Studying the Optimal Ventilation for Environmental Indoor Air Quality

Prepared for The JPB Foundation and Enterprise Community Partners

National Center for
HEALTHY HOUSING

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Purpose

People currently spend nearly 90% of their time indoors,[1] making indoor air quality central to our health and well-being. Low-income populations are disproportionally affected by a range of illnesses and adverse health effects that can be exacerbated by poor indoor air quality. Therefore, improvements to the indoor environment can be an important mechanism for addressing health disparities among low-income populations.

The Enterprise Green Communities Criteria (the Criteria) is a national green building standard designed exclusively for affordable housing that incorporates a strong emphasis on health-related factors. Among other health-promoting components, the Criteria requires substantial housing rehabilitation projects to comply with the industry standard for mechanical ventilation (e.g., bathroom or kitchen exhaust ventilation). This standard — ASHRAE Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Residential Buildings* — can be challenging and costly to implement, especially when rehabilitating existing affordable housing properties.[2]

During the past decade, researchers have investigated the benefits of green building practices on human health; however, few studies have evaluated the effect of mechanical ventilation on indoor air quality in affordable housing. The results of such a study could provide evidence to prompt changes to construction and rehabilitation financing policies and promote broader adoption of ASHRAE Standard 62.2, ultimately leading to better health for residents. Therefore, Enterprise Community Partners joined with the National Center for Healthy Housing, The JPB Foundation, University of Illinois Chicago School of Public Health, and Icahn School of Medicine at Mount Sinai to conduct a multisite, longitudinal study to determine the effects of mechanical ventilation on indoor air quality and by extension, on the health of residents of affordable housing.

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[1] Klepeis N, Nelson W, Ott W, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Sci Environ Epidemiol*. 2001;11(3): 231-252. doi:10.1038/sj.jea.7500165

[2] Eilers L, De Scisciolo S. *Overcoming Challenges in Housing-Based Research: Insights from a Longitudinal Study*. Enterprise Community Partners, The JPB Foundation, National Center for Healthy Housing; November 2020. Accessed November 8, 2021. https://www.enterprisecommunity.org/resources/overcoming-challenges-housing-based-research

Study Overview

The Studying the Optimal Ventilation for Environmental Indoor Air Quality (STOVE) study examined whether mechanical ventilation was effective in reducing levels of five common indoor air pollutants: nitrogen dioxide (NO_2), particulate matter 2.5 micrometers or less in diameter ($PM_{2.5}$), carbon dioxide (CO_2), carbon monoxide (CO), and formaldehyde. The study was conducted in 152 affordable homes across Chicago and New York City, with data collection occurring between 2018 and 2020.

The study compared housing rehabilitated using green building practices that included compliance with ASHRAE Standard 62.2 (study group) with housing rehabilitated using green building practices but not intended to meet the requirements of ASHRAE Standard 62.2 (comparison group). The ASHRAE standard is used to determine the amount of outdoor air that should be supplied based on the square footage of the dwelling and the number of bedrooms. This determination is intended to help control for contaminants that can be released by building materials, as well as by occupants and their activities, such as cooking. The primary difference between the study and comparison groups was the type of ventilation in the home. All homes in the study group contained, by design, bathroom mechanical exhaust ventilation that operated either continuously or on a timed intermittent schedule; some study group homes also had continuous kitchen mechanical exhaust ventilation ducted to the exterior. The comparison group homes had ventilation insufficient to meet the ASHRAE requirement.

All study and comparison group homes had a working gas stove, a known source of indoor air contaminants. Air sampling measurements were collected in the primary living space of each dwelling. Structured health interviews with residents were conducted to assess health, and visual assessments were done to document housing condition.

Findings in Brief

Levels of four of the five indoor contaminants ($PM_{2.5}$, CO_2, CO, and formaldehyde) improved substantially with mechanical ventilation. The marked improvement in $PM_{2.5}$ is particularly noteworthy because of the significant public health implications of exposure to high levels of $PM_{2.5}$, especially in individuals who have asthma or other existing health issues. No effect of mechanical ventilation on NO_2 levels was observed.

Contaminant	Health Effect of Improved Contaminant Levels	Study Group Level	Comparison Group Level	Measured Difference*	Guidance Level
		Geometric Mean			
Nitrogen dioxide (ppb)	Improved respiratory and cardiovascular health	25.6	25.3	No significant change observed	21[a]
Particulate matter ($PM_{2.5}$) ($\mu g/m^3$)	Improved respiratory and cardiovascular health and decreased levels of mortality	13.3	17.7	20% improvement	12 (annual), 35 (daily)[b]
Carbon dioxide (ppm)	Improvement in cognition and reasoning	715	823	13% improvement	1,000[c]
Carbon monoxide (15-minute maximum) (ppm)	Reduced risk of cardiovascular impairment	2.3	2.8	25% improvement (with continuous kitchen exhaust)	87[d]
Formaldehyde (ppb)	Reduced risk of cancer	15.7	17.8	44% improvement (with continuous kitchen exhaust)	7–80[e]

Key: $\mu g/m^3$ = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter; ppb = parts per billion; ppm = parts per million

* difference after controlling for confounding variables

[a] *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. World Health Organization; 2010. Accessed November 8, 2021. https://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf

[b] The U.S. Environmental Protection Agency (EPA) has a 12 $\mu g/m^3$ annual outdoor limit and a 35 $\mu g/m^3$ daily outdoor limit for $PM_{2.5}$. EPA *National Ambient Air Quality Standards*. U.S. Environmental Protection Agency. Updated February 10, 2021. Accessed November 8, 2021. https://www.epa.gov/criteria-air-pollutants/naaqs-table

[c] Residential Indoor Air Quality Guidelines: Carbon Dioxide. Health Canada; March 2021. Accessed November 8, 2021. https://www.canada.ca/en/health-canada/services/publications/healthy-living/residential-indoor-air-quality-guidelines-carbon-dioxide.html

[d] California Office of Environmental Health Hazard Assessment (7 ppb) and WHO (80 ppb). OEHHA Acute, 8-Hour and Chronic Reference Exposure Level (REL) Summary. California Office of Environmental Health Hazard Assessment; November 4, 2019. Accessed November 8, 2021. https://oehha.ca.gov/air/general-info/oehha-acute-8-hour-and-chronic-reference-exposure-level-rel-summary. WHO Guidelines for Indoor Air Pollutants (Op. cit.).

[e] *Ibid.*

The use of continuous ventilation was critical to generating the reductions in contaminant levels seen overall. Air exchange rates were higher in the dwellings with continuous ventilation than in those without continuous ventilation because exhaust ventilation extracts air from the home and replaces it with outdoor air, which generally contains lower pollutant levels, entering through gaps in the building envelope.

The location of the mechanical ventilation also proved to be important. Bathroom exhaust ventilation appeared to be the cause of the reduction in $PM_{2.5}$ levels, both in homes with high levels of nicotine and in homes with low levels, likely because bathroom exhaust can ventilate the entire home. CO and formaldehyde levels were lower in dwellings with kitchen exhaust ventilation ducted to the exterior than in dwellings without kitchen exhaust, possibly because gas stoves, certain cooking methods, chemical reactions with cooking oil byproducts, and building products localized to the kitchen all can be sources of CO or formaldehyde. No difference in CO_2 was associated with the location of the mechanical ventilation, although an overall improvement in CO_2 levels was observed in the study group homes. The self-reported health differences between the study group and comparison group were inconclusive. However, the improvement in air contaminants can be expected to yield significant health improvements.

Recommendations

The study's findings provide support for the use of green building standards — in particular compliance with ASHRAE Standard 62.2 — during rehabilitation of affordable housing to improve indoor air quality and the health of residents. Specifically, this report provides the following recommendations:

Systems Interventions

- Incorporate ASHRAE Standard 62.2 for both moderate and substantial rehabilitation in all green building standards, certification programs, local building codes, and subsidy and tax credit requirements.
- Ensure housing rehabilitation financing programs include the cost of installing mechanical ventilation as a portion of housing improvement budgets.
- Simplify ASHRAE Standard 62.2 so that affordable housing owners, developers, and engineers are able to understand and achieve compliance.
- Establish enforceable residential standards for indoor air contaminants.

Building Interventions

- Eliminate or reduce indoor contaminant sources and replace gas stoves with electric.
- Adopt smoke-free housing policies.
- Install mechanical ventilation systems and improve maintenance of existing ones.

Education

- Educate occupants about the importance of ventilation and how to operate existing ventilation systems.
- Provide technical assistance to building owners, property managers, developers, and financing institutions to expand adoption of ASHRAE Standard 62.2.
- Invest in public education about the benefits of healthy indoor air quality.

Further research efforts are needed in three areas: indoor air chemical reactions and how such reactions can influence health, air quality sensor technologies and the capability to link them to automated ventilation systems, and how housing studies can better engage the public and potential participants in their design and implementation.

Conclusion

The STOVE study demonstrated that mechanical ventilation that complies with ASHRAE Standard 62.2 can reduce levels of common indoor air contaminants found in homes. This finding provides support for the use of green building standards during rehabilitation of affordable housing to improve indoor air quality and the health of residents. The results of the STOVE study have strengthened the evidence base in support of mechanical ventilation's benefits. Ultimately, financing policy changes that address the complexity and cost of improving ventilation are needed to achieve broader adoption of green building practices that include mechanical ventilation, ultimately leading to population health improvements.

The Study Team

Enterprise Community Partners provided overall project management and oversight to the STOVE study. The National Center for Healthy Housing served as the Coordinating Center for the study. Two institutions (Icahn School of Medicine at Mount Sinai in New York City, NY, and the University of Illinois Chicago School of Public Health in Chicago, IL) served as local investigators and directed the technical aspects of the study in their respective locations.

1 Introduction

1.1 Summary of Objectives

The Studying the Optimal Ventilation for Environmental Indoor Air Quality (STOVE) study was conducted to help determine whether mechanical ventilation in multifamily affordable housing results in improved indoor air quality and health outcomes for residents. Mechanical ventilation, which refers to ventilation achieved through mechanical means (e.g., kitchen or bathroom exhaust ventilation), is a component of green building practices, standards, or criteria, but often developers of affordable housing properties consider it too expensive or too difficult to incorporate when rehabilitating an existing property. Strengthening the evidence base about the effects of mechanical ventilation on indoor air pollutants was a primary motivation for the study. Demonstrating the health benefits of mechanical ventilation could warrant changes to affordable housing financing policies and building practices that would lead to its more widespread adoption and potentially improve resident health.

The STOVE study examined the effectiveness of mechanical ventilation in reducing the levels of common indoor air pollutants: nitrogen dioxide (NO_2), particulate matter 2.5 micrometers or less in diameter ($PM_{2.5}$), carbon dioxide (CO_2), carbon monoxide (CO), and formaldehyde. Specifically, the STOVE study was designed to evaluate whether indoor levels of these contaminants were significantly lower in housing that was rehabilitated using green building practices that included compliance with ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Residential Buildings* (published in 2010 or later), than in housing that was rehabilitated using green building practices but was not intended to meet the requirements of the ASHRAE standard. ASHRAE Standard 62.2 is the industry standard for ventilation and indoor air quality in residential buildings and defines the amount of outdoor air to be delivered to the home and how the air is to be distributed.

The STOVE study was preceded by the *Healthy Homes, Happy Kids* study, which was an attempt to study children with poorly controlled asthma living in affordable green housing, using self-reported and clinical health measures, visual assessment, environmental sampling, and ventilation measurements. Due to low enrollment, the *Healthy Homes, Happy Kids* study underwent a substantial redesign that resulted in the STOVE study. Two reports document the efforts made and lessons learned by the *Healthy Homes, Happy Kids* study team.[3,4]

The ultimate goal of both study designs was to evaluate the impact of green building practices on the respiratory health of residents of affordable housing. When the original research goals proved difficult to achieve, the research team, with the assistance of the study's National Advisory Council, redesigned the study with the same objective in mind. While the original design required measurements before and after green rehabilitation, the STOVE study looked only at properties that already had been rehabilitated using green building practices within the previous 5–8 years. Measuring the effect of ventilation on indoor air contaminants served as a proxy for measuring improvements in human health. Based on the literature, it was reasonable to expect that lower levels of indoor air contaminants would lead to better health outcomes and that efforts to reduce indoor contaminant levels — such as mechanical ventilation — could be considered health promoting. To ensure that differences observed between housing units that complied with ASHRAE Standard 62.2 and those that did not were statistically significant, a known source of indoor contaminants was needed. The literature also identifies gas stoves as a common indoor source of NO_2, $PM_{2.5}$, CO_2, CO, and formaldehyde. Thus, the STOVE study included only housing units with working gas stoves.

1.2 Importance of Green Building Standards on Human Health

Green building practices can lead to healthy, efficient, and environmentally responsible homes. According to the U.S. Environmental Protection Agency (EPA), "green building is the use of approaches that create buildings and development that are environmentally responsible and resource-efficient throughout a building's life cycle."[5] In some ways, energy-efficiency improvements have been

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[3] *Measuring the Impact of Affordable Housing Interventions: Strategies for Study Design and Implementation*. Enterprise Community Partners; April 2017. Accessed November 8, 2021. https://www.enterprisecommunity.org/sites/default/files/2021-09/FINAL%20Healthy%20Home%2C%20Happy%20Kids_Strategies%20for%20Study%20Design%20%26%20Implementation_2017.pdf

[4] Eilers L, De Scisciolo S. *Overcoming Challenges in Housing-Based Research: Insights from a Longitudinal Study*. Enterprise Community Partners, The JPB Foundation, National Center for Healthy Housing; November 2020. Accessed November 8, 2021. https://www.enterprisecommunity.org/resources/overcoming-challenges-housing-based-research

[5] *Location and Green Building*. U.S. Environmental Protection Agency. Updated July 8, 2021. Accessed November 8, 2021. https://www.epa.gov/smartgrowth/location-and-green-building

the main force behind the growing adoption of green building criteria. On average, more than half of a household's annual energy consumption is for space heating and air conditioning.[6] Green building standards have evolved during the last several decades to encompass not only features that promote energy efficiency, but also those that improve health.

1.2.1 Health Effects of the Indoor Environment

With people spending nearly 90% of their time indoors,[7] focused attention is needed on the quality of the indoor environment and its direct effect on health. The importance of living in a home that supports health has been underscored by the COVID-19 pandemic because many people were encouraged or required to spend more time in their homes. As a result, the need for improved ventilation has become even more important for respiratory health in light of COVID-19. People of color or those with low incomes suffer disproportionately from poor health due to poorly constructed or substandard housing.[8,9] Many studies have documented illness and injuries associated with inadequate housing, including asthma, respiratory illnesses, cardiovascular health problems, neurological deficits, increased stress, and other physical and mental health problems.[10–12] More than 25 million people in the United States suffer from asthma, with more than 1.6 million having visited an emergency department for their asthma in 2018 and more than 3,500 having died from asthma in 2019.[13] Moreover, asthma is the most common chronic respiratory condition among children in the United States, with children of color and those living in low-income households suffering a greater burden of the disease.[14] Therefore, the quality of these residents' housing brings additional urgency.

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[6] *Use of Energy Explained: Energy Use in Homes*. U.S. Energy Information Administration. Updated June 23, 2021. Accessed November 8, 2021. https://www.eia.gov/energyexplained/use-of-energy/homes.php

[7] Klepeis N, Nelson W, Ott W, et al. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Sci Environ Epidemiol*. 2001;11(3): 231-252. doi:10.1038/sj.jea.7500165

[8] Jacobs DE. Environmental health disparities in housing. *Am J Public Health*. 2011;101(Suppl S1):S115-S122. doi:10.2105/AJPH.2010.300058

[9] *WHO Housing and Health Guidelines*. World Health Organization; November 13, 2018. Accessed November 8, 2021. https://www.who.int/publications/i/item/WHO-CED-PHE-18.10

[10] World Health Organization Regional Office for Europe. *Report on the WHO technical meeting on quantifying disease from inadequate housing: Bonn, Germany, November 28-30, 2005*. Copenhagen: WHO Regional Office for Europe; 2006. Accessed November 8, 2021.

[11] Office of the Surgeon General (US). *The Surgeon General's Call to Action to Promote Healthy Homes*. U.S. Department of Health and Human Services; 2009. Accessed November 8, 2021. https://www.ncbi.nlm.nih.gov/books/NBK44192/

[12] Jacobs DE and Reddy AL. The housing environment. In: Knechtges PL, Kearney GD, Resnick BA, eds. *Environmental Public Health: The Practitioner's Guide*. APHA Press; 2018. Accessed November 8, 2021. https://ajph.aphapublications.org/doi/book/10.2105/9780875532943

[13] *Most Recent National Asthma Data*. U.S. Centers for Disease Control and Prevention. Updated March 25, 2019. Accessed November 8, 2021. https://www.cdc.gov/asthma/most_recent_data.htm

[14] Akinbami LJ, Moorman JE, Bailey C, et al. Trends in asthma prevalence, health care use, and mortality in the United States, 2001-2010. *NCHS Data Brief*. 2012;(94):1-8. https://pubmed.ncbi.nlm.nih.gov/22617340/

Such health problems also place a significant burden on the health care system. Health care costs related to asthma total more than $50 billion each year,[15] and if lost school days and lost workdays are added, asthma-related costs total $63 billion annually.[16] According to data from 2019, African American women were 20% more likely to have asthma than non-Hispanic whites.[17] In 2018, African Americans were almost three times more likely to die from asthma-related causes than non-Hispanic whites.[18] In 2017, African American children were five times more likely to be admitted to the hospital for asthma than non-Hispanic white children, and in 2019, they had a death rate from asthma that was eight times that of non-Hispanic white children.[18]

> In 2017, African American children were five times more likely to be admitted to the hospital for asthma than non-Hispanic white children, and in 2019, they had a death rate from asthma that was eight times that of non-Hispanic white children.

One root cause of these disparities is the lack of quality affordable housing. Housing costs remain the single largest expense in a person's life. More than 95 million Americans spend more than 30% of their income on housing, leaving little for transportation, healthy foods, and medical bills. Poor health also contributes to reduced income, creating a negative feedback loop sometimes referred to as the health–poverty trap.[19] The lack of quality affordable housing means many families find themselves living in substandard, unhealthy housing with little ability to improve these conditions. Treating a child's asthma or other health issue in the hospital only to have that child return to the home that contributed to the illness does little to improve the child's long-term health and can deplete scarce resources.

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[15] President's Task Force on Environmental Health Risks and Safety Risks to Children. *Coordinated Federal Action Plan to Reduce Racial and Ethnic Asthma Disparities*. U.S. Environmental Protection Agency; 2012. Accessed November 8, 2021. https://www.epa.gov/sites/default/files/2014-08/documents/federal_asthma_disparities_action_plan.pdf

[16] Jang J, Chan KCG, Huang H, Sullivan SD. Trends in cost and outcomes among adult and pediatric patients with asthma: 2000–2009. *Ann Allergy Asthma Immunol*. 2013;111(6):516–522. doi:10.1016/j.anai.2013.09.007

[17] Table 4-1. *Current Asthma Prevalence Percents by Age, United States: National Health Interview Survey, 2019*. Accessed November 8, 2021. https://www.cdc.gov/asthma/nhis/2019/table4-1.htm.

[18] Office of Minority Health. *Asthma and African Americans*. U.S. Department of Health and Human Services. Updated February 11, 2021. Accessed November 8, 2021. https://minorityhealth.hhs.gov/omh/browse.aspx?lvl=4&lvlid=15

[19] Khullar D and Chokshi DA. Health, income, and poverty: where we are and what could help. *Health Affairs* Health Policy Brief. October 4, 2018. doi:10.1377/hpb20180817.901935

Addressing the underlying social and environmental causes of disease, including housing quality, increasingly is recognized as a fundamental means of improving health outcomes and reducing disparities. Although health-related housing improvements (known as "interventions" in the health community) have been reviewed systematically to assess their effectiveness for biological, chemical, or injury prevention outcomes, these interventions typically are not included as separate elements in the context of housing rehabilitation.[20–24] Examples of health-based housing interventions include lead paint abatement, radon mitigation, mold mitigation, and injury control. A holistic approach to improving the quality of affordable housing — such as that promoted by green building standards — has the potential to reduce health disparities and improve the health and well-being of families across the United States. Green building standards, including model codes, rating systems, and certification programs, offer promise in rehabilitating housing to support health through sustainable design to enhance comfort, improve indoor air quality, reduce health care costs, and decrease exposure to potentially toxic chemicals.

1.2.2 Enterprise Green Communities Criteria

Making housing both affordable and healthy acknowledges the deep connection between housing and health. To operationalize this connection, Enterprise Community Partners (Enterprise) launched the Green Communities Initiative in 2004 with the goal of transforming the way affordable housing is designed, located, built, and rehabilitated across the country. In 2005, Enterprise released the first national standard for green and healthy affordable homes, the Enterprise Green Communities Criteria (the Criteria).

