
    - For homes >1,000 ft^2, a CE of 50 percent or an airflow of 110 cfm.
    - For homes 750–1,000 ft^2, a CE of 55 percent or an airflow of 130 cfm.
    - For homes <750 ft^2, a CE of 65 percent or an airflow of 160 cfm.

Since pollutants are generated from cooking with any energy source, exclusion of gas cooking appliances does not eliminate the need for effective kitchen ventilation. However, as seen from the requirements noted above, the exclusion of gas effectively mitigates the hazards of combustion pollutants, principally NO_2, and provides more flexibility in kitchen ventilation.

Recommendations

Based on the findings of the work performed during this project, the research team offers the following recommendations.

The kitchen ventilation requirements in the state building standards should be tightened to require better performance, framed as capture efficiency but allowing an equivalent airflow in recognition that the number of available products with CE test results may be limited for some time. This is already far along the implementation process for the 2022 standards.

In conjunction with an improved performance standard, there is a need to improve adherence to the standard. In both the field study conducted in apartments in this project and the recently completed field study of single-detached homes, a substantial fraction had equipment that did not meet the building standards either based on equipment specifications or measured performance. Better adherence to the requirements could be achieved through a combination of better education of builders, installers, raters, and code officials, and more effective enforcement.

It is additionally important to expand public understanding of the importance of using both kitchen ventilation and dwelling unit ventilation to control cooking-related air pollutant levels, especially in smaller homes. Potential avenues to achieve this include broad-based public information campaigns and targeted education and training of new home buyers. It may also be helpful to add a label to the installed equipment to inform occupants of the importance of kitchen ventilation use.

Public information and guidance should emphasize the following:

- Range hood use is particularly important when cooking in ways that result in substantial emissions of fine and ultrafine particles, especially frying and broiling.
- It is particularly important to use a range hood whenever there is a substantial use of gas cooking burners or cooking of a large meal on any burners.
- Almost all range hoods are much more effective when cooking occurs on back burners.

Widespread use of range hoods would be aided by reductions in their noise levels, especially at settings that can achieve high capture efficiency.

The following additional issues should be considered in relation to code requirements.

- Kitchen exhaust fans may be substantially less effective at controlling cooking-related pollutants compared to traditional range hoods or over-the-range microwave exhaust devices, especially for open kitchens in smaller dwelling units. In larger homes, mixing throughout the house increases exposures for those outside of the kitchen, but reduces the higher exposures experienced by people in the kitchen area.
- Automatic range hoods that are activated either by a signal from the cooking appliance or by environmental sensors could yield substantial health benefits by reducing reliance on individuals to effectively operate their range hoods. A production quality prototype of an automatic range hood has been demonstrated in a project supported by the US Department of Energy's Building America Program (within the Building Technologies Office).
- Any requirement for automatic range hoods should carefully consider user-acceptability issues especially sound levels, allowances for user inactivation of the automatic functionality and cautions to users about inactivation of automatic operation.

Research is needed to develop knowledge about the potential benefits of induction cooking appliances to reduce air pollutant emissions as well as other hazards including burns (especially of children) and cooking-related fires.

CHAPTER 8: Benefits to Ratepayers

There is a substantial body of research demonstrating that use of natural gas cooking burners without adequate ventilation can relatively commonly result in 1h averaged nitrogen dioxide (NO_2) concentrations inside kitchens that exceed health-based limits set for outdoor air quality. Additionally, particles produced and emitted during cooking can lead to fine particulate matter ($PM_{2.5}$) concentrations that exceed World Health Organization guidelines set for health protection. The presence and use of effective kitchen ventilation equipment enables Californians to safely cook in their homes, without having to experience hazardous air pollutant levels.

The aggregate public health burden of exposure to NO_2 from gas cooking burners and $PM_{2.5}$ and other air pollutants from cooking is substantial. Focusing first on combustion pollutants from burners, the work of Logue and Singer (Logue and Singer 2014) estimated annual health costs of $940,000 and 19.2 disability adjusted life years (DALYs) lost per year per 100,000 people if there is no range hood use. The research team assumes that the cost of a DALY is $100,000 and assume that 85 percent of the 13.6 million Californians live in homes with natural gas cooking. The research team also assumes that a range hood is used during roughly 35 percent of cooking events and the hood is 55 percent effective. This means that under the baseline situation, the health benefits of range hood use reducing acute exposures are estimated at about $63 million annually. If capture efficiency were increased to 95 percent, the total benefit would be $110 million annually, for a net benefit of $47 million annually. If range hood use is doubled with high capture hoods, the total avoided health costs and impacts would be $220 million or a difference of about $160 million. These estimates were developed from simulations of homes in Southern California. The estimate of 55 percent capture was based on measurements (B. C. Singer et al. 2012) and the range hood use estimates were approximated from surveys conducted by LBNL over the past decade (Mullen et al. 2016; W. R. Chan et al. 2019; Klug, Lobscheid, and Singer 2011).

Surveys indicate that many Californians feel that their kitchen ventilation equipment is too noisy or ineffective. Standards that address these performance issues will result in products that are more effective and provide comfort and health benefits to consumers.

The results of this project helped the CEC formulate and establish science-based performance requirements that are no more strict than essential for maintaining public safety, leading to significant but hard-to-estimate cost savings relative to the potential alternative of a more onerous and restrictive standard that could have occurred in the absence of this work.

There are also substantial benefits to equity and environmental justice as the populations most harmed by inadequate kitchen ventilation performance standards are those living in smaller homes, which are disproportionately lower-income Californians.

LIST OF ACRONYMS

Term	Definition
AAQS	Ambient Air Quality Standards
AEA	Association for Energy Affordability
AQMIS	Air Quality Management Information System
ASTM	ASTM International, an international standards organization formerly known as American Society for Testing and Materials
BEES	California's Building Energy Efficiency Standards, also referred to as "Title 24", updated every three years by the California Energy Commission
CASE	Codes and Standards Enhancement
CE	Capture Efficiency, fraction of contaminants emitted at cooktop directly pulled into range hood and exhausted to outdoors before mixing throughout the house.
CEC	California Energy Commission
cfm	Cubic feet per minute, a unit for measuring ventilation air flow.
CO	Carbon monoxide, an air pollutant that is produced by gas burners.
EPA	Environmental Protection Agency
h	Hour
HCHO	Formaldehyde, an air pollutant.
HENGH	Healthy and Efficient New Gas Homes field study
HVI	Home Ventilating Institute
IAQ	Indoor Air Quality
LBNL	Lawrence Berkeley National Laboratory, also known as LBNL
MV	Mechanical ventilation
NO_2	Nitrogen dioxide, an air pollutant that is produced by gas burners.
OTR	"Over the range" microwave/exhaust fans that are mounted above the cooktop.
$PM_{2.5}$	Fine particulate matter, an air pollutant produced by combustion (including by gas burners and cooking).
ppb	Parts per billion
µg	Microgram
WHO	World Health Organization

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