The Criteria, and Enterprise's associated certification program, remain the only national green building standards designed exclusively for affordable housing. The Criteria has been used to create or rehabilitate into green and healthy affordable

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[20] Jacobs DE, Brown MJ, Baeder A, et al. A systematic review of housing interventions and health: introduction, methods, and summary findings. *J Public Health Manag Pract*. 2010;16(5 Suppl):S5-S10. doi:10.1097/PHH.0b013e3181e31d09

[21] Krieger J, Jacobs DE, Ashley PJ, et al. Housing interventions and control of asthma-related indoor biologic agents: a review of the evidence. *J Public Health Manag Pract*. 2010;16(5 Suppl):S11-S20. doi:10.1097/PHH.0b013e3181ddcbd9

[22] Sandel M, Baeder A, Bradman A, et al. Housing interventions and control of health-related chemical agents: a review of the evidence. *J Public Health Manag Pract*. 2010;16(5 Suppl):S24-S33. doi:10.1097/PHH.0b013e3181e3cc2a

[23] DiGuiseppi C, Jacobs DE, Phelan KJ, Mickalide AD, Ormandy D. Housing interventions and control of injury-related structural deficiencies: a review of the evidence. *J Public Health Manag Pract*. 2010;16(5 Suppl):S34-S43. doi:10.1097/PHH.0b013e3181e28b10

[24] Jacobs DE. *Healthy homes intervention update*. Prepared for U.S. Department of Housing and Urban Development. October 20, 2015;(unpublished).

homes more than 127,000 dwellings in virtually every state.[25] Currently, 27 states and Washington, D.C., require or incentivize the Criteria as part of their affordable housing finance efforts, often through the state's Qualified Allocation Plan for the distribution of Low-Income Housing Tax Credits. No other green building program has seen such progress. To date, Enterprise has leveraged $3.9 billion in the development and preservation of green and affordable homes.

The Criteria, which was updated in 2020, consists of technical requirements in eight key areas:

1. Integrative Design
2. Location and Neighborhood Fabric
3. Site Improvement
4. Water
5. Operating Energy
6. Materials
7. Healthy Living Environment
8. Operations, Maintenance, and Resident Engagement

The Criteria is the only green standard that requires compliance with health-related criteria; health-related housing improvements included in other green building standards are optional. The following health-related requirements are included in the Criteria:

- Radon and lead paint testing and mitigation (if needed)
- Venting of furnaces and installation of smoke and CO alarms
- Isolation of garages to avoid infiltration of exhaust
- Integrated pest management
- Establishment of a smoke-free building requirement
- Bathroom and kitchen mechanical exhaust ventilation and, for new construction and substantial rehab[26] projects, compliance with the standard for indoor air

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[25] *2020 Enterprise Green Communities Criteria*. Enterprise Community Partners. Accessed November 8, 2021. https://www.greencommunitiesonline.org/introduction

[26] According to the 2020 Enterprise Green Communities Criteria, "A Substantial Rehab is defined as a project where the work area exceeds 50% of the aggregate area of the building … . Aggregate area of the building includes anything within the surrounding exterior walls, including covered exterior spaces, e.g., balconies that have a roof or floor above (does

quality established by ASHRAE Standard 62.2, *Ventilation and Acceptable Indoor Air Quality in Residential Buildings*[27]

- Dehumidification in humid climates (if needed)
- Dust and noise reduction during construction
- A health action plan

Additionally, the Criteria is aligned with the Surgeon General's definition of a healthy home: "A healthy home is sited, designed, built, renovated, and maintained in ways that support the health of residents."[28] The Criteria also is aligned with the 10 key principles to healthy housing identified by the National Center for Healthy Housing (NCHH).[29] These principles define healthy homes as being —

- Properly ventilated
- Dry
- Clean
- Free of pests
- Free of injury hazards
- Without chemical contaminants
- Maintained
- Thermally controlled
- Accessible
- Affordable

An NCHH comparison of the available green standards against the key principles of healthy housing found that "the Enterprise Community Partners' Green Communities Program ranked the highest."[30] Another review of green housing

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not include roof, outdoor space, etc.). Work area is defined as the area on the plans that will be considered reconfigured, addition or removal of a window or door, or reconfiguration or extension of any system, or installation of a new system. A Moderate Rehab is defined as a project where the work area does not exceed 50% of the aggregate area of the building (the work scope is less than an ICC level 3 alteration), yet is still able to comply with the energy performance requirements of Criterion 5.1b)."

[27] The Criteria does not require ASHRAE compliance for moderate rehabs.

[28] Office of the Surgeon General (US). *The Surgeon General's Call to Action to Promote Healthy Homes*. U.S. Department of Health and Human Services; 2009. Accessed November 8, 2021. https://www.ncbi.nlm.nih.gov/books/NBK44192

[29] *The Principles of a Healthy Home*. National Center for Healthy Housing. Accessed November 8, 2021. https://nchh.org/information-and-evidence/learn-about-healthy-housing/healthy-homes-principles

[30] Morley RL, Tohn E. *How Healthy Are National Green Building Programs?* National Center for Healthy Housing; September 2008. Accessed November 4, 2021. https://nchh.org/resource-library/report_how-healthy-are-national-green-building-programs_.pdf

standards, by the National Academies of Sciences, Engineering and Medicine, found that the Enterprise standard had the best evidence base of health outcomes and recommended its use in the context of disaster recovery. Specifically, the Institute recommended the following:

> "To reduce housing-related health risks, federal, state, and local governmental housing agencies should require that new residential construction and substantial rehabilitation of existing residences financed with public funds after disasters comply fully with Enterprise Green Communities standards or their equivalent and with the minimum requirements set forth in the National Healthy Housing Standard. Federal and state funding agencies should tie these requirements to recovery funds, and private funders should consider incentivizing compliance with these standards."[31]

Most of the properties included in the STOVE study were certified by the Criteria. Those that were not certified by the Criteria employed green building practices comparable to those included in the Criteria.

1.2.3 Evidence of the Health Effects of Green Building Standards

Several studies have examined whether using green building standards improves health and indoor air quality. These studies are reviewed in detail in **Appendix A, Literature Review of Green Healthy Housing Studies**. The following health outcomes were found to be associated with green building practices:

- Improvements in mental and physical health[32]
- Improved NO_2 and $PM_{2.5}$ levels, as well as 47% fewer symptoms related to low building ventilation rates, known as "sick building syndrome"[33]
- Improved general health in adults, as well as improved respiratory health of those with asthma and those without[34]

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[31] Committee on Post-Disaster Recovery of a Community's Public Health, Medical, and Social Services; Board on Health Sciences Policy; Institute of Medicine. *Healthy, Resilient, and Sustainable Communities After Disasters: Strategies, Opportunities, and Planning for Recovery*. Washington (DC): National Academies Press (US); September 10, 2015. doi:10.17226/18996

[32] Breysse J, Dixon SL, Jacobs DE, Lopez J, Weber W. Self-reported health outcomes associated with green-renovated public housing among primarily elderly residents. *J Public Health Manag Pract*. 2015;21(4):355-367. doi:10.1097/PHH.0000000000000199

[33] Colton MD, MacNaughton P, Vallarino J, et al. Indoor air quality in green vs. conventional multifamily low-income housing. *Environ Sci Technol*. 2014;48(14):7833-7841. doi:10.1021/es501489u

[34] Breysse J, Jacobs DE, Weber W, et al. Health outcomes and green renovation of affordable housing. *Public Health Rep*. 2011;126(Suppl 1):64-75. doi:10.1177/00333549111260S110

- Improvements in allergen levels and adult general health[35]
- Improved mental health, asthma, hay fever, sinusitis, and fewer lost school days due to asthma[36]
- Increased asthma symptom–free days, fewer emergency room visits, fewer asthma triggers, and increased caretaker quality of life[37]
- Improvements in continuous daily respiratory symptoms, asthma symptoms disrupting sleep in the past month, urgent visits to a health care professional for asthma in the past 3 months, days with asthma symptoms, asthma episodes, and days of work, school, and day care missed[38]

Few such studies, however, have focused specifically on ventilation. Ventilation often has been regarded as the most technically difficult and expensive of the healthy homes interventions to implement, especially in rehabilitation of housing.[39] The studies that did focus on ventilation examined health and various measures of environmental quality usually before and after green housing rehabilitation and typically without a comparison group. The studies also did not specifically address the effect of ventilation on the indoor air quality of homes with gas stoves.

1.2.4 Study Goals and Hypotheses

The STOVE study set out to gather new information on the implementation of ASHRAE Standard 62.2 in affordable housing (i.e., ASHRAE compliance) and on the extent to which mechanical ventilation, a key component of ASHRAE, can support good health and indoor air quality. Currently, a gap in knowledge exists about the impact of ASHRAE compliance on indoor air quality and resident health. A major goal of the STOVE study was to help close this knowledge gap and to better understand how improvements to ventilation can result in indoor environmental or resident health benefits.

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[35] Jacobs DE, Breysse J, Dixon SL, et al. Health and housing outcomes from green renovation of low-income housing in Washington, D.C. *J Environ Health*. 2014;76(7):8-60.

[36] Jacobs DE, Ahonen E, Dixon SL, et al. Moving into green healthy housing. *J Public Health Manag Pract*. 2015;21(4):345-354. doi:10.1097/PHH.0000000000000047

[37] Takaro TK, Krieger J, Song L, Sharify D, Beaudet N. The Breathe-Easy Home: the impact of asthma-friendly home construction on clinical outcomes and trigger exposure. *Am J Public Health*. 2011;101(1):55-62. doi:10.2105/AJPH.2010.300008

[38] Garland E, Steenburgh ET, Sanchez SH, et al. Impact of LEED-certified affordable housing on asthma in the South Bronx. *Prog Community Health Partnersh*. 2013; 7(1):29-37. doi:10.1353/cpr.2013.0010

[39] Eilers L, De Scisciolo S. *Overcoming Challenges in Housing-Based Research: Insights from a Longitudinal Study*. Enterprise Community Partners, The JPB Foundation, National Center for Healthy Housing; November 2020. Accessed November 8, 2021. https://www.enterprisecommunity.org/resources/overcoming-challenges-housing-based-research

ASHRAE Standard 62.2 is often the most difficult of the green criteria to meet, especially in moderate rehab. Many developers of affordable housing are not able to comply with the standard when rehabbing an existing property because of logistical and financial constraints. By examining the potential indoor air quality benefits of mechanical ventilation, the research team hypothesized that the findings would support the case for routinely including mechanical ventilation in the rehabilitation of affordable housing and help open up new financing pathways to overcome financial barriers experienced by developers.

The STOVE study attempted to answer the question of whether better ventilation in multifamily dwellings that have undergone green rehabilitation results in improved indoor air quality and better health outcomes. Specifically, the study asked whether compliance with the ventilation requirements in ASHRAE Standard 62.2 (published in 2010 or later) was associated with variations in indoor air quality and general health measures. The study's hypotheses were as follows:

Primary Hypothesis

- Multifamily housing that has undergone green rehabilitation with ASHRAE-compliant ventilation (study group) will have significantly lower indoor levels of NO_2, compared with multifamily housing that has undergone green rehab without modifications to achieve ASHRAE-compliant ventilation (comparison group) during an 8-month period.

Secondary Hypotheses

- Study group homes will have significantly lower indoor levels of $PM_{2.5}$, CO_2, CO, and formaldehyde, compared with comparison group homes.
- Residents living in the study group homes will have better physical, mental, general, and respiratory health, compared with residents living in the comparison group homes.

To address a gap in the research, the STOVE study focused on populations living in affordable housing that had been rehabilitated using green building practices. All residents had low incomes, and the vast majority were families of color. Children and elderly residents also were included because these populations are known to be at higher risk of respiratory problems. The study used an array of data collection methods to provide insight into the associations between multifamily building design, ventilation, indoor air quality, and health status. The project used validated or well-known tools and methods to elucidate these still poorly understood associations. Enrollment criteria and data collection methods are described in more detail in the **Methods** section.

1.3 Contaminants Studied

The STOVE study examined ventilation, air contaminants, and associated self-reported health indicators in multifamily affordable housing developments. Five contaminants were chosen for the study because of their potential to adversely affect human health. These five contaminants were NO_2, $PM_{2.5}$, CO_2, CO, and formaldehyde. Homes included in the STOVE study were required to have gas stoves, a known source of these contaminants indoors. The following subsections discuss the health hazards of each contaminant and existing guidance or standards for limiting exposure. Nicotine levels also were measured to assess the influence of resident smoking, and temperature and relative humidity were measured as potentially confounding variables.

1.3.1 Nitrogen Dioxide (NO_2) and Particulate Matter 2.5 Micrometers or Less in Diameter ($PM_{2.5}$)

Both NO_2 and $PM_{2.5}$ are known to affect respiratory health adversely. Exposure to these contaminants pose a higher risk to low-income populations because of these populations' overall poorer general health and higher asthma rates. Authoritative reviews of NO_2 and $PM_{2.5}$ toxicity are available elsewhere and summarized later in this section.[40,41]

NO_2 is a gaseous air pollutant composed of nitrogen and oxygen and forms when fossil fuels are burned outdoors or indoors. Indoor combustion sources can include stoves, ovens, hot-water heaters, furnaces, clothes driers, unvented heaters, candles, smoking, and certain hobbies. Increased NO_2 also may disproportionately affect people living or spending time in homes near or on high-traffic roads.[42]

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[40] *Integrated Science Assessment (ISA) for Oxides of Nitrogen—Health Criteria*. U.S. Environmental Protection Agency. EPA/600/R-15/068; January 2016. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879

[41] *Integrated Science Assessment (ISA) for Particulate Matter*. U.S. Environmental Protection Agency. EPA/600/R-19/188; December 2019. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534

[42] Health Effects Institute. *Traffic-related air pollution: a critical review of the literature on emissions, exposure, and health effects*; 2010. https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health

NO_2 concentration typically is expressed in parts per billion (ppb). NO_2 is one of six widespread air pollutants for which outdoor air limits are set according to the EPA's National Ambient Air Quality Standards (NAAQS), which are enforceable.[43] EPA has established a NAAQS for NO_2 of 100 ppb (1-hour average) and 53 ppb (annual average).[44] Although no legal limit exists for residential indoor air, the World Health Organization (WHO) has established a guidance level of 100 ppb (1-hour average) and 21 ppb (annual average) for indoor air. Evidence has shown NO_2 concentrations for a range of time periods to be in the range of 13–32 ppb outdoors and 7–33 ppb indoors. In European homes, maximum levels associated with the use of gas appliances (gas cooking and heating) are in the range of 96–1,330 ppb.[45]

Because NO_2 has both indoor and outdoor sources, the STOVE study included data on both indoor and outdoor air. The outdoor air data were provided by EPA.

$PM_{2.5}$ is an airborne dust composed of very small inhalable particles that penetrate deep into the lungs. In general, each $PM_{2.5}$ particle has a diameter of 2.5 micrometers or less, which is about 30 times smaller than a human hair.[46] In outdoor air, most particles are formed from complex reactions of such chemicals as sulfur dioxide and nitrogen oxides, which are pollutants emitted from power plants, factories, automobiles, and other sources. In indoor air, particles can be emitted from cooking, combustion activities (e.g., burning of candles, use of fireplaces, use of unvented space heaters or kerosene heaters), cigarette smoking, and other activities.[47] Gas stoves are thought to be one of the main indoor air sources of $PM_{2.5}$.

Concentrations of $PM_{2.5}$ are expressed as micrograms of dust per cubic meter of air (µg/m^3). The NAAQS for $PM_{2.5}$ is 35 µg/m^3 (24-hour average) and 12 µg/m^3 (annual average). WHO has established lower limits for outdoor air: 15 µg/m^3 (24-hour average) and 5 µg/m^3 (annual average). For residential indoor air, however, no legal

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[43] *Nitrogen Dioxide: What Is Nitrogen Dioxide?* American Lung Association. Updated February 12, 2020. Accessed November 8, 2021. https://www.lung.org/clean-air/outdoors/what-makes-air-unhealthy/nitrogen-dioxide

[44] *EPA National Ambient Air Quality Standards*. U.S. Environmental Protection Agency. Updated February 10, 2021. Accessed November 8, 2021. https://www.epa.gov/criteria-air-pollutants/naaqs-table

[45] Jarvis DJ, Adamkiewicz G, Heroux ME, et al. Nitrogen dioxide. *WHO Guidelines for Indoor Air Quality: Selected Pollutants*. Geneva: World Health Organization. 2010;5. Accessed November 8, 2021. https://www.ncbi.nlm.nih.gov/books/NBK138707

[46] *Particulate Matter (PM) Pollution: Particulate Matter (PM) Basics*. U.S. Environmental Protection Agency. Updated May 26, 2021. Accessed November 8, 2021. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics

[47] *Indoor Particulate Matter: Levels of PM Indoors*. U.S. Environmental Protection Agency. Updated October 13, 2020. Accessed November 8, 2021. https://www.epa.gov/indoor-air-quality-iaq/indoor-particulate-matter#Levels_in_Homes

limit exists, and WHO offers no recommendation. One study of U.S. residences[48] reported an average indoor air concentration of $PM_{2.5}$ to be 15.9 µg/m^3.

Asthma and Other Respiratory Impacts of NO_2 and $PM_{2.5}$

Extensive scientific literature has shown that both NO_2 and $PM_{2.5}$ are causally linked to many adverse health conditions. Establishing causality is a difficult scientific endeavor and is determined only after exhaustive evidence has been analyzed. Causality (or a judgment that an association is likely to be cause-and-effect) is determined based on the following factors:

- Consistency across studies
- Coherence of multiple lines of evidence
- Biological plausibility
- The exposure–response relationship (a higher exposure is associated with a worse health outcome)
- Strength of the relationship (such that it is highly unlikely to be due to chance alone)
- Experimental evidence
- Timing (the cause comes before the effect)
- Specificity of the observed adverse health outcome
- Analogy (whether similar chemical substances produce similar adverse health effects)

Research conducted by EPA has found a causal relationship between short-term NO_2 exposures (similar to those levels measured in the STOVE study) and many respiratory problems, including asthma exacerbation. NO_2 has been shown to cause allergic inflammation in controlled human exposures studies, and short-term NO_2 exposure is known to trigger an asthma attack independently. NO_2 is an oxidant (a reactive chemical) that produces enzymes in the fluid lining the lungs, which is what causes the allergic inflammation and airway responsiveness typical of asthma attacks. Epidemiologic results consistently link short-term increases in ambient NO_2 concentration with increases in hospital admissions and emergency department

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[48] Logue JM, Price PN, Sherman MH, Singer BC. A method to estimate the chronic health impact of air pollutants in U.S. residences. *Environ Health Perspect*. 2012;120(2):216-222. doi:10.1289/ehp.1104035

visits for asthma, increases in respiratory symptoms and airway inflammation in people with asthma, and decreases in lung function in children with asthma.

These health associations exist not only with outdoor average ambient NO_2 concentrations, but also with NO_2 concentrations inside homes. One of the strengths of the STOVE study is its inclusion of both outdoor and indoor NO_2 measurements; many previous studies have relied on outdoor data to estimate interior home exposures. Studies that measured pollutant levels indoors have shown that NO_2 is associated with asthma-related effects, even after accounting for $PM_{2.5}$. Associations between NO_2 and asthma development are independent of socioeconomic status and exposure to smoking. For more information on the means by which NO_2 causes asthma attacks and is related to asthma development, see EPA's 2016 *Integrated Science Assessment for Oxides of Nitrogen — Health Criteria.*[49]

EPA also determined that recent epidemiologic studies demonstrate strong evidence for a causal relationship between short-term $PM_{2.5}$ exposure — such as that measured in the STOVE study — and asthma exacerbation, chronic obstructive pulmonary disease (COPD) exacerbation, and combined respiratory-related diseases. The consistent, positive associations observed for asthma and COPD emergency department visits and hospital admissions have been shown in multiple studies that controlled for the potential confounding effects of weather (e.g., temperature) in different ways. The relationship also has been supported by evidence of increased symptoms and medication use.[50] For further information about the health effects of $PM_{2.5}$, see EPA's 2019 *Integrated Science Assessment for Particulate Matter*.[51]

Other Adverse Health Impacts of NO_2 and $PM_{2.5}$

Both NO_2 and $PM_{2.5}$ can cause non-respiratory adverse health outcomes, as well. NO_2 exposure is associated with cardiovascular effects (e.g., heart attacks, heart disease), diabetes, adverse birth outcomes, reduced fetal growth, cancer, and death. $PM_{2.5}$ exposure has been causally linked to cardiovascular-related emergency department visits and hospital admissions, ischemic heart disease and heart failure, and cardiovascular-related mortality. The cardiovascular

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[49] *Integrated Science Assessment (ISA) for Oxides of Nitrogen — Health Criteria*. U.S. Environmental Protection Agency. EPA/600/R-15/068; January 2016. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879

[50] *Integrated Science Assessment (ISA) for Particulate Matter*. U.S. Environmental Protection Agency. EPA/600/R-19/188; December 2019. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534

[51] *Integrated Science Assessment (ISA) for Particulate Matter*. U.S. Environmental Protection Agency. EPA/600/R-19/188; December 2019. Accessed November 8, 2021.

effects, as well as nervous system effects, are supported by animal studies. Preliminary evidence also exists of an association with autism. Research by EPA also determined that a causal association is likely between $PM_{2.5}$ exposure and lung cancer, even in people who have never smoked. EPA concluded that a causal relationship exists between long-term $PM_{2.5}$ exposure and non-accidental deaths, including studies showing that increases in life expectancy are due to decreases in long-term $PM_{2.5}$ exposure.[52,53]

Gas Stoves as an Indoor Source of NO_2 and $PM_{2.5}$

Gas stoves, which are used in about one-third of U.S. households,[54] emit NO_2 and $PM_{2.5}$ (as well as CO_2, CO, and formaldehyde,[55,56] which also were measured in the STOVE study and are described in later sections). A simulation study showed that gas burners add 25–33% to the week-averaged indoor NO_2 concentrations during summer and 35–39% during winter.[57] EPA summarized many studies on NO_2 levels in the presence of gas stoves, finding that 24-hour averages in U.S. homes ranged from 36 ppb to 65 ppb, with peak levels of 157 ppb.[58] The presence of a gas stove has been shown to be the largest contributor to indoor NO_2 concentrations, even in homes with a gas furnace.[59] Some jurisdictions have begun to ban gas appliances in new construction in light of both health concerns and climate change.[60]

Other studies of the effect of gas stoves on NO_2 concentrations have demonstrated the following findings:

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[52] *Integrated Science Assessment (ISA) for Particulate Matter*. U.S. Environmental Protection Agency. EPA/600/R-19/188; December 2019. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534

[53] *Integrated Science Assessment (ISA) for Oxides of Nitrogen—Health Criteria*. U.S. Environmental Protection Agency. EPA/600/R-15/068; January 2016. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879

[54] Nicole W. Cooking up indoor air pollution: emissions from natural gas stoves. *Environ Health Perspect*. 2014;122(1):A27. doi:10.1289/ehp.122-A27

[55] Jarvis D, Chinn S, Sterne J, Luczynska C, Burney P. The association of respiratory symptoms and lung function with the use of gas for cooking. European Community Respiratory Health Survey. *Eur Respir J*. 1998;11(3):651-658. http://www.ncbi.nlm.nih.gov/pubmed/9596117

[56] Jarvis D, Chinn S, Luczynska C, Burney P. Association of respiratory symptoms and lung function in young adults with use of domestic gas appliances. *Lancet*. 1996;347(8999):426-431. doi:10.1016/s0140-6736(96)90009-4

[57] Logue JM, Klepeis NE, Lobscheid AB, Singer BC. Pollutant exposures from natural gas cooking burners: a simulation-based assessment for Southern California. *Environ Health Perspect*. 2014;122(1):43-50. doi:10.1289/ehp.1306673

[58] *Integrated Science Assessment (ISA) for Oxides of Nitrogen—Health Criteria*. U.S. Environmental Protection Agency. EPA/600/R-15/068; January 2016. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879

[59] Hansel NN, Breysse PN, McCormack MC, et al. A longitudinal study of indoor nitrogen dioxide levels and respiratory symptoms in inner-city children with asthma. *Environ Health Perspect*. 2008;116(10):1428-1432. doi:10.1289/ehp.11349

[60] Sommer L. *Give up your gas stove to save the planet? Banning gas is the next climate push*. NPR, All Things Considered; August 5, 2019. Accessed November 8, 2021. https://www.npr.org/2019/08/05/745051104/give-up-your-gas-stove-to-save-the-planet-banning-gas-is-the-next-climate-push

- The average home indoor 24-hour NO_2 concentration was 58 ppb, with a range of 12–276 ppb. Each hour of kitchen appliance use was associated with an 18 ppb increase in 24-hour NO_2 concentration. Each 10-fold increase in previous-day NO_2 was significantly associated with increased nighttime inhaler use for asthma.[61]
- Every five-fold increase in NO_2 exposure above a threshold of 6 ppb led to an increased risk of higher asthma severity score, wheeze, night symptoms, and rescue medication use.[62]
- In 18 cities across 15 countries, use of a gas stove in the home was the dominant activity influencing NO_2 concentrations, with a 67% increase in mean personal NO_2 exposure when a gas stove was present.[63]
- In Baltimore, MD, median baseline NO_2 concentrations were 17.9 ppb in the kitchen and 13.1 ppb in the bedroom. NO_2 could be reduced by installation of a room air cleaner and replacement of the gas stove with an electric one.[64] Installation of exhaust range hoods did not result in decreased NO_2 levels, possibly because they were not used regularly by residents while cooking. (Also, range hoods can have limited capture efficiency, depending on distance from the source, crosscurrents, thermal effects, and other reasons.)[65]

$PM_{2.5}$ is also associated with gas stoves. One study[66] showed that cooking produced $PM_{2.5}$ between 24.7–50.0 μg/m^3. Another study showed that although smoking and burning candles were likely the largest emitters of $PM_{2.5}$, gas stoves produced an average of 1,700 μg of $PM_{2.5}$ per hour. The type of food being cooked, the type of cooking, and the type of oil used were factors.

Outdoor Pollution as a Source of NO_2 and $PM_{2.5}$

In the United States generally and in many major cities, motor vehicle emissions are the largest contributor of NO_2 in the ambient air. Power plants, industrial

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[61] Paulin LM, Williams D'L, Peng R, et al. 24-h Nitrogen dioxide concentration is associated with cooking behaviors and an increase in rescue medication use in children with asthma. *Environ Res*. 2017;159:118-123. doi:10.1016/j.envres.2017.07.052

[62] Belanger K, Holford TR, Gent JF, Hill ME, Kezik JM, Leaderer BP. Household levels of nitrogen dioxide and pediatric asthma severity. *Epidemiology*. 2013;24(2):320-330. doi:10.1097/EDE.0b013e318280e2ac

[63] Levy JI, Lee K, Spengler JD, Yanagisawa Y. Impact of residential nitrogen dioxide exposure on personal exposure: an international study. *J Air Waste Manag Assoc*. 1998;48(6):553-560. doi:10.1080/10473289.1998.10463704

[64] Paulin LM, Diette GB, Scott M, et al. Home interventions are effective at decreasing indoor nitrogen dioxide concentrations. *Indoor Air*. 2014;24(4):416-424. doi:10.1111/ina.12085

[65] Walker I. *Evaluating Cooker Hood Effectiveness*. Lawrence Berkeley National Laboratory; May 31, 2019. Accessed November 8, 2021. https://www.youtube.com/watch?v=dbfmOz0NZGU

[66] Shehab M, Pope FD, Delgado-Saborit JM. The contribution of cooking appliances and residential traffic proximity to aerosol personal exposure. *J Environ Health Sci Eng*. 2021;19(1):307-318. doi:10.1007/s40201-020-00604-7

facilities, other forms of transportation, and wildfires also can contribute considerably to ambient NO_2 concentrations. Annual average NO_2 concentrations range from 9–27 ppb at near-road air monitoring stations; the range in a day's highest 1-hour NO_2 concentration is 35–90 ppb at near-road sites and 12–73 ppb at sites not near roads. Concentrations are not always higher at near-road sites because many factors can affect NO_2 outdoor air concentrations, including distance from the road, local NO_2 sources besides traffic, chemical reactions with ozone (O_3) in the air, season, and wind direction.[67]

$PM_{2.5}$ in outdoor air has similar sources. Most primary $PM_{2.5}$ emissions are from anthropogenic sources, including industry, construction, motor vehicles, cooking, fuel combustion, and wildfires. However, in many locations, secondary particulate matter can be emitted from chemical reactions of sulfur dioxide, nitrogen oxides (including NO_2), ammonia, and volatile organic compounds (VOCs) and can account for most of the $PM_{2.5}$ in outdoor air.[68]

Given that NO_2 and $PM_{2.5}$ are present in both indoor and outdoor air, the STOVE study acquired data about both to help control for the influence of outdoor air.

1.3.2 Carbon Dioxide (CO_2)

CO_2 is a product of combustion, fermentation, and respiration. CO_2 is emitted during the use of a gas stove. Humans breathe in oxygen and exhale CO_2, a colorless, odorless, and nonflammable gas. CO_2 not only displaces oxygen in the air, but also has its own toxicity. At elevated concentrations, CO_2 can cause asphyxia, as well as have toxic effects at the cellular level. High concentrations can lead to an increased respiratory rate, tachycardia, cardiac arrhythmias, impaired consciousness, and even coma or death.

Much attention recently has been devoted to the increase in CO_2 levels as a result of greenhouse gas emissions. Average outdoor CO_2 levels were 316 parts per million (ppm) in 1958 and have since risen to 406 ppm in 2017 and 419 ppm in May 2021. Although no legal limit exists for indoor residential CO_2 concentrations, levels above 1,000 ppm traditionally have been regarded as a sign of inadequate

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[67] *Integrated Science Assessment (ISA) for Oxides of Nitrogen — Health Criteria*. U.S. Environmental Protection Agency. EPA/600/R-15/068; January 2016. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=310879

[68] *Integrated Science Assessment (ISA) for Particulate Matter*. U.S. Environmental Protection Agency. EPA/600/R-19/188; December 2019. Accessed November 8, 2021. https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534

outdoor air supply. ASHRAE has previously stated, "maintaining a steady-state CO_2 concentration in a space no greater than about 700 ppm above outdoor air levels [approximately 1,000 ppm] will indicate that a substantial majority of visitors entering a space will be satisfied with respect to human bioeffluents (body odor)."[69] In 2021, Health Canada established 1,000 ppm as its recommended CO_2 limit for indoor air in residential dwellings.[70]

One recent study showed that moderate decrements in decision-making performance occurred at 1,000 ppm, compared with 600 ppm. At 2,500 ppm, large and statistically significant reductions in decision-making performance occurred. Because human breathing can cause CO_2 to build up in indoor spaces that have too little outdoor air, CO_2 often is used as a surrogate measure of the amount of outdoor air introduced into homes.

1.3.3 Carbon Monoxide (CO)

CO is one of the most well-studied and extensively reviewed toxic substances. It forms when carbon in fuel is not burned completely; indeed, no fuel is completely combustible under normal conditions. CO is produced from both human-made and natural sources, but the most important human-made sources are automobile exhaust and improperly adjusted gas appliances, furnaces, wood-burning stoves, and fireplaces. Gas stoves are known to emit CO, which can be minimized by proper tuning and ventilation.

Exposure to CO results in formation of carboxyhemoglobin, which decreases the blood's ability to carry oxygen to body tissues and organs. Mild CO poisoning can cause headache, nausea, vomiting, dizziness, and blurred vision. Occasionally, fainting, chest pain, shortness of breath, tachycardia, rapid breathing, and other symptoms can occur. The effects of severe poisoning may be life-threatening, and acute CO poisoning during pregnancy has been associated with spontaneous abortion and fetal death. Smokers, because they have higher exposures to CO from smoking, have less tolerance to environmental CO exposures.

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[69] *Interpretation of ASHRAE Standard 62-1989 (IC 62-1989-29) on April 29, 1995*. ASHRAE. Accessed November 4, 2021. https://www.ashrae.org/File%20Library/Technical%20Resources/Standards%20and%20Guidelines/Standards%20Intepretations/IC_62-2001-07.pdf

[70] *Residential Indoor Air Quality Guidelines: Carbon Dioxide*. Health Canada; March 2021. Accessed November 8, 2021. https://www.canada.ca/en/health-canada/services/publications/healthy-living/residential-indoor-air-quality-guidelines-carbon-dioxide.html

Recent research has focused on health effects of low-level CO exposures that do not result in overt CO poisoning but instead affect the heart and cardiovascular system, brain, and developing nervous system, which all are particularly sensitive to CO. CO poisoning results in more than 430 deaths and 50,000 emergency room visits per year in the United States.

EPA has established a NAAQS for CO in outdoor air of 9 ppm (8-hour average) and 35 ppm (1 hour average). No legal limit exists for residential indoor air. WHO has established a guidance level of 87 ppm (15-minute average), 30 ppm (1-hour average), and 9 ppm (8-hour average) for indoor air. Most CO alarms are set to alert at 70–400 ppm (depending on averaging time). CO alarms often are required by local housing codes, as well as green building standards.

1.3.4 Formaldehyde

Formaldehyde is common in the outdoor environment as a result of natural processes, such as forest fires. It also is released into the outdoor air via industrial emissions, incineration, and fuel combustion. Additionally, some VOCs can react with O_3 in the air to produce formaldehyde.[71] In homes, formaldehyde can be generated from gas stoves when cooking at low temperatures. Formaldehyde also is found in many household products; in particular, it is widely used in composite wood products that have resins containing formaldehyde. It is found in building materials and insulation, glues, permanent press fabrics, paints, lacquers, and other coatings. Most green building practices discourage the use of building materials that include formaldehyde. For example, the Criteria calls for using building materials that comply with the California Air Resources Board requirements, which requires that no formaldehyde be added during the manufacturing process.[72] Personal care products — such as shampoos, soaps, hair care products, body washes, and nail polish — also can contain formaldehyde.

Formaldehyde exposure has been linked to many adverse health effects, including eye, nose, and throat irritation at low levels and skin rashes, shortness of breath, wheezing, and changes in lung function at higher levels.[73] Formaldehyde toxicity,

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[71] *Formaldehyde*. California Air Resources Board. Accessed November 8, 2021. https://ww2.arb.ca.gov/resources/fact-sheets/formaldehyde

[72] *2020 Enterprise Green Community Criteria*: Section 6.4. Enterprise Community Partners. Accessed November 8, 2021. https://www.greencommunitiesonline.org/materials

[73] *Formaldehyde and Your Health*. Agency for Toxic Substances and Disease Registry. Updated February 10, 2016. Accessed November 8, 2021. https://www.atsdr.cdc.gov/formaldehyde/index.html

which has been reviewed extensively, has focused primarily on cancer and respiratory sensitization.[74–78] The U.S. Department of Health and Human Services' National Toxicology Program states that formaldehyde is a "known carcinogen, based on sufficient evidence of carcinogenicity from studies in humans and supporting data on mechanisms of carcinogenesis."[79]

Research has shown that formaldehyde from wood products in homes is associated with an adverse immune response, as measured by elevated circulating immunoglobulin G (IgG) and E (IgE) autoantibodies (antibodies that attack one's own proteins) and a decrease in T cells (a type of white blood cell that influences allergies).[80] Long-term exposure to formaldehyde has been shown to be associated with genetic changes in patients who either were exposed in the workplace, were residents of mobile homes, or were residents of homes containing particleboard subflooring. Hypersensitivity associated with formaldehyde could be a reason that asthma and other health complaints also are associated with formaldehyde exposure.[81]

Chronic formaldehyde exposures are especially concerning for children because studies have demonstrated the following findings:

- Increased formaldehyde levels are associated with greater negative impacts on lung function in children, compared with adults in the same household. Decreased lung function in children at concentrations as low as 30 ppb was more pronounced in those with asthma, as measured by peak expiratory flow rate. Between 60 ppb and 120 ppb, a greater prevalence of diagnosed asthma and chronic bronchitis was shown in children, but not adults.[82]

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[74] *Addendum to the Toxicological Profile for Formaldehyde*. Agency for Toxic Substances and Disease Registry, Division of Toxicology and Environmental Medicine; October 2010. Accessed November 8, 2021. https://www.atsdr.cdc.gov/ToxProfiles/formaldehyde_addendum.pdf

[75] National Toxicology Program. *14th Report on Carcinogens: Formaldehyde*. U.S. Department of Health and Human Services; November 3, 2016. Accessed November 8, 2021. https://ntp.niehs.nih.gov/whatwestudy/assessments/cancer/roc/index.html

[76] *Chronic Toxicity Summary, Formaldehyde*. California Office of Environmental Health Hazard Assessment, California; 2005.

[77] State of California. *Prioritization of Toxic Air Contaminants — Children's Environmental Health Protection Act: Formaldehyde*. California Office of Environmental Health Hazard Assessment; October 2001.

[78] State of California. *TSD for Noncancer RELs Dec. 2008: Appendix D. Individual Acute, 8-Hour, and Chronic Reference Exposure Level Summaries*. California Office of Environmental Health Hazard Assessment. Updated July 2014.

[79] National Toxicology Program. *14th Report on Carcinogens: Formaldehyde*. U.S. Department of Health and Human Services; November 3, 2016. Accessed November 8, 2021. https://ntp.niehs.nih.gov/whatwestudy/assessments/cancer/roc/index.html

[80] Thrasher JD, Wojdani A, Cheung G, Heuser G. Evidence for formaldehyde antibodies and altered cellular immunity in subjects exposed to formaldehyde in mobile homes. *Arch Environ Health*. 1987;42(6):347-350. doi:10.1080/00039896.1987.9934357

[81] Thrasher JD, Broughton A, Madison R. Immune activation and autoantibodies in humans with long-term inhalation exposure to formaldehyde. *Arch Environ Health*. 1990;45(4):217-223. doi:10.1080/00039896.1990.9940805

[82] Krzyzanowski M, Quackenboss JJ, Lebowitz MD. Chronic respiratory effects of indoor formaldehyde exposure. *Environ Res*. 1990;52(2):117-125. doi:10.1016/s0013-9351(05)80247-6

- Formaldehyde-specific antibodies (e.g., IgE) and respiratory symptoms improved when children were transferred from school buildings with formaldehyde concentrations of 40–75 ppb to school buildings with concentrations of 23–29 ppb.[83]
- Increased sensitization in children was associated with homes that had a median formaldehyde level of 12 ppb.[84]

For non-cancer health effects, the state of California has adopted a chronic reference exposure level of 7 ppb to address nasal obstruction and discomfort, lower airway discomfort, and eye irritation caused by formaldehyde.[85] Other agencies also have adopted exposure limits for indoor air, although none are legally enforceable. WHO has issued indoor air guidance for formaldehyde of 80 ppb; the National Institute for Occupational Safety and Health (NIOSH) has a recommended exposure limit of 16 ppb for workplaces that the Federal Emergency Management Association has applied to temporary homes in disaster recovery. Additionally, the Agency for Toxic Substances and Disease Registry has issued a minimum risk level of 8 ppb, and California issued a recommended exposure limit for non-cancer health effects of 7 ppb.

1.4 ASHRAE Standard 62.2

ASHRAE Standard 62.2 is the industry standard for ventilation and indoor air quality in low-rise residential buildings and for residences in high-rise buildings. Many ventilation codes and energy-efficiency programs in the United States currently base their requirements on ASHRAE Standard 62.2, including the U.S. Department of Energy's Weatherization Assistance Program.[86] The Weatherization Assistance Program's requirement began in large part because of the nation's experience with the energy crisis in the 1970s. In order to conserve energy, widespread attempts were made to drastically reduce outdoor air supply in homes. This resulted in the first recognition of health problems associated with low building ventilation rates, known as "sick building syndrome."[87] The need remains for more studies of the

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[83] Wantke F, Demmer CM, Tappler P, Götz M, Jarisch R. Exposure to gaseous formaldehyde induces IgE-mediated sensitization to formaldehyde in school-children. *Clin Exp Allergy*. 1996;26(3):276-280.

[84] Garrett MH, Hooper MA, Hooper BM, Rayment PR, Abramson MJ. Increased risk of allergy in children due to formaldehyde exposure in homes. *Allergy*. 1999;54(4):330-337. doi:10.1034/j.1398-9995.1999.00763.x

[85] State of California. *TSD for Noncancer RELs Dec. 2008*. California Office of Environmental Health Hazard Assessment. Updated July 2014.

[86] *Weatherization Program Notice 11-6, Effective Date: January 12, 2011, Weatherization Health and Safety Guidance*. Department of Energy. Accessed November 8, 2021. https://www.energy.gov/sites/prod/files/2015/12/f27/WAP-WPN-11-6.pdf

[87] Sundell J, Levin H, Nazaroff WW, et al. Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air*. 2011;21(3):191-204. doi:10.1111/j.1600-0668.2010.00703.x

relationship between ventilation rates and health, especially in diverse climates, locations with polluted outdoor air, and buildings other than offices.

ASHRAE Standard 62.2 was first was published in 1973, and a major revision occurred in 1989. The 1989 edition considered 0.35 air changes per hour (ACH) — but no less than 15 cubic feet per minute (cfm) per person — to be the appropriate minimum ventilation rate for dwellings. This air change rate is substantially lower than standards for most nonresidential occupancies, and many other countries have higher ventilation standards, on the order of 0.5 ACH.[88] Discussions within the ASHRAE committee indicate that most homes in the United States do not comply with the ASHRAE standard because it is voluntary. Recently, in light of the COVID-19 pandemic, ASHRAE and other organizations have begun to consider whether changes to guidance are needed to help control the spread of the virus. This remains an ongoing area of inquiry as this report is being written.

Interestingly, the first known ventilation requirement — for the Parliament in England in 1836 — required 4 cfm of outdoor air per person. Ventilation rate guidance shifted to 30 cfm per person in 1895 and was followed by successive changes shown in **Figure 1-1**. The initial rationale for building ventilation was to control contagion, but this subsequently shifted to odor control.

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[88] Sherman M. How ASHRAE set the rates for residential ventilation. *ASHRAE Journal*. 2015;57(7):20-23.

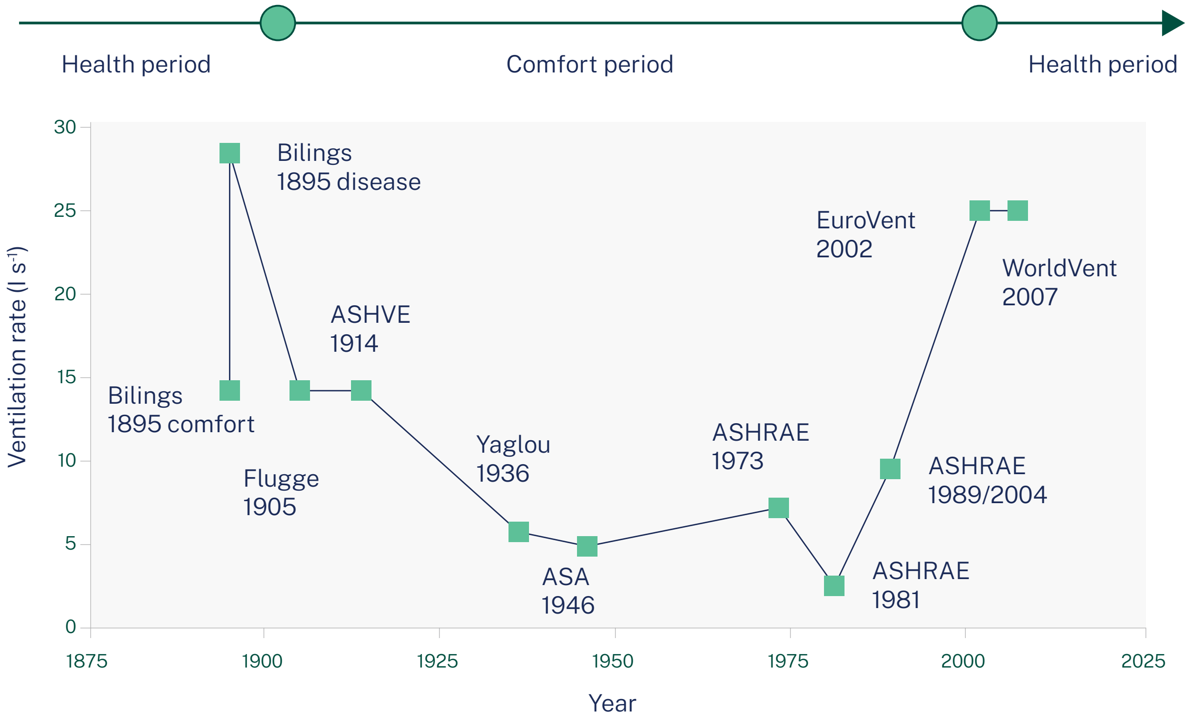

Figure 1-1. Ventilation rate guidance has shifted over time.

Source: Nielsen PV, Li Y. Ventilation. In: Nriagu J, ed. *Encyclopedia of Environmental Health*. Elsevier; 2019. p. 344-355; Wargocki P, personal communication, October 1, 2021.

1.4.1 Types of Ventilation and Ventilation Strategies

Indoor air contaminants that originate indoors can come from two main sources: (1) people, who exhale CO_2 and other gases (together with their behaviors, such as smoking and cooking), and (2) building materials and processes. Building materials can release formaldehyde from adhesives and other sources, and appliances like stoves can release NO_2, $PM_{2.5}$, and other byproducts of combustion, such as CO_2, CO, and formaldehyde.

Two main types of ventilation are used to control such contaminants: natural ventilation and mechanical ventilation. Opening windows to allow fresh air to enter is a form of natural ventilation. Mechanical exhaust ventilation includes kitchen stove exhaust hoods and bathroom exhaust fans. To achieve acceptable indoor air quality, ASHRAE Standard 62.2 defines “the roles and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality (IAQ) in residential buildings.”[89] As a

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[89] *ANSI/ASHRAE Standard 62.2-2019: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. ASHRAE. Accessed November 8, 2021. https://www.ashrae.org/technical-resources/standards-and-guidelines/read-only-versions-of-ashrae-standards

voluntary standard, however, compliance with ASHRAE Standard 62.2 is only required when the standard is adopted by a construction specification or program. The Criteria, for example, requires ASHRAE Standard 62.2 compliance for a substantial rehabilitation project, but it makes compliance optional for a moderate rehabilitation project.

ASHRAE Standard 62.2 generally provides for three ventilation strategies: balanced ventilation, supply-only ventilation, and exhaust-only ventilation. In short, a balanced system provides enough supply air to match the exhaust airflow, which has the advantage of not creating negative pressure within the housing unit. The supply-only option delivers enough outdoor air to meet the ASHRAE requirements and keeps the housing unit under positive pressure. The exhaust-only option also can meet the ASHRAE requirements but could potentially put the unit under negative pressure if insufficient makeup air is present. The study group units in the STOVE study all used the exhaust-only option with adequate makeup air and no reverse flows in chimneys or flues were observed in the homes studied here.

To determine how much air needs to be delivered to achieve sufficient ventilation and offset the contaminants emitted by both people and building materials, ASHRAE Standard 62.2 uses a formula that combines the number of occupants (usually defined as the number of bedrooms plus 1) and the square footage of the dwelling floor area:

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

where
Q_{tot} = total required ventilation rate, cfm
A_{floor} = dwelling-unit floor area, ft^2
N_{br} = number of bedrooms (not to be less than 1)

The standard also provides for an “infiltration credit” to account for the amount of outdoor air that is delivered through building leakage, but only for units that do not share common walls, floors, or ceilings.[90] To determine the credit, a blower door test measurement is needed, which measures how much air is coming into a dwelling. The infiltration credit is one element of the equation to determine ASHRAE Standard 62.2 compliance. The study also collected other data — such as unit square footage, exhaust flow rates, and building envelope square footage — to

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[90] *ANSI/ASHRAE Standard 62.2-2019: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. ASHRAE. Accessed November 8, 2021.

gain clarity on actual ventilation rates. Further details on the ventilation measures in this study can be found in sections **2.5, Participant Eligibility and Recruitment**, and **3.2, Characteristics of Buildings and Ventilation Testing Results**.

1.4.2 Barriers to Implementation of ASHRAE Standard 62.2

Widespread adoption of ASHRAE Standard 62.2 has been challenging for various reasons, including complexity, feasibility, financing, energy usage, and awareness. Despite the widespread recognition that mechanical ventilation is a key component of successful building operations, durability, and health, most of the U.S. housing stock has no planned system to deliver known amounts of outdoor air into a building's interior. Although many homes in the United States are equipped with central heating systems, these typically recirculate indoor air and rely on building leakage to supply outdoor air. Some ventilation systems exist that do not recirculate air from conditioned spaces and instead rely on supply air from basements. One such design has been linked to mold contamination and possible fatalities in infants, a concern that led to the nation's healthy homes movement in 1999.[91,92]

Although attempts have been made to simplify ASHRAE Standard 62.2 through the introduction of online calculators, the standard is complex. For example, differing methods of compliance introduce flexibility but also complexity. Additionally, blower door tests are not routinely available, and the number of occupants in a dwelling can change, might not be fully known, or might not align with the definition in the formula.

The feasibility of complying with the standard is a challenge for buildings undergoing moderate rehabilitation. For example, some multifamily buildings do not have existing forced-air systems — such as existing ductwork to deliver air to living spaces — and instead rely on radiators or baseboard electric heaters in each living space. Creating ducts, which requires cutting holes through building walls, can pose structural issues. Similarly, bathroom and kitchen exhaust fans should be vented to the building exterior, but this also requires creating new holes in the building's exterior envelope. Instead, some kitchen fans recirculate air rather than exhaust it to the exterior, which was the case in some of the STOVE study homes.

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[91] Jacobs DE, Friedman W, Ashley P, McNairy M. *The Healthy Homes Initiative: A Preliminary Plan (Full Report). Report to Congress*. U.S. Department of Housing and Urban Development, Office of Lead Hazard Control; April 1999. Accessed November 8, 2021. https://nchh.org/resource-library/hud_the-healthy-homes-initiative_a-preliminary-plan_full-report.pdf

[92] Dearborn DG, Smith PG, Dahms BB, et al. Clinical profile of 30 infants with acute pulmonary hemorrhage in Cleveland. *Pediatrics*. 2002;110(3):627-637. doi:10.1542/peds.110.3.627

Bathroom exhaust fans also are sometimes exhausted into building cavities or chases, which might not have planned exterior venting and can lead to mold, odor, and other deficiencies.

Financing is another barrier. Most affordable housing moderate rehabilitation projects have limited budgets (as do substantial rehabilitation projects, although more funding typically is available). Often, the budget is consumed by upgrading homes for compliance with local plumbing, electrical, and structural codes, which are legal requirements. Because compliance with ASHRAE typically is not required by law, it might not be prioritized when limited resources are available. No separate funding stream exists to finance ASHRAE compliance.

Compliance with the ASHRAE standard is sometimes thought to impose an "energy penalty" because conditioned air must be exhausted, and incoming air to replace it requires heating, cooling, and humidification. Although these "penalties" can be overcome through efficient use of heat recovery systems and other innovations, many energy efficiency experts believe that implementation of ASHRAE standards increases overall energy use. However, several green building studies have demonstrated that proper sealing of building envelopes, together with installation of planned ventilation systems that comply with the ASHRAE standard, can reduce energy costs.[93] In light of these studies the U.S. Department of Energy now requires use of ASHRAE Standard 62.2 in its Weatherization Assistance Program.

Another barrier to compliance is ensuring that designed ventilation systems continue to operate as intended. For example, fans that break or do not have sufficient airflow to overcome the static pressure from long air ducts, as well as simple cleaning of air vents, can pose a barrier to ongoing compliance.

Finally, many architects and engineers remain unfamiliar with ASHRAE Standard 62.2. During attempts to enroll prospective buildings into the STOVE study, the majority of developers and owners did not know whether their buildings were designed to comply with the ASHRAE standard. ASHRAE and others have developed training and additional and supplemental outreach activities, but a lack of awareness and understanding remains a key barrier.

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[93] Breysse J, Jacobs DE, Weber W, et al. Health outcomes and green renovation of affordable housing. *Public Health Rep.* 2011;126 Suppl 1(Suppl 1):64-75. doi:10.1177/00333549111260S110

2 Methods

2.1 Overall Study Design

The STOVE study is a two-group, non-randomized, post-rehab study with multiple data collection time points to help control for seasonal effects. All dwellings included working gas stoves and had completed rehabilitation using green building practices within 8 years before the start of the study. Residents of eligible housing units must have lived in the unit at least 4 months before the start of the study and must have continued to reside in the unit throughout the 8-month study period. The study is considered observational because the assignment of dwellings to the study group versus the comparison group was outside the power of the study investigators; in other words, all dwellings had been rehabilitated regardless of whether households chose to participate in the study. The buildings studied were located in Chicago, IL, and New York, NY.

The overall study process is shown in **Figure 2-1**. Enterprise was responsible for identifying buildings with potential for enrollment. These buildings were placed initially into the ASHRAE-compliant study group or the non-ASHRAE–compliant comparison group, based on the intent of the designer and/or a review of architectural drawings or specifications. The preliminary assignment was later verified by dwelling performance (ventilation) testing. If the buildings were potentially eligible, meetings were held among the researchers, developers, and community members to explain the study in further detail. For families who were interested in participating, a detailed informed-consent/assent process typically was carried out at the enrollment visit, the first of the three planned home visits. The study's National Advisory Council reviewed all procedures.

Data collection for the STOVE study occurred at three time points: at enrollment, 4 months after enrollment, and 8 months after enrollment. These intervals were chosen intentionally to help quantify seasonal influences. Season is a potentially important variable because residents tend to spend more time outdoors in the warmer months and encounter more respiratory and allergy symptoms during certain seasons. Window use also varies by season. Additionally, NO_2, $PM_{2.5}$, and formaldehyde levels fluctuate by season.

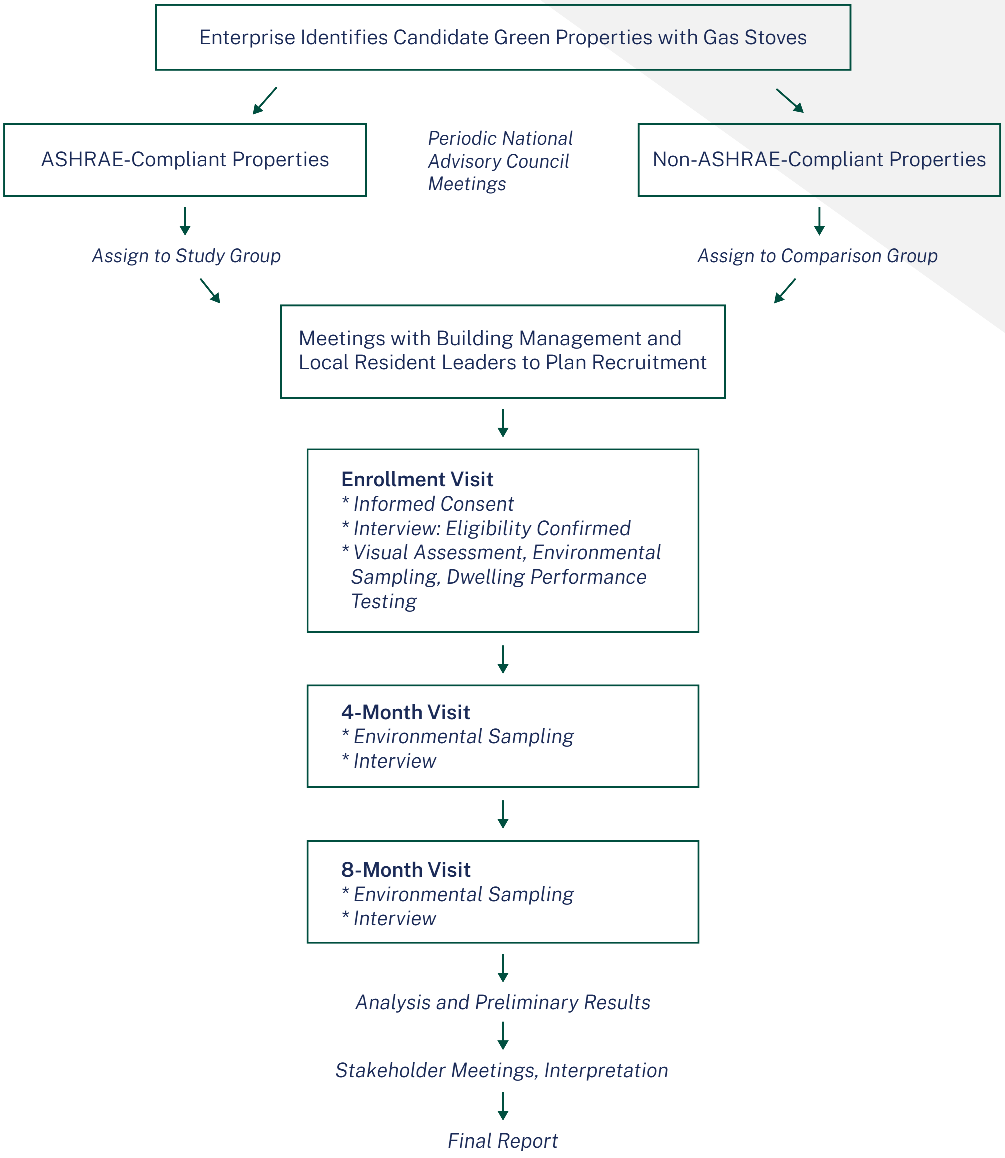


Figure 2-1. Overall study flow.

The indoor air quality characteristics measured in all enrolled dwellings were NO_2, $PM_{2.5}$, CO_2, CO, formaldehyde, and nicotine levels, as well as temperature and relative humidity. The study also recorded the self-reported frequency of use and characteristics of the gas stove (e.g., pilot light vs. electronic ignition) and operation parameters of home ventilation systems (e.g., kitchen and other local exhaust ventilation) via a combination of direct observation and interview. Demographic data were collected via interview.

Self-reported general health measures were collected for up to three adults and three children (a total of up to six individuals) in each household during each of the three study visits during the 8-month period. Structured interviews were conducted by trained data collectors (typically graduate students). Residents were administered the 10-Item Short Form Survey Instrument for Children (SF-10™) or the 36-Item Short Form Survey Instrument for Adults (SF-36™), and additional interview questions addressed nasal irritation, smoking, mental health, and other measures, described later in section **2.5.2, Participant Recruitment**, and **Appendix B, Study Protocol Version 1.4**. Study forms are available upon request from the report authors. The self-reported general health data collected at the 8-month period asked residents to assess their health during the previous 12 months. The health interview is available upon request. Data were entered into Health Insurance Portability and Accountability Act (HIPAA)-compliant secure databases using laptop computers.

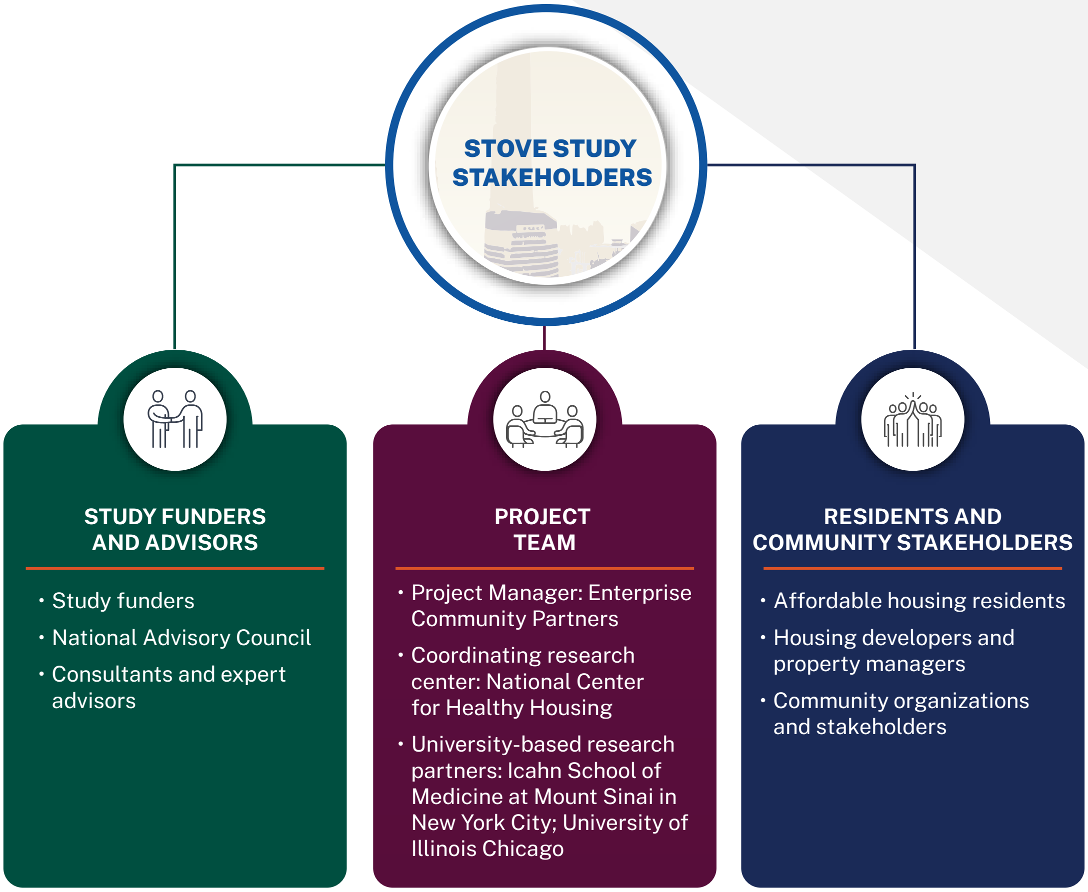
A visual assessment of home conditions and dwelling performance (ventilation) testing was used to measure air leakage and quantify compliance (or noncompliance) with ASHRAE Standard 62.2. These assessments were conducted once during the study, typically during (or shortly after) the enrollment visit, because ventilation systems and building conditions were unlikely to change during the 8-month study period. The visual assessment form is available upon request from the report authors.

2.2 Study Management

2.2.1 Lead Organizations

Development and implementation of the STOVE study required coordination and flexibility among the lead organizations (see **Figure 2-2**). Enterprise provided overall project management and oversight to the study and helped to identify affordable housing property owners in each location who would coordinate with the research teams to provide access to properties.

NCHH served as the Coordinating Center for the study. NCHH collaborated with the two local research centers and advisors on the design of the study, preparation of the study protocols, the quality assurance plan, and the central institutional review board (IRB) application. NCHH developed a system for securely receiving, reviewing, and maintaining the data and was responsible for all data analysis. NCHH also was responsible for assuring the protocols were consistently implemented; training data collectors at each site; and supervising environmental sampling, ventilation testing, and related laboratory analysis.



STOVE STUDY STAKEHOLDERS

STUDY FUNDERS AND ADVISORS

- Study funders
- National Advisory Council
- Consultants and expert advisors

PROJECT TEAM

- Project Manager: Enterprise Community Partners
- Coordinating research center: National Center for Healthy Housing
- University-based research partners: Icahn School of Medicine at Mount Sinai in New York City; University of Illinois Chicago

RESIDENTS AND COMMUNITY STAKEHOLDERS

- Affordable housing residents
- Housing developers and property managers
- Community organizations and stakeholders

Figure 2-2. Study roles and responsibilities.

Two institutions — Icahn School of Medicine at Mount Sinai in New York, NY, and the University of Illinois Chicago School of Public Health in Chicago, IL — served as local investigators and directed the technical aspects of the study in their respective locations. This included management of a consortium agreement or other arrangement with a local IRB (if applicable), data collection, and environmental assessments. Each institution had its own principal investigator, site coordinator, and data collectors. Local personnel administered the resident health interviews, maintained relationships with residents, supervised local data collectors (including environmental sampling), and performed local quality assurance and data review. Local personnel also were responsible for recruitment, screening, and conducting the informed-consent/assent process.

A National Advisory Council (see the **Acknowledgments** at the beginning of this report for a full list of Council members and affiliations) was convened to provide guidance on the study design, study implementation, interpretation of findings, and draft reports. Members of the Council had expertise in study design, environmental sampling, dwelling performance (ventilation) testing, health economics, conduct of multisite studies, community-based participatory research, statistical analysis, and measurement of self-reported health outcomes. The Council was convened periodically during the course of the study.

2.2.2 Training of Study Personnel

Training was conducted by NCHH personnel to support all staff involved in the research study, ensure uniformity of research practices, and maintain confidentiality of personal information collected. All study personnel collecting, entering, or managing data signed confidentiality agreements pledging to protect the confidentiality of information. All data collectors received in-depth training on data collection procedures using the same training curriculum delivered by the same training providers. A short "refresher" training was conducted periodically with the data collectors to ensure that procedures remained consistent through the duration of the study. For those conducting visual assessments, training included exercises that calibrated each visual assessor's opinion of the severity of a given building defect. The exercises included reviews of pictures of housing defects drawn from the U.S. Department of Housing and Urban Development's (HUD) training curriculum for the Public Housing Assessment System and other sources.

Similarly, those conducting health interviews practiced doing so to ensure interviews were conducted uniformly across sites. Those administering environmental sampling and dwelling performance (ventilation) testing were trained in procedures for environmental sampling or dwelling performance testing, respectively, as needed. Training covered the following topics:

- Goals and aims of the study
- Personal conduct during home visits
- Confidentiality and protection of data and forms
- Enrollment, protection of human subjects, and informed-consent/assent procedures
- Assignment of study IDs
- Methods of recording data
- Hard-copy forms (e.g., informed-consent/assent form, signed chain-of-custody forms)

- Electronic forms (e.g., health interview questionnaire, visual assessment form, environmental sampling form, laboratory chain-of-custody form, dwelling performance [i.e., ventilation] testing form)
- Environmental sampling procedures
- Dwelling performance (ventilation) testing (separate training)
- Handling missing data or data requiring correction
- Security during collection and transmission of study data
- Practicum: practicing data collection procedures
- Quality-control procedures
- Mandated reporting procedures
- Personal safety
- Procedures for unanticipated occurrences

2.2.3 Study Ethics and Institutional Review Boards

Advarra IRB (formerly Chesapeake Research Review) served as the central IRB for the study. Advarra reviewed the study design, protocols, forms, and other materials. The design, protocols, and other materials also were approved by local IRBs at Mount Sinai and the University of Illinois Chicago. This project complied with all Human Subject Protection requirements in the following ways:

1. NCHH is registered with the Department of Health and Human Services' (HHS) Office for Human Research Protections (OHRP) Federalwide Assurance (FWA): FWA00004590 (NCHH), indicating that the HHS OHRP has approved the institutional procedures to comply with the federal policy for the protection of human subjects.
2. NCHH used Advarra IRB as the central IRB for this project; this IRB has been fully accredited by the Association for the Accreditation of Human Research Protection Programs since 2004.
3. All NCHH and site staff with responsibility for health data collection and/or management completed the online Human Subject Assurance Training or other applicable training required by a local IRB (if any).
4. Self-reported health information was kept confidential and disclosed only to the entities identified on the consent form and under law, as reviewed and approved by the IRB.

5. Environmental and dwelling performance data collected through this project for a given dwelling was disclosed to that specific participating household following receipt of results from the laboratories.
6. All data were stored and analyzed at NCHH using password-protected and secured computer networks.
7. All personnel complied with the Federal Policy for the Protection of Human Subjects (i.e., the "Common Rule" 45 *Code of Federal Regulations* [CFR] Part 46).

The original completed data collection instruments and signed informed-consent/assent forms were stored in locked cabinets at Mount Sinai and the University of Illinois Chicago. NCHH maintained copies in locked cabinets or as scanned electronic files. All electronic data were encrypted or stored on encrypted systems. To ensure the privacy of all study participants, only aggregate results were disseminated publicly at the end of the project, and no unique personal identifiers of the study participants were included in any publicly disseminated document. On an annual basis, NCHH submitted an update on IRB-related activities to its IRB for review and approval, and site coordinators did the same as required by the site IRBs.

2.2.4 Compensation for Study Participants

Participants in the STOVE study were compensated for their time in the form of money orders. NCHH was responsible for purchasing the money orders and providing them to the individual sites for distribution to study participants. The payment for participation in a single study phase was $75 per home; each household received the $75 money order only after the environmental sampling equipment was retrieved. If payment was made at the conclusion of a home visit, the head of household signed a receipt or log documenting that the payment was received. If payment was made by mail, a mail system with a traceable number was used to document receipt.

In total, each household could receive up to $225 ($75 for completion of each of three environmental sampling visits). Households that terminated participation or were lost to follow-up received funds only for the environmental sample retrieval visits that were completed.

2.2.5 Quality Assurance

The STOVE study featured extensive, detailed quality assurance procedures, which are described more fully in the study protocol (see **Appendix B, Study Protocol Version 1.4**). In brief, the quality assurance procedures covered uniform, valid, and complete data collection; secure data transfer using encrypted databases; periodic site visits by supervisory personnel; uniform and periodic training for all data collectors; specified use of duplicate and blank samples, where feasible; review of both hard-copy and electronic data by local and central data managers; and methods to correct any deficiencies, if found.

2.3 Determination of Study Cohort Size and Recruitment Targets

As described previously, the primary hypothesis of the study was that study group dwellings would have significantly lower indoor levels of NO_2 when compared with comparison group dwellings. To determine the cohort size necessary to have adequate statistical power to test this hypothesis, a power calculation was completed during the study design stage. The enrollment target was determined using assumptions based on three earlier studies.[94–96] The power calculation was based on a two-sample t-test with equal variances assuming a mean difference between the two groups of 4.7 ppb and a standard deviation of 8 ppb. The results of this power calculation found that a minimum of 47 dwellings were needed in each group to potentially see a statistically significant difference (with 80% power and 95% confidence) in NO_2 between the two groups.

Based on the study team's experience with enrollment during the initial design of the *Healthy Homes, Happy Kids* study, 20% of households within a building were likely to agree to participate in the redesigned study. Taking into account expected participant retention rates, which are discussed further in section **2.7, Participant Retention Rates**, the team was able to determine that at least 420 study-compliant dwellings and 420 comparison dwellings were needed. Section **2.4, Building and Dwelling Eligibility and Recruitment**, describes the process to recruit properties into the study, section **2.5, Participant Eligibility and Recruitment**, describes the process to recruit and enroll households/dwellings into the study, and section **2.7, Participant Retention Rates**, discusses retention rates.

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[94] Fabian MP, Adamkiewicz G, Stout NK, Sandel M, Levy JI. A simulation model of building intervention impacts on indoor environmental quality, pediatric asthma, and costs. *J Allergy Clin Immunol*. 2014;133(1):77-84. doi:10.1016/j.jaci.2013.06.003

[95] Li R, Weller E, Dockery DW, Neas LM, Spiegelman D. Association of indoor nitrogen dioxide with respiratory symptoms in children: application of measurement error correction techniques to utilize data from multiple surrogates. *J Expo Sci Environ Epidemiol*. 2006;16(4):342-350. doi:10.1038/sj.jes.7500468

[96] Mullen NA, Li J, Russell ML, Spears M, Less BD, Singer BC. Results of the California Healthy Homes Indoor Air Quality Study of 2011-2013: impact of natural gas appliances on air pollutant concentrations. *Indoor Air*. 2016;26(2):231-245. doi:10.1111/ina.12190

2.4 Building and Dwelling Eligibility and Recruitment

2.4.1 Eligibility

To be eligible for inclusion in the study, buildings had to be open to residents of all ages. To ensure families could participate, housing reserved exclusively for the elderly was not eligible. Buildings also had to have working gas stoves. The presence of a functioning gas stove was confirmed visually at the first home visit.

All enrolled housing dwellings were located in multifamily affordable housing developments that ranged from one-story row homes to multiple-story high-rise apartment buildings. Building owners and developers were interviewed to determine if the dwellings met the study's requirement for compliance with the Criteria or an equivalent green standard (e.g., Leadership in Energy and Environmental Design [LEED] 4.1 Residential Silver and above, EarthCraft: Green Point Rated: Earth Advantage) when undergoing moderate or substantial rehabilitation. The Criteria requires compliance with ASHRAE Standard 62.2 for new construction and substantial rehabilitation, but not for moderate rehabilitation (where it is optional), due primarily to complexity and feasibility.[97] All the dwellings in this study were required to have undergone moderate or substantial rehabilitation within 8 years before the start of the study. The rehabilitation must have included green building practices, such as —

- The use of low-or no-VOC paints, primers, adhesives, and sealants to avoid chemical contaminants
- A clothes dryer exhausted to the outdoors to help prevent mold and moisture problems (if present inside the dwellings)
- Mold prevention in bathrooms and other wet surfaces by not using carpeting in these rooms
- Integrated pest management that minimizes the intrusion of insects, rodents, and other pests
- Avoidance of formaldehyde-containing building products

The study team also determined if the dwellings were designed to comply with ASHRAE Standard 62.2 to permit a preliminary assignment to either the study or

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[97] *2020 Enterprise Green Communities Criteria*: Section 7.7. Enterprise Community Partners. Accessed November 8, 2021. https://www.greencommunitiesonline.org/healthy-living-environment

the comparison group. ASHRAE compliance was determined initially by review of specifications and later confirmed by dwelling performance (ventilation) testing.

The main difference between the study and comparison groups was the type of ventilation provided. All homes included in the study group had, by design, bathroom mechanical exhaust that operated continuously or through scheduled intermittent operation. This type of operation provided enough airflow to not only exhaust the bathroom, but also to ventilate the entire dwelling unit to meet the ASHRAE requirement (some dwellings also had additional continuous kitchen exhaust). The air needed to replace the exhausted bathroom air was delivered to the unit through building leakage. All buildings and dwellings experience some leakage, which occurs through very small, usually invisible gaps in the unit's building envelope (e.g., exterior walls, ceilings, floors). Outdoor air or air from adjacent dwellings enters through these gaps. This can create negative pressure within the dwelling but is designed to be not so great as to cause reverse airflows in chimneys, hot water heaters, or clothes dryers.

The STOVE study comparison group homes had ventilation insufficient to meet the ASHRAE requirement. Instead, these dwellings relied on passive airflow through building leakage or on-demand (resident-controlled) bathroom ventilation, which is typical for much of the U.S. housing stock.

None of the dwellings in this project had balanced or supply-air ventilation; instead, they employed exhaust ventilation. All study group dwellings had bathroom exhaust vented to the exterior, but some also had kitchen exhaust that either (1) was vented to a continuously operating roof fan, (2) had an on-demand kitchen range hood fan that was vented outside, or (3) was recirculating (not vented to the exterior). Some comparison group dwellings had neither bathroom nor kitchen exhaust.

2.4.2 Building Recruitment

Enterprise led the effort to identify potentially eligible housing developments, leveraging its existing relationships with property owners in New York City and Chicago. Additionally, as the manager of the Green Communities Criteria certification program, Enterprise was able to use program data to identify properties that had been renovated to green standards within the previous 8 years, the required timeframe for eligibility. Enterprise staff in New York City and Chicago contacted housing owners directly to determine if any of their buildings might be eligible for the study.

During the initial contact, Enterprise staff provided an overview of the study and asked about potential interest in the study. Many housing owners had questions about the study, specifically the data collection process, the type of information residents would be asked to provide and would receive in return, the level of involvement needed from property management staff, and the impact the study might have on residents or on them as the property owner. Ultimately, Enterprise's personal and institutional relationships with housing owners made it possible to initiate these conversations, address concerns that were raised, and eventually engage directly with residents. These relationships with housing owners proved critical throughout the initial stages to ensure they remained interested and responsive.

After the initial determination of interest, Enterprise staff and NCHH worked with the local research teams and the local building owners to determine property eligibility. To determine a property's eligibility, several criteria had to be met. First, properties had to have undergone rehabilitation within the previous 8 years. Second, properties had to have gas stoves. Third, properties designated for the study group needed to comply with ASHRAE Standard 62.2. The first two criteria were relatively straightforward to confirm, but determining ASHRAE compliance required significant background information about the scope of construction work and specific details about the properties, such as unit size and types of fans installed. Often, obtaining the necessary information required coordination with the architect or engineer that worked on the rehabilitation effort. Once obtained, the research team reviewed the documentation to determine ASHRAE compliance. In some cases, it was determined that the property was not eligible for the study; in others, a lack of responsiveness from the property owner throughout the process indicated a lack of interest in participating in the research.

2.5 Participant Eligibility and Recruitment

2.5.1 Eligibility

To be eligible for the STOVE study, participants had to meet the following requirements:

- Residence in an affordable housing unit that had been rehabilitated using the Criteria or equivalent for at least 4 continuous months before enrollment in the study and intention to remain for at least another 8 months (residence for this study is defined as spending at least 5 nights per week in the home).

- Agreement by the adult resident (usually the children's parent) most knowledgeable about the health of the household (the individual who knew the most about the health of children, hereafter called the primary adult) to answer questions pertaining to their own health and the health of up to three children at least 5–17 years old living in the same dwelling. If other adults lived in the home, up to two of them were interviewed based on availability, as well. In total, up to six people (three adults and three children), including the primary interviewee, were eligible to be included. If the family included more than three children, the youngest children who were at least 5 years old were selected first to minimize potential bias.
- Residence in a housing unit that was safe for data collectors to enter as assessed by the data collectors.
- Agreement to permit air sampling, a visual assessment, and dwelling performance (ventilation) testing of the dwelling.
- Agreement to refrain from smoking or vaping indoors (including smoking near an open window) during the air sampling periods.
- Agreement to use the kitchen stove exhaust hood during cooking (if one was present) during the air sampling periods.
- Review and signed completion of the informed-consent/assent forms.

Additionally, at the enrollment visit and during each of the three 4-day air sampling periods, households agreed to (1) keep exterior doors closed except for entry and egress (exterior doors are those connecting the unit to a common area or the outside), (2) keep windows closed (unless there was no air conditioning in the unit), and (3) operate bathroom exhaust fans as usual if present and keep the bathroom door open when not in use. Fan use and cooking behaviors were captured at the end of each air sampling visit.

2.5.2 Participant Recruitment

Once a property was confirmed to be eligible for the study, the local university research team worked with property management staff to coordinate recruitment efforts, a critical step in gaining access to properties and determining site-specific recruitment activities. When property managers were available to provide the research staff with access to a property and offer introductions to residents, recruitment efforts frequently yielded success in enrolling participants. When property managers were not available, on-site recruitment activities were more challenging to conduct.

The purpose of the study and its eligibility criteria were explained at community meetings at each of the eligible housing developments. Study staff distributed IRB-approved recruitment fliers to residents by visiting buildings and knocking on doors. Staff also made telephone calls and sent email and text messages to identify households with residents who were interested in volunteering to participate in the study. Additionally, the study team worked with local leaders and community organizations that spoke the languages commonly spoken in the buildings, and the recruitment flier was made available in both English and Spanish. Other recruitment methods included identification of resident leaders who assisted with promoting the study to neighbors and other informal referrals. In some cases, property managers were willing to post fliers and support the legitimacy of the study.

Overall, the study had a recruitment success rate of 17% — 160 enrolled dwellings out of a total of 941 dwellings in the participating properties. This number may somewhat underestimate the actual success rate because some of these dwellings may have been vacant and therefore ineligible for enrollment.

Screening Questionnaire

Following recruitment, study staff contacted each household by telephone, email, text message, or door knocking to administer a screening questionnaire and make a preliminary determination of household eligibility. If the household did not have a listed telephone number, a preliminary screening visit was conducted in person. In some cases, to reduce the burden on the residents, the screening visit occurred at the same time as the first home visit. The screening form was used during or immediately after recruitment to answer the following questions:

1. Have you lived in your home or housing development for at least 4 months?
2. Do you plan to remain in this home for at least 8 months?
3. Do you have a working gas stove?

If the answer to all of the screening questions was “Yes,” the recruiter then scheduled the first home visit. If the answer to any of the questions was “No,” then the recruiter asked for the person’s address and recorded the reason for the household’s ineligibility for study participation.

Enrollment

During the enrollment visit, pursuant to the IRB-approved informed-consent/assent forms, study staff provided participants with a description of the nature of the study, including its risks and benefits. Staff also offered an explanation of how to obtain further information, explained how personal confidentiality would be protected, and answered any questions. The informed-consent/assent discussion emphasized that participation for the household was entirely voluntary.

To confirm study enrollment, the primary adult signed two copies of the informed-consent/assent form, one copy for the household to keep and the other copy to be retained by the site coordinator. If non-primary adults were interviewed, they also signed informed-consent/assent forms. Children without asthma were not interviewed for this study, so no assent was needed, pursuant to IRB approval; however, children with asthma who were taking the Childhood Asthma Control Test[98] were assented, pursuant to IRB approval. One primary adult and up to two non-primary adults were interviewed for each household. The primary adult answered questions about their own health, their home, and the health of any children selected for inclusion. Non-primary adults answered questions about their own health. Data collection did not proceed until the household was determined to be eligible and the applicable informed-consent/assent forms were signed.

2.6 Data Collection Methods

2.6.1 Home Visits

Each of the three environmental sampling sessions was performed during a 4-day period that included both weekdays and weekends (see section **2.6.3, Environmental Methods**). The intent was to capture both routine weekly activities and routine weekend activities because behaviors, particularly cooking, can differ depending on the day of the week. **Table 2-1** summarizes the home visit schedule.

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[98] *Take the Asthma Control Test™*. Asthma.com. Accessed November 8, 2021. https://www.asthma.com/understanding-asthma/severe-asthma/asthma-control-test

Table 2-1. Summary of Home Visits

Phase	Length of Time Between Visits	Activities[a]
Phase 1 home visit	Enrollment visit	• Obtain informed consent. • Conduct health interview. • Conduct visual assessment. • Conduct dwelling performance (ventilation) testing. • Deploy samplers for NO_2, $PM_{2.5}$, formaldehyde, and nicotine. • Deploy dataloggers for CO_2, CO, temperature, and relative humidity.
Phase 1 environmental sampling retrieval	4 days after deployment of Phase 1 samplers and dataloggers	• Retrieve all samplers. • Download data and retrieve dataloggers. • Provide compensation.
Phase 2 home visit	4 months after enrollment visit (±30 days)	• Conduct health interview. • Deploy samplers for NO_2, $PM_{2.5}$, formaldehyde, and nicotine. • Deploy dataloggers for CO_2, CO, temperature, and relative humidity.
Phase 2 environmental sampling retrieval	4 days after deployment of Phase 2 samplers and dataloggers	• Retrieve all samplers. • Download and retrieve dataloggers. • Provide compensation.
Phase 3 home visit	8 months after enrollment visit (±30 days)	• Conduct health interview. • Deploy samplers for NO_2, $PM_{2.5}$, formaldehyde, and nicotine. • Deploy dataloggers for CO_2, CO, temperature, and relative humidity.
Phase 3 environmental sampling retrieval	4 days after deployment of Phase 3 samplers and dataloggers	• Retrieve samplers. • Download data and retrieve dataloggers. • Provide compensation.

Key: CO = carbon monoxide; CO_2 = carbon dioxide; NO_2 = nitrogen dioxide; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

[a] Some activities occurred on separate visits. For example, dwelling performance (ventilation) testing and initial environmental sampling sometimes took place on separate visits from the enrollment visit.

In all enrolled study group and comparison group dwellings, field technicians assessed the visual condition of the housing during Phase 1 using a visual assessment electronic form in Research Electronic Data Capture (REDCap). REDCap is a HIPAA-compliant secure application for managing online databases and is widely used for this type of research study. The visual assessment questions were based on HUD's *National Survey of Lead and Allergens in Housing* and the HUD/Centers for Disease Control and Prevention (CDC) *Healthy Housing Inspection Manual*.[99,100] The visual assessment, available upon request, was used to compare the overall condition of the study and comparison group dwellings, which conceivably could affect both air sampling and health interview results. For example, broken windows could affect airflows, and mold could affect health.

2.6.2 Health Interview Methods

All health interviews, during every phase of the study, were conducted in person, with the same adult(s) interviewed at each phase. The interviews were conducted in the home, with the exception of a few interviews that were conducted over the telephone to accommodate participants' schedules. The health interview questionnaire was drawn from the following sources:

- The Green Housing Study (adapted from the CDC's *National Health Interview Survey* and the Behavioral Risk Factor Surveillance System), previously used in three Green Housing Study sites
- General Health Interview Questions: physical and mental health questions from the validated SF-10 (for children) and SF-36 (for adults)[101]
- *National Health and Nutrition Examination Survey* for tobacco and e-cigarette use[102]
- Asthma Control Test and Childhood Asthma Control Test[103]
- *Inner City Asthma Study* questions on asthma control and asthma health care utilization[104]
- Allergic Rhinitis, using the validated Total Symptom Nasal Score[105]
- Perceived Stress Scale[106]

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[99] Vojta PJ, Friedman W, Marker DA, et al. First National Survey of Lead and Allergens in Housing: survey design and methods for the allergen and endotoxin components. *Environ Health Perspect*. 2002;110(5):527-532. doi:10.1289/ehp.02110527

[100] Centers for Disease Control and Prevention and U.S. Department of Housing and Urban Development. *Healthy Housing Inspection Manual*. Atlanta: U.S. Department of Health and Human Services; 2008. Accessed November 8, 2021. https://www.cdc.gov/nceh/publications/books/inspectionmanual/healthy_housing_inspection_manual.pdf

[101] *Health Surveys*. Quality Metric. Accessed November 8, 2021. https://www.qualitymetric.com/health-surveys

[102] National Center for Health Statistics. *National Health and Nutrition Examination Survey: Tobacco and E-Cigarette Use*. Centers for Disease Control and Prevention. Accessed November 8, 2021. https://wwwn.cdc.gov/nchs/nhanes/continuousnhanes/default.aspx?BeginYear=2017

[103] *Asthma Control Test*. Quality Metric. Accessed November 8, 2021. https://www.asthmacontroltest.com/en-gb/welcome

[104] *The National Cooperative Inner City Asthma Study—Phase I*. Asthma Community Network. Accessed November 8, 2021. https://www.asthmacommunitynetwork.org/NCICAS

[105] *Total Nasal Symptom Score*. Northwest ENT and Allergy. Accessed November 8, 2021. https://www.nwentallergy.com/docs/Total_Nasal_Symptom_Score.pdf

[106] *Perceived Stress Scale*. Accessed November 8, 2021. https://www.sprc.org/system/files/private/event-training/Penn%20College%20-%20Perceived%20Stress%20Scale.pdf

All interview data collected during the study were entered into REDCap at the time of the interview or on hard copy and subsequently entered into REDCap.

2.6.3 Environmental Methods

To characterize the indoor environment in both the study and comparison groups, NO_2, $PM_{2.5}$, CO_2, CO, formaldehyde, nicotine, temperature, and relative humidity in the air were sampled in all enrolled dwellings.

Because cooking frequency, amount of time spent at home, and other variables can differ between weekdays and weekends, air samplers and dataloggers during each sampling phase remained in place for a 4-day period inclusive of a Saturday and Sunday (for example, sampling could be started on a Thursday and completed on a Monday). This way, both weekend and weekday exposures were measured as either time-weighted averages or time-resolved data.

All indoor sampling equipment was placed in the main living area of the home (e.g., living room, dining room) at a height of 5–7 feet and in an area that was out of the reach of children. Placement in the kitchen was not permitted. The equipment was located at least 3 feet from forced-air heating vents, as well as away from areas where air did not circulate (i.e., “dead spots”), such as a corner, under a shelf, or near or on curtains. The equipment also was positioned at least 3 feet away from a window and out of direct sunlight. The sampling technician always requested permission from the household to place the sampling equipment in the selected location. For all sampling periods, the start and stop times were recorded to the nearest minute on the start and stop date.

Outdoor levels of NO_2, $PM_{2.5}$, and CO were determined using publicly available EPA ambient air sampling data for National Ambient Air Quality Standard compliance. Data from the nearest appropriate areawide NO_2, $PM_{2.5}$, and CO ambient air monitors were used to help control for the influence of outdoor levels on indoor levels in each dwelling. The hourly EPA data were used to construct a 4-day average that matches the 4-day average for the indoor samplers used in the study, according to ZIP code data for each home sampled.

Air Sampling Methods and Sample Analysis

To sample NO_2, $PM_{2.5}$, formaldehyde, and nicotine, a sampling equipment setup was placed in each home (see **Figure 2-3**). NO_2 was sampled using the single-use SKC UMEx 200 Passive Sampler; this device collects NO_2 using a sample medium with a tape treated with triethanolamine. $PM_{2.5}$ was sampled using SKC Single-Stage Personal Modular Impactors, which are designed for the highly efficient collection of PM_{10}, $PM_{2.5}$, or coarse particulate matter (2.5–10 micrometers in diameter), although only $PM_{2.5}$ was measured in this study. Formaldehyde was sampled using single-use UMEx 100 Passive Samplers. Sampling for nicotine was accomplished using a passive method.[107]

Environmental samples for NO_2, $PM_{2.5}$, and formaldehyde were analyzed at the University of Wisconsin State Laboratory of Hygiene (WSLH), an operating unit of the University of Wisconsin–Madison. WSLH is affiliated with a network of public health laboratories throughout the United States and participates in technology and information transfer programs with the CDC, EPA, WHO, and numerous other institutions engaged in public health research. The laboratory is a fully accredited and certified environmental, clinical, and occupational exposure–testing laboratory and routinely performs a full range of EPA, CDC, NIOSH, and Occupational Safety and Health Administration (OSHA) analytical methods. WSLH is certified by EPA and the Clinical Laboratory Improvement Amendments (CLIA) and accredited by the National Environmental Laboratory Accreditation Program.

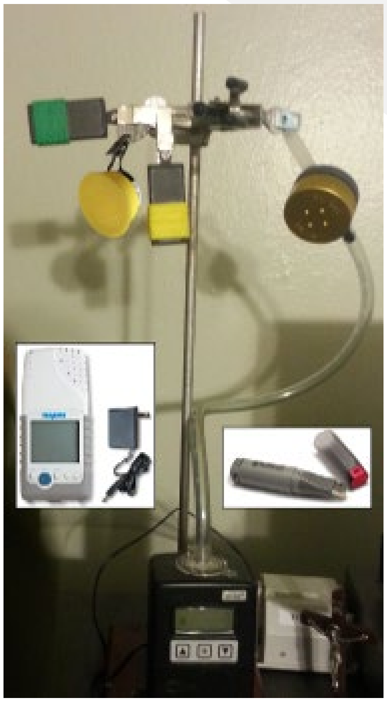

Figure 2-3. A typical indoor sampling setup used in the STOVE study contained monitors to measure the following pollutants (from left to right): formaldehyde (rectangular green), nicotine (circular yellow), NO_2 (rectangular yellow), and $PM_{2.5}$ (circular gold). The device labeled "Telaire" (lower left) was used to measure CO_2, temperature, and relative humidity. The gray device with the red cap (lower right) was used to measure CO.

Nicotine samples were analyzed at the Johns Hopkins University Secondhand Smoke Exposure Assessment Laboratory. This laboratory has developed methods for the analysis of contaminants in different media, including air, hair, urine, dust, saliva, and serum.

To measure CO_2, CO, temperature, and relative humidity, dataloggers were deployed at the same location as the other samplers (see **Figure 2-3**). CO was measured using the EL-USB-CO, a USB datalogger that measures

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[107] Hammond SK, Leaderer BP. A diffusion monitor to measure exposure to passive smoking. *Environ Sci Technol*. 1987;21(5):494-497. doi:10.1021/es00159a012

and stores up to 32,510 readings over a measurement range of 0–1000 ppm. CO_2, temperature, and relative humidity were measured using a Telaire 7001 monitor with a HOBO U30 datalogger.

Dwelling Performance (Ventilation) Testing

In each enrolled dwelling in both the study and comparison groups, a dwelling performance contractor completed dwelling performance (ventilation) testing during Phase 1 to measure volumetric airflow rate in exhaust and supply grilles, duct leakage, unit interstitial pressures, and building envelope tightness.

Each dwelling received a blower door test, the results of which were used to estimate the unit's air change rate in cfm at 50 pascals (Pa) (see **Appendix B, Study Protocol Version 1.4**, for more information). For the study group, this test verified that post-rehab dwelling performance complied with the specifications in ASHRAE Standard 62.2. Duct testing fans had an accuracy of ±5%, and pressure gauges had a resolution of 0.1 Pa and an accuracy of ±1% of the reading or 0.5 Pa, whichever was greater.

The airflow meter measured airflows at bathroom exhausts with an accuracy of ±5%. The estimated square footage of the unit was recorded and later verified with property developers and other databases. The number of bedrooms, approximate ceiling height, and estimated length of the full unit perimeter (in feet) also were recorded, as were measurements for duct leakage, unit leakage, and pressure differentials.

These data were used to calculate the unit air exchange rate; cfm_{50}/sfbe (cubic feet per minute at 50 Pa divided by the square footage of the building envelope); and percent compliance with ASHRAE Standard 62.2 for the entire housing unit. The percent compliance was calculated as follows: First, the outdoor air supply requirement was determined by the square footage and the number of bedrooms in each housing unit, using the ASHRAE formula (see section **1.4.1, Types of Ventilation and Ventilation Strategies**). Second, the total cfm was determined using the volumetric flow rates measured from bathroom and (if present) kitchen exhaust ducted to the exterior and by blower door data. Third, the measured volumetric airflow (in cfm) was divided by the total required volumetric airflow (also in cfm) multiplied by 100. Note that if units were over-ventilated (i.e., they had more exhaust than required), the percent compliance with the ASHRAE standard could exceed 100%. If no exhaust was present, as was the case in the comparison group units, then percent compliance was effectively zero. If the unit was eligible for an infiltration credit due to its configuration (in this study a few townhomes), then that credit was applied. The dwelling performance contractor entered the ventilation data into an encrypted Microsoft Access database and uploaded the data securely to NCHH.

2.6.4 Data Collection During the COVID-19 Pandemic

When the COVID-19 pandemic emerged, the study team adapted the methods described previously and implemented a modified approach to minimize the risk of infection for residents and field staff associated with home visits. The three IRBs associated with the study (Advarra, Mount Sinai, and University of Illinois Chicago) reviewed and approved the modified approach before it was initiated. The COVID-19 protocol modification is included in **Appendix C, COVID-19 Protocol Modification**.

Because the first two air sampling visits had been conducted before the pandemic began, residents were familiar with the air sampling process. For visits during the pandemic, which were easier to schedule with residents because less time in the dwelling was needed, all equipment and containers were disinfected before and after each use. Immediately before each scheduled visit, the data collectors assembled the equipment in a sanitized plastic bin. The bin was left outside each resident's apartment for the resident to retrieve and deploy inside while study personnel watched from outside. The researchers were available by telephone during deployment to answer any questions, an approach that was found to be very effective.

The residents were asked to take the assembly out of the bin, place it in the same location where it had been placed at the previous visit, and plug it into an electrical outlet. The total weight of the bin and equipment was approximately 8 pounds; although it is possible that individuals with disabilities or elderly individuals might have struggled with deploying the equipment, no such instances were reported. Interestingly, the time required for participants to deploy the equipment in their homes (typically a few minutes) was less than field staff needed during the previous visits because all equipment was assembled in advance. Once the equipment had been deployed, the resident called the researchers to let them know the equipment setup was complete. After the notification, the study team departed. Health interviews were conducted via telephone. In some cases in

New York, participants asked the researchers to enter their apartment to set up or retrieve the equipment.

Study personnel returned 4 days later to collect the equipment, including samples. Precautions during delivery and pickup of equipment included mask wearing, use of hand sanitizer, social distancing, and other precautions. After study personnel explained why such precautions were important, residents acknowledged and appreciated the care being taken. Overall, participants were grateful to be able to continue participating in the study.

2.6.5 Resident Notification of Sampling Results

To engage with study participants, upon completion of the environmental sampling and dwelling performance (ventilation) testing, NCHH mailed a letter to each household containing the results for that household after the completion of each phase. Each letter included comparison values for all contaminants except $PM_{2.5}$. The research team did not identify any consensus indoor air guidance for $PM_{2.5}$ at the start of the study. The letter also included a page of actions that residents can take to reduce contaminant levels and contact information to allow residents to follow up with questions (see **Appendix D, Template Resident Letter With Air Sampling Results**).

2.7 Participant Retention Rates

Enrollment and data collection for the STOVE study began in November 2018 and continued until March 2020, when field work was paused because of COVID-19 pandemic restrictions. As of March 2020, 76 study dwellings and 84 comparison dwellings had been enrolled in the study. The study planned to enroll an additional 8 study dwellings in New York City, but those plans were canceled due to the pandemic. The final number of developments and dwellings enrolled by site are presented in **Table 2-2**.

Table 2-2. Final Number of Developments and Dwellings by Site

Study Group	Chicago	New York	Total
Study	1 development 43 dwellings	2 developments 33 dwellings	3 developments 76 dwellings
Comparison	4 developments 42 dwellings	5 developments 42 dwellings	9 developments 84 developments
Total	5 developments 85 dwellings	7 developments 75 dwellings	12 developments 160 dwellings

When data collection was paused due to COVID-19, the study teams had completed 160 Phase 1 visits (76 study and 84 comparison dwellings), 127 Phase 2 visits (62 study and 65 comparison dwellings), and 87 Phase 3 visits (38 study and 49 comparison dwellings). Field collection resumed in July 2020 using the COVID-19 protocols described in section **2.6.4, Data Collection During the COVID-19 Pandemic**, and ended in September 2020. The field collectors completed 24 Phase 3 visits using the modified protocols (18 study and 6 comparison dwellings) for a total of 111 Phase 3 visits (56 study and 55 comparison dwellings).

The overall study had target retention rates of 78% for Phase 2 and 62% for Phase 3. The field collectors achieved the retention rates listed in **Table 2-3**, which exceeded nearly all of the study targets.

Table 2-3. Retention Rates

Phase	Retention Target	Study Group Actual Retention	Comparison Group Actual Retention
2	78%	82%	77%
3	62%	74%	65%

2.8 Data Processing

Following final laboratory analyses and quality control efforts, the study team closed the dataset in December 2020. The quality control efforts included environmental sampling reliability assessments (e.g., an indoor CO_2 reading cannot be substantially lower than outdoor levels), assessment of sufficient data collection when dataloggers were used, and statistical outlier analyses. Following the assessments, a few results were excluded from the dataset (see **Table 2-4**).

Table 2-4. Results Excluded From Final Dataset

Contaminant	Results Excluded	Reason(s)
Nitrogen dioxide (NO_2)	8	8 readings had extreme outliers.
Particulate matter 2.5 micrometers or less in diameter ($PM_{2.5}$)	11	8 samplers stopped functioning within 24 hours. 3 readings had extreme outliers.
Carbon dioxide (CO_2)	12	1 sampler stopped functioning within 24 hours. 11 readings were too low compared to outdoor levels.
Carbon monoxide (CO)	10	10 samplers stopped functioning within 24 hours.
Formaldehyde	4	4 readings had extreme outliers.

Because the primary focus of the study was to assess the effect of ventilation on indoor air quality and the downstream effects on health, a requirement was established that dwelling performance (ventilation) test data had to be available for a dwelling to be included in the final dataset. Eight dwellings (three study and five comparison dwellings) were excluded from analysis because a dwelling performance (ventilation) test could not be scheduled with the resident, despite numerous attempts. Four other visits were excluded because no household usage data (i.e., gas stove use, window use, smoking during sampling) could be collected.

The final dataset included data from 152 dwelling units (73 study and 79 comparison dwellings) and included data from 151 Phase 1 visits, 122 Phase 2 visits, and 106 Phase 3 visits. Data for all three phases were available for 98 dwellings (51 study and 47 comparison dwellings).

2.9 Statistical Methods and Candidate Variables

2.9.1 Analytical Methods

Repeated measures multivariable regression models were used to identify predictors of log-transformed contaminant levels while controlling for the lack of independence of measurements in the same home at different visits. Two different tracks of multivariable models were developed for each contaminant. The first retained the variable comparing study group to comparison group regardless of the significance of its effect. Those models did not include other unit or bathroom-related ventilation variables. A sub-analysis to the first track of models allowed kitchen ventilation variables to enter the model to determine whether they added information beyond the study group. The second track of models allowed all variables, including ventilation variables, to enter or drop from the model according to their significance.

First, to develop the multivariable models, simple repeated measures models (bivariate analyses) were run to predict the log-transformed contaminant based on each potential predictor. Potential predictors were identified initially by expert opinion of factors that might reasonably affect a contaminant. For the models that retain study group regardless of significance, simple repeated measures models were run to predict the log-transformed contaminant based on each potential predictor while controlling for study group. For the other models, study group was not included in the bivariate analysis. Covariates with an observed significance level (*P* value) of .2 or less were considered candidate variables for the multivariable models. The list of candidate variables by contaminant are presented in section **2.9.2, Candidate Variables for Analysis**. Furthermore, for any factor that could act only in a single direction, the direction of the relationship was assessed to determine if it was reasonable. For example, smoking would only be expected to increase indoor contaminant levels; a negative bivariate relationship for such a case was excluded.

Second, candidate variables were added into a model, and a backward stepwise elimination was conducted to drop nonsignificant variables. If variables were closely related to each other, sub-analyses were conducted to select the best one for inclusion. Variables that met a $P < .1$ criterion were retained preliminarily. Once again, the same directionality conditions were applied; if a variable changed to an illogical direction, it was eliminated from further model runs.

Third, a forward stepwise procedure was applied to determine if any variables should be added to the preliminary model. The backward and forward steps were repeated if needed.

Last, regression diagnostics were analyzed to assess model validity. Variables that depended on extreme values to meet the $P < .1$ criteria were eliminated from further modeling. If any variable was eliminated, a final forward regression step was applied to make sure all possible variables were considered. Results that have a *P* value of < .05 are reported as significant. Results with a *P* value of .05 to < .1 are reported as marginally significant.

None of the models initially included a site effect. As a final check, the site effect variable was added to each model to ascertain whether site differences remained significant after controlling for the predictors.

Whenever possible, the power of the SAS® statistical software was employed to select the best predictor. For example, if nicotine concentration was expected to be a better predictor of a contaminant than smoking, but the analysis found that only one of the variables could be retained and smoking had the stronger association, then smoking was retained, and the nicotine variable was eliminated.

Several other statistical methods were used to test for differences between study and comparison group homes and occupants. Chi-squared tests were used to check for a difference between the distributions of study and comparison group homes or occupant attributes (e.g., person ever diagnosed with asthma [yes/no]). Two-sample t-tests were used to test for a difference in the mean scores between study and comparison home occupants (e.g., adult physical health score from the SF-36). Two-sample Wilcoxon tests were used to test for a difference in the median values between the study and comparison groups (e.g., median adult age). The Holm-Bonferroni method was used to adjust for multiple comparisons (see sections **3.8, Assessing the Effect of Study Group on Contaminants by Adjusting for Multiple Comparisons**, and **3.9, Health Interview Findings**).

Missing values for some independent variables were addressed as follows: If 10 or fewer values for a variable were missing, the missing value was replaced with the average value from the same property. If more than 10 values for a variable were missing, multiple imputation with 10,000 replicates was used. No dependent variables (contaminant levels) were imputed.

2.9.2 Candidate Variables for Analysis

Table 2-5 lists the candidate variables that were considered for each contaminant in the multivariable models.

Table 2-5. Variables Meeting Eligibility Criteria for Inclusion in Models (i.e., Bivariate $P < .2$)

Variable	Nitrogen Dioxide (NO_2)	Particulate Matter ($PM_{2.5}$)			Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Formaldehyde
		All	Low Nicotine[a]	High Nicotine[a]			
Ventilation Measures							
Exhaust air changes per hour (ACH) (kitchen and bath)	✓	✓	✓	✓	✓	✓	✓
Exhaust ACH (kitchen and bath) > 0 (yes/no)					✓		✓
Bathroom exhaust ACH		✓	✓	✓	✓	✓	
Bathroom exhaust ACH > 0 (yes/no)	✓					✓	
Kitchen exhaust ACH	✓				✓		✓
Kitchen exhaust ACH > 0 (yes/no)	✓					✓	
Total air exchange ACH (includes infiltration)	✓	✓	✓	✓	✓	✓	✓
Total air exchange ACH (includes infiltration) > 0 (yes/no)							✓
Percent compliance with ASHRAE Standard 62.2-2016					✓	✓	
At least 50% ASHRAE compliance (yes/no)					✓	✓	✓
At least 90% ASHRAE compliance (yes/no)					✓	✓	✓
At least 100% ASHRAE compliance (yes/no)	✓	✓	✓	✓	✓	✓	✓
Inclusion in study group (yes/no)		✓	✓		✓		✓
Inclusion in study group (modified)[b] (yes/no) (not relevant for models with study group included)	✓	✓	✓		✓	✓	✓

Continued on page 58

Table 2-5, continued

Variable	Nitrogen Dioxide (NO_2)	Particulate Matter ($PM_{2.5}$)			Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Formaldehyde
		All	Low Nicotine[a]	High Nicotine[a]			
On-Demand Ventilation Measures							
Bathroom fan used always[c] (yes/no)	✓	✓		✓	✓	✓	✓
Bathroom fan used always/frequently[c] (yes/no)		✓	✓	✓	✓	✓	
Bathroom fan left on all the time during 4 days of sampling (yes/no)		✓	✓	✓	✓	✓	✓
Bathroom fan used after shower/bath during 4 days of sampling (yes/no)	✓	✓	✓	✓	✓	✓	✓
Stove fan used always[c] (yes/no)	✓	✓	✓	✓	✓	✓	✓
Stove fan used always/frequently[c] (yes/no)	✓	✓	✓	✓	✓		✓
Stove fan used when cooking during 4 days of sampling (yes/no	✓	✓	✓	✓	✓		
Natural Ventilation Measures and Leakage							
Windows or doors kept open during 4 days of sampling (yes/no)		✓	✓	✓	✓		✓
Opened windows ≥ 4 hours per day during 4 days of sampling (yes/no)		✓	✓	✓	✓		✓
Opened windows ≥ 12 hours per day during 4 days of sampling (yes/no)		✓	✓	✓	✓		✓
Opened windows during 4 days of sampling (yes/no)	✓	✓	✓	✓	✓		✓
Total air infiltration ACH		✓	✓	✓			✓

Continued on page 59

Table 2-5, continued

Variable	Nitrogen Dioxide (NO_2)	Particulate Matter ($PM_{2.5}$)			Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Formaldehyde
		All	Low Nicotine[a]	High Nicotine[a]			
Cubic feet per minute at 50 pascals (cfm_{50}) per square foot of building envelope		✓	✓	✓			
Outdoor Pollutants (Only Eligible for Matching Indoor Contaminant)[d]							
Log outdoor NO_2 (ppb)	✓						
Log outdoor $PM_{2.5}$ (μg/m³) (did not meet criteria for inclusion)							
Log CO outdoor mean (ppm)						✓	
Log CO outdoor max (ppm)						✓	
Gas Stove Usage							
Number of cooked meals during 4 days of sampling	✓				✓	✓	✓
Cooked any meals during 4 days of sampling (yes/no)	✓				✓	✓	✓
Cooked ≥ 4 meals during 4 days of sampling (yes/no)	✓				✓	✓	
Cooked ≥ 8 meals during 4 days of sampling (yes/no)	✓				✓	✓	✓
Smoking							
Log nicotine (μg/m³)	✓	✓	✓	✓		✓	✓
Smoked or vaped in the home during 4 days of sampling (yes/no)		✓	✓	✓			
Any smoke in the home during last 12 months[e] (yes/no)	✓	✓	✓	✓			

Continued on page 60

Table 2-5, continued

Variable	Nitrogen Dioxide (NO_2)	Particulate Matter ($PM_{2.5}$)			Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Formaldehyde
		All	Low Nicotine[a]	High Nicotine[a]			
Smoke from tobacco cigars, cigarettes, e-cigarettes, or pipes in the home during last 12 months[c] (yes/no)	✓	✓		✓			
Smoking allowed in the home[e] (yes/no)	✓	✓		✓			
Number of people who live in the household and currently smoke cigarettes, e-cigarettes, cigars, or pipes[c]	✓	✓		✓			
Number of days of the past 30 days that anyone has smoked anywhere inside the home[e]	✓	✓					
Other Factors							
Number people that live in the home at least 5 nights per week		✓	✓	✓	✓		✓
Number people at least 5 years old that live in the home at least 5 nights per week		✓	✓	✓	✓		✓
Square footage of living space	✓				✓		✓
Square footage of living space per occupant		✓	✓	✓	✓		✓
Story (floor) of dwelling					✓	✓	✓
Number of stories in building			✓		✓	✓	✓
Resident noticed musty smells inside the home more than a few times[c] (yes/no)		✓	✓	✓			

Continued on page 61

Table 2-5, continued

Variable	Nitrogen Dioxide (NO_2)	Particulate Matter ($PM_{2.5}$)			Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Formaldehyde
		All	Low Nicotine[a]	High Nicotine[a]			
Average indoor relative humidity (%) during 4 days of sampling				✓		✓	✓
Average indoor temperature (°F) during 4 days of sampling				✓			✓
Season (winter, spring, summer, fall)	✓		✓		✓	✓	✓
Door left open for circulation during 4 days of sampling (yes/no)							✓
Room air filtration device present in the home[f] (yes/no)					✓		
Air deodorants or filters present in the home[f] (yes/no)				✓			

Key: µg/m³ = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter; ppb = parts per billion; ppm = parts per million

[a] Low nicotine is < 0.1 µg/m³. High nicotine is ≥ 0.1 µg/m³.

[b] Dwelling performance (ventilation) tests determined that five comparison dwellings with intermittent mechanical performed similarly to the study group. The effect of treating these five dwellings like study group units was analyzed.

[c] Collected at each visit.

[d] Bivariate tests were not conducted when no reasonable causal pathway existed (e.g., outdoor $PM_{2.5}$ would not affect indoor NO_2). Cells are shaded for those variables.

[e] Collected during the Phase 3 visit only.

[f] Collected during the Phase 1 visit only

3 Results

3.1 Characteristics of Participants

The study participants all were residents of affordable housing and primarily were persons of color. The demographics between the study and comparison groups did not differ significantly, except for the median adult age, which was marginally significantly higher for the study group (see **Table 3-1**).

Table 3-1. Participant Characteristics

Participant Numbers	Study Group	Comparison Group
Number of adults — Phases 1, 2, 3	78, 65, 58	90, 72, 59
Number of children — Phases 1, 2, 3	31, 24, 27	39, 30, 24
Participant Demographics	**Study Group**	**Comparison Group**
Median household income (*P* = .904)	\$10,000–\$19,999	\$10,000–\$19,999
Median adult age (*P* = .095)	44 years	35 years
Adult education more than high school graduate or GED (*P* = .234)	52%	43%
Adult race (*P* = .463)		
Black	67%	68%
White	23%	17%
Other	10%	15%
Adult is Hispanic, Latino, or Spanish (*P* = .450)	44%	49%

3.2 Characteristics of Buildings and Ventilation Testing Results

3.2.1 Visual Assessment Results

The visual assessment, which consisted of approximately 40 inspectable items, was conducted to evaluate overall conditions at the home. The conditions were recorded by members of the study team at the enrollment visit. No immediate dangers were identified in any of the buildings. Most of the differences in the buildings' inspectable items between the study and comparison groups were small, so the overall visual condition between the two groups was generally equivalent. This aligns with expectations that the main differences between the two groups would be their ventilation systems. Visual assessment findings are presented in **Table 3-2**.

Table 3-2. Visual Assessment Findings

Dwelling Condition or Characteristic	Study Group	Comparison Group
Windows not intact or cannot be opened	5%	0%
Window sill missing or damaged	1%	4%
Window caulking failure	1%	13%
Door surface damaged	3%	12%
Holes in walls, ceilings, or floors	3%	8%
Peeling/nonintact paint on walls, ceilings, or floors	8%	21%
Water stains/damage on walls, ceilings, or floors	9%	13%
Condensation on windows, doors, or walls	0%	0%
Bedroom carpet damp to touch	0%	0%
Room dehumidifier present	5%	2%
Room humidifier present	13%	14%
Moldy or musty odor present	11%	5%
Visible mold present	0%	7%
Gas-fired water heater in dwelling	33%	25%
Gas-fired water heater exhaust vent misaligned	8%	0%
Gas-fired heating equipment in dwelling	61%	46%
No air conditioning in dwelling	5%	21%
If air conditioning present —		
Central air conditioning	63%	38%
Window air conditioner(s)	37%	62%
Room air filtration device in dwelling	8%	4%
Space heaters present	4%	5%
Unvented combustion appliances present	0%	1%
Garbage/debris in dwelling not properly stored	15%	29%
Kitchen plumbing leak	0%	6%
Kitchen floor carpeted	5%	4%
Bathroom plumbing leak	3%	4%
Bathroom floor carpeted	0%	2%
Cockroaches observed	3%	1%
Other insects or vermin observed	3%	1%
Air freshener or deodorant present	68%	63%

Continued on page 64

Table 3-2, continued

Dwelling Condition or Characteristic	Study Group	Comparison Group
Tobacco butts, smoke, or odor present	21%	11%
Dust on surfaces in rooms	50%	65%
Clutter present	66%	68%

3.2.2 Ventilation Measurement Results

The study group consisted of homes with bathroom mechanical exhaust vented to the exterior that operated continuously to provide enough airflow not only to exhaust the bathroom, but also to ventilate the entire dwelling unit. Study participants were asked to leave the bathroom doors open during the sampling period when the bathroom was not in use. Additionally, some study group dwellings had kitchen exhaust that was vented to a continuously operating roof exhaust fan (24%). Most other study group dwellings had a recirculating range hood that was not vented to the outdoors (73%).

The comparison group dwellings had ventilation insufficient to meet the ASHRAE Standard 62.2 requirement. Except for five dwellings that had timed intermittent exhaust ventilation, the comparison group dwellings relied on passive airflow through building leakage and/or on-demand (resident-controlled) bathroom ventilation, which is typical of much of the U.S. housing stock. The majority of comparison group dwellings had a recirculating kitchen range hood (82%).

The mean air exchange rate for the study group dwellings in both Chicago and New York City was 0.65 ACH in apartments and 0.53 ACH in townhomes. **Table 3-3** summarizes the ventilation rates for the different types of building unit configurations. In general, study group units had continuous mechanical ventilation, while comparison group units did not have such ventilation. This means that most apartments in the comparison group had zero air exchange known to be from outdoor air. However, five comparison group units had timed intermittent ventilation that resulted in measurable air exchange. For some supplemental analyses, these five units were combined with the study group units to assess the effect of either continuous ventilation or intermittent ventilation, compared with units without either type of ventilation.

Table 3-3. Raw Unadjusted Geometric Mean Ventilation Levels by Ventilation Group and Sampling Site

	Number of Dwellings	Percent Exhaust Measured[a]	Mean Total ACH[b]	Mean Exhaust ACH[c]	Mean Kitchen ACH[d]
New York	75				
Units with CIMV[e]	38	68%	0.65	0.65	0.39
Units without CIMV	37	NA	0	0	0
Chicago	77				
Units with CIMV[f]	40				
Apartment units	22	91%	0.65	0.65	0
Townhome units	18	83%	0.49	0.53	0
Units without CIMV	37	NA	0	0	0
Apartment units	32	NA	0	0	0
Townhome units[g]	5	NA	0.42	0	0
TOTAL	152				

Key: ACH = air changes per hour; CIMV = continuous (or intermittent) mechanical ventilation; NA = not applicable

[a] Percent of visits to a study unit where exhaust could be measured

[b] Total ACH from outdoor air, including exhaust air exchange and building leakage

[c] Dwelling unit ACH from outdoor air from bathroom and kitchen exhaust (measured units only)

[d] Dwelling unit ACH from outdoor air from kitchen exhaust only (measured units only)

[e] Rooftop fans were ducted to 100% of bathrooms and 85% of kitchens in measured units

[f] Bathroom exhaust fans

[g] The ASHRAE standard allows an infiltration credit for townhomes

3.2.3 Presentation of Results

Sections **3.3, NO_2 Findings**; **3.4, $PM_{2.5}$ Findings**; **3.5, CO_2 Findings**; **3.6, CO Findings**; and **3.7, Formaldehyde Findings** describe the outcomes for each of the five contaminants studied. As outlined in the **Methods** section, each analysis had six statistical models prepared. The first model considered the effect of study group on the contaminant level. Study group was retained in this model regardless of its level of significance, and no other measure of mechanical ventilation was allowed to enter the models. This model was prepared to address the central question of this study: Does continuous mechanical ventilation designed to comply with ASHRAE Standard 62.2 have a significant effect on contaminant levels? After the initial model was prepared, the influence of study site (Chicago vs. New York) was tested in an alternate version of the first model. Site was added at the end in case an unmeasured local factor might explain differences in contaminant levels. A third model considered the effect of kitchen exhaust ventilation on the contaminant. Kitchen exhaust ventilation is a form of mechanical ventilation present in a subset of the study group dwellings. Like the first model, study group was forced to remain in the model. If kitchen exhaust ventilation was not significant, the third model is not presented. If kitchen exhaust ventilation was significant, a fourth model with study site was prepared. A fifth model was prepared that allowed all measures of mechanical ventilation to be candidates. Study group was not forced into this model. If the study group as defined by the ASHRAE standard was not significantly associated with the contaminant but some other measure of ventilation — such as the air exchange rate, was significant — it would be reported here. A sixth model that added study site to the fifth model was prepared.

After these models were prepared, it was observed that the ventilation measures in the third and fifth models often were different and offered interesting insights into the impact of mechanical ventilation. It also was observed that the covariates/confounding factors were usually the same across the six models. If a factor — such as the frequency of use of the gas stove or the opening of windows — was significant in one model, it was commonly significant in the other models. Within each section of results, the variables that are statistically significant in the models are **bolded**.

To streamline the presentation of this information, each individual model is not discussed in the text. Instead, the significant covariates across the models for a contaminant are reported with a range of the effect size and a range of the level of statistical significance (e.g., *P* value). For example, across the CO_2 models, cooking at least one meal on the gas stove increased CO_2 between 11% and 12%, with a *P* value that ranged from .035 to .052. The model output with all of the covariates for each model, the coefficients, and the *P* values are available at the end of each section.

3.3 NO_2 Findings

3.3.1 Background

NO_2 is a byproduct of the incomplete combustion of fossil fuels. Combustion generates NO, which can form NO_2 in the presence of free radical oxygen atoms. NO, NO_2, and most other compounds of nitrogen and oxygen — often referred to as NOx — are unstable. The main hypothesis of this study is that by adding sufficient whole-house mechanical ventilation (i.e., ventilation in the bathroom and/or kitchen sufficient to ventilate the whole dwelling), NO_2 levels would substantially decrease.

Outdoor NO_2 pollution comes from emissions from transportation sources (e.g., cars, trucks, buses, trains, planes, ships); electricity-generating power plants; on-site heating and cooling; industrial production; and natural sources, such as wildfires and controlled burns. Factors that affect the variation of local outdoor NO_2 in heavily urbanized areas include the density of on-road traffic, especially diesel-fueled traffic, and the density of buildings with fossil-fuel fired boilers for heating. The large multistory buildings in New York often have older inefficient oil and natural gas boilers that produce substantial amounts of NOx. Outdoor NO_2 levels are a main contributor to indoor levels in homes without gas appliances. A main source of indoor NO_2 is from gas stoves and other combustion sources. See the **Introduction** section for more information on exposure limits and toxicity.

3.3.2 Measured NO_2 Levels

The geometric mean (GM) indoor NO_2 level was 25.5 ppb overall (both study and comparison dwellings) — 23.8 ppb in Chicago and 27.6 ppb in New York. The GM outdoor NO_2 level (as measured at EPA ambient air monitoring stations) was lower than indoors: 12.8 ppb overall — 12.9 ppb in Chicago and 12.7 ppb in New York. The GM indoor/outdoor ratio (a ratio of 1 means the indoor levels equaled the outdoor levels) was 2.0 overall — 1.8 in Chicago, and 2.2 in New York. See **Figure 3-1** for box-and-whisker plots comparing study and comparison homes.

3.3.3 Results of Multivariable Modeling of NO_2

Variables significantly related to NO_2 are presented in **Table 3-4**. Detailed results related to NO_2 are presented in **Table 3-5** and **Table 3-6** in section **3.3.5, Detailed NO_2 Multivariable Results**.

Mitigation

Multivariable modeling showed that when study group dwellings were compared with comparison group dwellings, controlling for all other significant factors, no study effect on NO_2 level was seen (adjusted study and comparison GMs were 25.5 ppm and 25.2 ppm, respectively; $P = .828$). The study effect remained nonsignificant when this analysis also controlled for the location of the dwellings (Chicago vs. New York) ($P = .703$). When other measures of mechanical ventilation were assessed, again, no significant effects on NO_2 were observed.

The use of windows was shown not to be related to the levels of NO_2 in the dwellings.

Sources of NO_2

Three sources of NO_2 — outdoor NO_2, cooking with a gas stove, and smoking — were significantly associated with NO_2 levels in the models:

- **Log outdoor NO_2** ($P < .001$). Indoor NO_2 increased 2% for each 10% increase in outdoor NO_2. After controlling for other factors, indoor NO_2 increased 14% from summer to winter based on the summer GM outdoor level (9.1 ppb) and the winter GM outdoor level (16.7 ppb).
- **Gas stove usage** as measured by number of meals cooked ($P < .001$). Indoor NO_2 increased 13% for each additional meal cooked per day. In other words, a dwelling where eight meals were cooked on the stove during the 4-day sampling period had 13% higher NO_2 than a dwelling where four meals were cooked. Residents reported cooking an average of 4.3 meals per sampling period in study units and 4.8 meals per sampling period in comparison units.
- **Smoking** as measured by report of tobacco smoke in the dwelling in the year before the final visit ($P = .047$). Indoor NO_2 was 19–20% higher in dwellings where tobacco smoke was reported in the past year than in dwellings without tobacco smoke. Smoking was reported in 11% of study dwellings and 22% of comparison dwellings.

Other Factors

The **size (square footage) of the dwelling** was a marginally significant variable ($P = .088$). For each additional 100 sq. ft. of floor area in a dwelling, NO_2 levels declined by 2%.

Site Effect

As a final step in the modeling process, **sampling site (Chicago or New York)** was tested as a possible factor. For NO_2, site was a marginally significant factor, with New York having higher NO_2 levels than Chicago ($P = .093$ [see **Table 3-5**] and .098 [see **Table 3-6**]). When site was added, square footage of the dwelling dropped out of the models. New York dwellings were smaller than Chicago dwellings. Prior studies have found that NO_2 levels decline as dwelling size increases. It remains unclear if the dwelling size effect or some other unexplained factor related to site influenced NO_2 levels.

Table 3-4. Variables Significantly Related to Nitrogen Dioxide[a]

Variable	n Total (Study, Comparison)	Overall (95% CI)	Study (95% CI)	Comparison (95% CI)	*P* Value[b]
Indoor NO_2 (GM) (ppb)	370 (182, 188)	25.5 (24.3, 26.7)	25.6 (24.0, 27.4)	25.3 (23.7, 27.0)	.836
Outdoor NO_2 (GM) (ppb)	370 (182, 188)	12.8 (12.3, 13.3)	13.6 (12.9, 14.4)	12.0 (11.4, 12.7)	<.001
Mean number of meals cooked with stove (during sampling)	370 (182, 188)	4.5 (4.2, 4.9)	4.3 (3.8, 4.8)	4.8 (4.2,5.3)	.268
% visits to dwellings with tobacco smoke in past year[c]	301 (156, 145)	17% (13%, 21%)	12% (7%, 17%)	23% (16%, 30%)	.011
Mean square footage of dwelling	370 (182, 188)	815 (793, 838)	814 (786, 843)	816 (781, 851)	.956
% visits to dwellings located in Chicago	370 (182, 188)	54% (49%, 59%)	58% (51%, 65%)	50% (43%, 57%)	.138

Key: CI = confidence interval; GM = geometric mean; n = number of visits; NO_2 = nitrogen dioxide; ppb = parts per billion

[a] Variable significantly related to NO_2 in multivariable modeling

[b] *P* value for the tests that the variable was different in study and comparison homes.

[c] Participants were interviewed during Phase 3 about their smoking; their responses were applied to their Phase 1 and Phase 2 visits. Because 47 of 152 participants were no longer participating in the study during Phase 3, 69 Phase 1 and Phase 2 visits did not have smoking data. Participants reported tobacco smoke in the dwelling during the past year for 17% of the 301 visits with associated smoking data. Additionally, 16% of dwellings, or 105 units, reported tobacco smoke in the dwelling during the past year.

3.3.4 Interpretation of NO_2 Results

Effect of Continuous Mechanical Ventilation

The primary hypothesis of this study was that the addition of whole-house, continuous mechanical ventilation (i.e., ventilation in the bathroom or kitchen sufficient to ventilate the whole dwelling) to dwellings with a gas stove would substantially reduce NO_2 levels through the removal of air containing NO and NO_2 and its replacement with outdoor air containing lower levels of NO_2. In this study, indoor NO_2 was significantly related to the use of gas stoves. As the number of meals cooked with a gas stove during the sampling period increased, both the GM indoor NO_2 levels and the indoor/outdoor NO_2 ratio increased. This supports prior research findings that greater gas stove usage can increase indoor NO_2 levels.

However, no significant difference in NO_2 levels was found between the study group (with continuous mechanical ventilation) and the comparison group (without continuous mechanical ventilation). Based on prior studies and simulations, NO_2 levels were expected to be 4.7 ppb lower in the study group than in the comparison group. Instead, GM NO_2 levels were nearly the same between the two groups (*P* = .956). Several factors — such as season, outdoor NO_2 levels, and indoor air chemical reactions — might have influenced the effect of ventilation.

Winter Effects

The properties studied were located in high-traffic areas of highly urbanized cities. The information used to build the study's hypothesis, which included data from EPA's outdoor air monitoring system, suggested that outdoor ambient air in such locations would contain substantially lower levels of NO_2 than air found in dwellings with gas stoves. Therefore, ventilation was expected to reduce indoor NO_2 levels. However, in 27% of winter visits in Chicago and 17% of winter visits in New York, outdoor NO_2 levels *exceeded* indoor NO_2 levels. Furthermore, recent data from the New York City Community Air Survey (NYCCAS) show that average outdoor NO_2 levels at *street level* in New York generally exceeded 23 ppb during winter, whereas the average ambient NO_2 levels as measured by EPA monitors, which typically are located on building roofs, was 17.8 ppb (see section **3.3.6, Comparison of U.S. Environmental Protection Agency Air Monitoring in New York City and New York City Department of Health and Mental Hygiene Air Monitoring**). If the street-level monitors used in NYCCAS are more representative of the content of the air that infiltrates buildings, the indoor/outdoor NO_2 differential for dwellings with gas stoves would be lower than in the earlier studies. Thus, the dilution of indoor air through improved ventilation would have a more limited impact during winter. Community-level NO_2 data are not available for Chicago but, based on the ambient NO_2 levels measured by Illinois and published by EPA, as well as the levels of street traffic in Chicago, community levels of outdoor NO_2 likely are generally similar to or slightly lower than those in New York.

Summer Effects

The indoor/outdoor NO_2 differential was much larger during summer than during winter. Based on EPA monitoring data, outdoor NO_2 was 44% lower during summer than during winter, yet indoor NO_2 was only 6% lower during summer. Continuous mechanical ventilation did not change between seasons; if any difference in total air exchange would be expected, total air exchange should have increased during summer because of increased window usage. The primary impetus for whole-house ventilation is that, when dwellings are made more energy efficient, natural ventilation through the building envelope leakage declines such that mechanical ventilation is necessary for proper air exchange with outdoor air. The study design assumed that in green, energy-efficient dwellings, window usage would have been limited. Furthermore, residents were asked to refrain from using their windows during each 4-day sampling period. However, residents were more likely to open their windows during the summer sampling periods (60%) than during winter (40%). Even with much more window usage than expected by the study design, window usage was not statistically associated with indoor NO_2 levels.

Further research is needed to determine if outdoor O_3 or oxides that were not measured in the STOVE study may have played a role in the higher indoor/outdoor NO_2 ratio during summer. NO_2 and its related compounds — including NO, the main nitrogen-based byproduct of gas stove emissions — are very reactive. In the presence of other free radical compounds, NO can convert to NO_2. O_3 also is very reactive and results in a common chemical reaction: $NO + O_3 \rightarrow NO_2 + O_2$. Pre-study research suggested that in weatherized dwellings with tighter building envelopes, indoor levels of O_3 would be insufficient to have a substantial effect on indoor NO_2 generation. However, given the open-window conditions in both New York and Chicago during summer sampling, this may be incorrect; NYCCAS and EPA both reported higher O_3 levels during summer than during winter. One study suggested that 70% of outdoor O_3 could have migrated indoors. This may increase the rate of reactions with NO generated by gas stove use, thus increasing indoor NO_2 levels. The anticipated ventilation/dilution effect of lower outdoor NO_2 may have been countered by the effect of $NO–O_3$ reactions.

Previous simulation analyses[108–110] estimated a significant and substantial reduction in NO_2 when residential air exchange rates increased in homes with gas stoves, especially when kitchen exhaust ventilation was utilized. The STOVE study did not show a reduction, possibly because NO_2 samples were not collected

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[108] Logue JM, Klepeis NE, Lobscheid AB, Singer BC. Pollutant exposures from natural gas cooking burners: a simulation-based assessment for Southern California. *Environ Health Perspect*. 2014;122(1):43-50. doi:10.1289/ehp.1306673

[109] Li R, Weller E, Dockery DW, Neas LM, Spiegelman D. Association of indoor nitrogen dioxide with respiratory symptoms in children: application of measurement error correction techniques to utilize data from multiple surrogates. *J Expo Sci Environ Epidemiol*. 2006;16(4):342-350. doi:10.1038/sj.jes.7500468

[110] Fabian P, Adamkiewicz G, Levy JI. Simulating indoor concentrations of NO(2) and PM(2.5) in multifamily housing for use in health-based intervention modeling. *Indoor Air*. 2012;22(1):12-23. doi:10.1111/j.1600-0668.2011.00742.x

immediately outside of the studied properties, and no data were collected on NO and O_3 levels. Further research is needed to understand the relationship of outdoor NO_2 on indoor NO_2 in dense urban areas across seasons and to assess the potential effect of indoor chemical reactions on NO_2 generation during periods when outdoor O_3 and oxide levels are elevated.

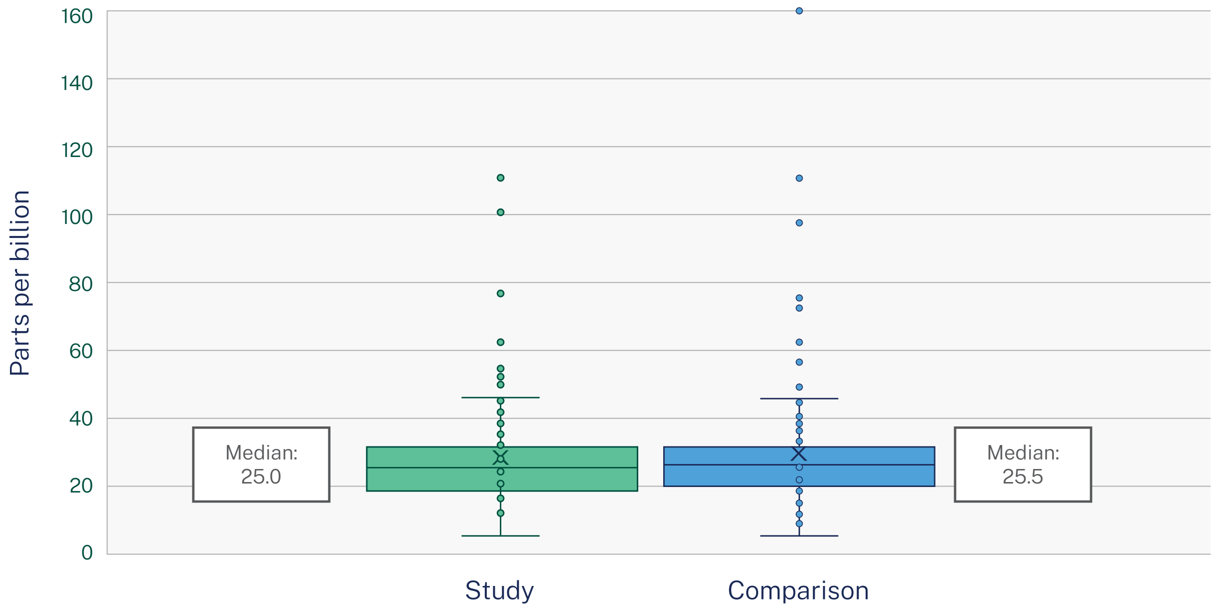

Figure 3-1. Nitrogen dioxide levels by group — unadjusted data.

Note: The STUDY group contains one additional data point — 360 ppb — that is not displayed.

Interpretation: The top, middle, and bottom of each box are the 75th, 50th (median), and 25th percentiles, respectively. The interquartile range (IQR) is the difference between the 75th and 25th percentiles. The whiskers (vertical lines) extend from the ends of the box to the minimum value and maximum value that are within 1.5 times the IQR. Observations beyond 1.5 times IQR are considered outliers and are dots on the plot.

3.3.5 Detailed NO_2 Multivariable Results

Table 3-5. Predictors of Log Indoor Nitrogen Dioxide (Parts Per Billion) — Study Group Forced Into Model (n = 370 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	2.686 (2.308, 3.063)	<.001	2.656 (2.278, 3.034)	<.001
Study group (vs. comparison group)	0.012 (-0.102, 0.126)	.828	0.021 (-0.092, 0.135)	.703
Log outdoor NO_2 (ppb)	0.217 (0.100, 0.333)	<.001	0.218 (0.101, 0.334)	<.001
Number of meals cooked	0.031 (0.018, 0.044)	<.001	0.029 (0.016, 0.043)	<.001
Any tobacco smoke in dwelling in past year	0.179 (0.003, 0.354)	.047	0.177 (0.002, 0.352)	.047
Square feet of living space (thousands)	−0.220 (−0.475, 0.035)	.088	−0.114 (−0.397, 0.169)	.414
Site: Chicago (vs. New York)			−0.107 (−0.232, 0.019)	.093

Key: NO_2 = nitrogen dioxide; ppb = parts per billion

Table 3-6. Predictors of Log Indoor Nitrogen Dioxide (Parts Per Billion) — All Ventilation Variables Eligible (n = 370 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	2.689 (2.314, 3.065)	<.001	2.656 (2.278, 3.034)	<.001
Log outdoor NO_2 (ppb)	0.218 (0.103, 0.351)	<.001	0.220 (0.105, 0.335)	.703
Number of meals cooked	0.031 (0.018, 0.044)	<.001	0.029 (0.016, 0.042)	<.001
Any tobacco smoke in dwelling in past year	0.177 (0.003, 0.351)	.046	0.174 (0.001, 0.348)	<.001
Square feet of living space (thousands)	−0.221 (−0.475, 0.033)	.085	−0.118 (−0.400, 0.163)	.047
Site: Chicago (vs. New York)			−0.114 (−0.397, 0.169)	.414

Key: NO_2 = nitrogen dioxide; ppb = parts per billion

3.3.6 Comparison of U.S. Environmental Protection Agency Air Monitoring in New York City and New York City Department of Health and Mental Hygiene Air Monitoring

Data from the EPA air monitoring station closest to each property were used to determine outdoor NO_2 levels in this study. Because EPA data are reported daily, the average NO_2 level during all 4-day sampling periods could be calculated.[111] However, EPA monitoring devices generally are positioned on building roofs, which might not be representative of the NO_2 levels immediately outside each dwelling.

The New York City Department of Health and Mental Hygiene partnered with Queens College of the City University of New York in 2008 to begin collecting air sampling data under the NYCCAS program.[112] NYCCAS monitors are placed at street level (10–12 feet off the ground), and in 2018, 93 locations across the city were being sampled. NYCCAS reports data by community district for the winter and summer seasons.[113]

Despite limitations inherent in comparing EPA and NYCCAS data, such a comparison could offer insights into potential differences between roof-level and street-level NO_2 levels. The street-level NYCCAS samples were consistently higher than the EPA ambient levels. When GM indoor levels for each housing development were compared to the concurrent EPA ambient data by season, the indoor levels often were 50% to more than 200% higher. When comparing them to the average NYCCAS street-level result for the community district where the development is located, the levels are much closer, especially during winter (see **Table 3-7**, **Table 3-8**, and **Table 3-9**).

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[111] Data usually are available about 3 months after collection, although they are not final for about 1 year. See *Interactive Map of Air Quality Monitors*. U.S. Environmental Protection Agency. Accessed November 8, 2021. https://www.epa.gov/outdoor-air-quality-data/interactive-map-air-quality-monitors.

[112] NYC Health. *New York City Community Air Survey*. City of New York. Accessed November 8, 2021. https://www1.nyc.gov/site/doh/data/data-publications/air-quality-nyc-community-air-survey.page

[113] The data used for this analysis are from winter 2018 and summer 2019.

Table 3-7. Winter Results

Housing Development	Community District	n	GM Indoor NO_2 (STOVE) (ppb)	GM Outdoor NO_2 (EPA) (ppb)	Indoor/ Outdoor Ratio (STOVE/ EPA)	GM Outdoor NO_2 (NYCCAS) (ppb)	Indoor/ Outdoor Ratio (STOVE/ NYCCAS)
A	Brklyn-2	11	26.9	17.9	1.50	24.7	1.09
B	Bronx-4	5	26.8	22.1	1.79	23.8	1.13
C	Bronx-5	11	26.8	15.0	1.21	23.1	1.16
D	Brklyn-5	7	41.9	18.2	2.30	21.2	1.98
E	Brklyn-4	4	41.4	17.2	2.41	23.9	1.73
F	Bronx-5	4	26.1	13.1	1.99	23.1	1.13
G	Bronx-1	1	23.0	23.0	1.00	25.0	0.92

Key: EPA = U.S. Environmental Protection Agency; GM = geometric mean; n = number of dwellings; NYCCAS = New York City Community Air Survey; ppb = parts per billion; STOVE = Studying the Optimal Ventilation for Environmental Indoor Air Quality (STOVE Study)

Note: Study group properties are shaded blue.

Table 3-8. Summer Results

Housing Development	Community District	n	GM Indoor NO_2 (STOVE) (ppb)	GM Outdoor NO_2 (EPA) (ppb)	Indoor/ Outdoor Ratio (STOVE/ EPA)	GM Outdoor NO_2 (NYCCAS) (ppb)	Indoor/ Outdoor Ratio (STOVE/ NYCCAS)
A	Brklyn-2	11	20.9	10.3	2.02	18.0	1.16
B	Bronx-4	17	28.3	12.6	2.25	15.4	1.84
C	Bronx-5	4	26.8	7.8	3.44	14.9	1.80
D	Brklyn-5	9	24.5	9.0	2.71	11.6	2.11
E	Brklyn-4	5	27.7	10.5	2.65	14.8	1.87
F	Bronx-5	6	26.3	8.2	3.22	14.9	1.77
G	Bronx-1	4	25.1	12.6	2.00	16.5	1.52

Key: EPA = U.S. Environmental Protection Agency; GM = geometric mean; n = number of dwellings; NYCCAS = New York City Community Air Survey; ppb = parts per billion; STOVE = Studying the Optimal Ventilation for Environmental Indoor Air Quality (STOVE Study)

Note: Study group properties are shaded blue.

Table 3-9. Comparison of EPA Air Monitoring Data and NYCCAS Air Monitoring Data

Housing Development	GM Outdoor NO_2 — Summer (NYCCAS) (ppb)	GM Outdoor NO_2 — Summer (EPA) (ppb)	Ratio NYCCAS/ EPA	GM Outdoor NO_2 — Winter (NYCCAS) (ppb)	GM Outdoor NO_2 — Winter (EPA) (ppb)	Ratio NYCCAS/ EPA
A	18.0	10.3	1.74	24.7	17.9	1.38
B	15.4	12.6	1.22	23.8	22.1	1.08
C	14.9	7.8	1.91	23.1	15.0	1.54
D	11.6	9.0	1.29	21.2	18.2	1.16
E	14.8	10.5	1.41	23.9	17.2	1.39
F	14.9	8.2	1.82	23.1	13.1	1.76
G	16.5	12.6	1.31	25.0	23.0	1.09

Key: EPA = U.S. Environmental Protection Agency; GM = geometric mean; NYCCAS = New York City Community Air Survey; ppb = parts per billion

Note: Study group properties are shaded blue.

This analysis has limitations. NYYCAS collects data in 59 community districts; with 93 samplers, each district is represented by only one or two samplers, and the sampler could be located on a street that differs in characteristics from the streets adjacent to the study dwellings. Additionally, EPA data used in the analysis are from the same 4-day periods as the study sampling periods, whereas NYYCAS results are seasonal averages from the first winter (2018–19) of the two study sampling periods (2018–19 and 2019–20) and the first summer (2019) of the study, when most summer samples were collected. NYYCAS reports seasonal averages from every day of the season, whereas the study data were collected during a limited number of 4-day periods. For half of the study data points, the GM results are based on data from five or fewer sampling periods. Despite these various limitations, the outdoor data on NO_2 levels help to understand the influence of outdoor air quality on indoor air quality.

Potential Effects of Indoor Chemistry and Ozone

The higher indoor/outdoor ratios of nitrogen dioxide (NO_2) during summer might be related to the effects of chemical reactions with ozone (O_3). At the end of December and beginning of January, average outdoor O_3 levels are 10–15 parts per billion (ppb) at a U.S. Environmental Protection Agency air monitoring station in Bronx, New York; 6 months later, they are around 35 ppb at the same station. (Similar levels were observed at the local air monitoring station in Chicago.) Levels vary day to day and hour to hour, however, so these levels might be well below daily peaks. O_3 levels are lower during winter in part because of shorter days and less ultraviolet radiation and in part because O_3 is depleted during the conversion of nitrogen oxide (NO) to NO_2, as well as during other chemical reactions. Additionally, analysis of pollutant levels in New York finds that communities that have less traffic — and, therefore, less outdoor NO generation — experience less ground O_3 depletion.[a]

Typically, O_3 does not infiltrate tight buildings easily,[b] *but with 80% of study participants in New York opening windows during summer, ground-level O_3 can enter the dwellings. O_3 is a highly unstable gas that has a half-life of only 7–10 minutes in an indoor space experiencing 4–6 air changes per hour. In a well-ventilated dwelling, O_3 has little time to react with most chemicals. However, most of the study comparison dwellings did not experience 4–6 air changes per hour, except when windows were opened. Furthermore, NO reacts very quickly with O_3 to form NO_2.*[c]

Even if a gas stove is used for the same amount of time during summer as during winter and emits a similar amount of NO, the higher levels of O_3 during summer may cause more of the NO to be converted to NO_2. This could help explain the large increase in the indoor/outdoor NO_2 ratio from winter to summer, when most other factors did not change markedly. Furthermore, although many factors are at play, the larger increase in window usage from winter to summer by Chicago participants than New York participants might explain partially why the NO_2 indoor/outdoor ratio increased 85% from winter to summer in Chicago, compared with 47% in New York.[d]

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[a] NYC Health. The New York City Community Air Survey: Neighborhood Air Quality 2008–2014. City of New York; 2006:19-20.Accessed November 8, 2021. https://www1.nyc.gov/assets/doh/downloads/pdf/environmental/comm-air-survey-08-14.pdf

[b] Blondeau P, Iordache V, Poupard O, Genin D, Allard F. Relationship between outdoor and indoor air quality in eight French schools. Indoor Air. 2005;15(1):2-12. doi:10.1111/j.1600-0668.2004.00263.x

[c] Weschler CJ. Ozone in indoor environments: concentration and chemistry. Indoor Air. 2000;10:269-288. doi:10.1034/j.1600-0668.2000.010004269.x

[d] Older New York apartments — such as those in this study — often have heating systems that cannot be regulated by the occupant and can generate excess heat. To adjust the dwelling temperature, residents open their windows. In this study, New York windows were opened at least 4 hours per day during 43% of winter visits and 51% of summer visits. By comparison, Chicago dwellings were more likely to have thermostat-controlled heating systems and central air conditioning. Chicago windows were opened at least 4 hours per day during only 3% of winter visits and 26% of summer visits.

The levels of O_3 available in the study dwellings would need to be sufficient to react with the levels of NO emitted from gas stove usage. In a previous study, it was argued that under wintertime/largely closed-building conditions in Alameda County, California, indoor O_3 levels would be unlikely to exceed 4.5 ppb, which would be insufficient to generate substantial NO_2 in their study of dwellings with gas appliances.[e] *However, under summertime and open-window conditions, it seems reasonable to hypothesize that O_3 could have a more substantial impact. The half-life of 25 ppb of O_3 to react with NO and create NO_2 is estimated to be 1 minute.*[f] *This amount of time should be sufficient for the O_3 levels likely present in units with open windows to have an effect on NO_2 generation. This is especially true in the late afternoon, when outdoor O_3 levels reach their daily peak and dinnertime cooking begins. This relationship with O_3 is an area in need of further investigation.*

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[e] Mullen N, Li J, Singer B. Impact of Natural Gas Appliances on Pollutant Levels in California Homes. Ernest Orlando Lawrence Berkeley National Laboratory; 2012. Accessed November 8, 2021. https://indoor.lbl.gov/publications/impact-natural-gasappliances

[f] Weschler CJ. Ozone in indoor environments: concentration and chemistry. Indoor Air. 2000;10:269-288. doi:10.1034/j.1600-0668.2000.010004269.x

3.4 $PM_{2.5}$ Findings

3.4.1 Background

Particulate matter is a mixture of solid particles and liquid droplets in the air, and $PM_{2.5}$ refers to fine inhalable particles that are 2.5 micrometers in diameter and smaller. Small particles can pose health hazards, in part because they are inhaled deep into the lungs and enter the bloodstream. Exposure can affect the respiratory, cardiovascular, and other body systems (see the **Introduction** section for more information on health effects and exposure limits).

Solid particles can be generated as dust, soot, fume, or smoke. Particles also can be formed from chemical reactions, such as when sulfur oxides, NOx, or VOCs are converted in the atmosphere into sulfates, nitrates, ammonium, or organic carbon. $PM_{2.5}$ commonly is generated by road traffic (e.g., exhaust and non-exhaust emissions of vehicle combustion, tire wearing, particle resuspension), power generation from coal or other fossil fuel plants, domestic heating systems, and industrial and agricultural sources. Natural sources of PM — such as pollen and mold — tend to produce particulate matter of a larger size (although pollen and mold fragments[114,115] can be < $PM_{2.5}$).

Outdoor $PM_{2.5}$ is small enough to enter indoor spaces through small openings around doors, windows, and other openings in the building envelope that may not be visible to the naked eye. Indoor combustion sources, including stoves, cigarettes, and candles and incense, as well as the resuspension of particles during cleaning, can cause elevated indoor $PM_{2.5}$ levels. Tightly constructed modern nonresidential properties can have very low indoor levels compared with the outdoors, while properties with significant cooking or smoking and fewer outdoor emissions sources can have indoor $PM_{2.5}$ levels that may be more than 10 times higher than outdoors. Depending on the relative strength of indoor and outdoor sources, natural and mechanical ventilation may help dilute indoor levels or encourage the transport of outdoor levels to the inside.

$PM_{2.5}$ generation from gas stoves is complex. $PM_{2.5}$ is generated primarily by the cooking process and not solely from the gas combustion process. A small fraction of $PM_{2.5}$ comes from the chemical byproducts of combustion. Frying, sauteing, and grilling on either a gas or electric burner will generate PM, but studies have shown that cooking using the intense, directed heat from a gas burner will generate more $PM_{2.5}$ than the heat from an electric coil. Depending on the type of cooking activity (e.g., frying, boiling, baking), meals cooked with a gas stove will generate widely varying levels of $PM_{2.5}$.

Participants who smoked were not excluded from the STOVE study, but they were asked not to smoke within the dwelling during the three 4-day air sampling periods. Because the research team understood that compliance might be a concern, residents were asked whether any smoking occurred during the sampling period. Furthermore, nicotine samples were taken as part of the air sampling collection process.

3.4.2 Measured $PM_{2.5}$ Levels

The GM indoor $PM_{2.5}$ level was 15.4 μg/m³ (both study and comparison units combined) — 16.2 μg/m³ in Chicago and 14.4 μg/m³ in New York. The GM outdoor

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[114] Green BJ, Tovey ER, Sercombe JK, Blachere FM, Beezhold DH, Schmechel D. Airborne fungal fragments and allergenicity. *Med Mycol*. 2006;44 Suppl 1:S245-S255. doi:10.1080/13693780600776308

[115] Hughes D., Mampage C, Jones L, Liu Z, Stone E. Characterization of atmospheric pollen fragments during springtime thunderstorms. *Environ. Sci. Technol. Lett*. 2020;7(6):409-414. doi:10.1021/acs.estlett.0c00213

$PM_{2.5}$ levels as measured at EPA ambient air monitoring stations was 9.0 µg/m^3 in Chicago and 8.3 µg/m^3 in New York. The GM indoor/outdoor ratio was 1.8 in both sites. See **Figure 3-2** for box-and-whisker plots comparing study and comparison homes.

3.4.3 Results of Multivariable Modeling of $PM_{2.5}$

Variables significantly related to $PM_{2.5}$ are presented in **Table 3-10**, **Table 3-11**, and **Table 3-12**. Detailed results related to $PM_{2.5}$ are presented in **Table 3-13** and **Table 3-14** in section **3.4.6, Detailed $PM_{2.5}$ Multivariable Results**.

Mitigation

Study group dwellings had $PM_{2.5}$ levels that were 21% lower than comparison group dwellings (adjusted study and comparison GMs were 17.2 µg/m^3 and 13.7 µg/m^3, respectively; $P = .009$). This supports a secondary hypothesis of this study — that homes with continuous exhaust ventilation would have lower $PM_{2.5}$ levels than comparison group homes.

No difference in $PM_{2.5}$ was seen based on the type of the mechanical ventilation. Homes with kitchen extraction did not perform differently than homes with only bathroom exhaust ventilation. Five comparison group dwellings that had timed intermittent exhaust ventilation systems performed similarly to the dwellings in the study group. When these intermittent ventilation dwellings were included with the study group homes, the $PM_{2.5}$ levels were 22% lower than the remaining comparison group dwellings ($P = .005$).

Measures of window usage did not meet the statistical significance criterion for inclusion in the multivariable models. Thus, use of windows was not associated with $PM_{2.5}$ levels.

Sources of $PM_{2.5}$

Smoking as indicated by the **level of nicotine** in the dwelling during the sampling period was identified as significantly associated with $PM_{2.5}$ levels ($P < .001$). In homes where nicotine levels were 10 times higher than the detection level (0.0625 µg/m^3), $PM_{2.5}$ levels were 62% higher.

Residents were asked not to smoke indoors during the air sampling periods. The nicotine results, along with self-reports of smoking, suggest that some residents did not comply. The nicotine levels also might indicate residual nicotine present before sampling began or cross-contamination from adjoining dwellings.

Other Factors

Variables representing the use of gas stoves (e.g., number of meals cooked) and outdoor $PM_{2.5}$ levels did not meet the statistical significance criterion for inclusion in the multivariable models. Dwellings where the homeowner reported **a musty odor more than a few times** had higher levels of $PM_{2.5}$ than those that did not (marginally significant: *P* = .069). Musty odor is mainly an indicator of moisture and mold, but some people also associate it with cigarette smoke and pet odors.

Site Effect

As a final step in the modeling process, sampling site (Chicago or New York) was tested as a possible factor but did not reach statistical significance. The other factors in the model explained any differences in $PM_{2.5}$ between the two sites.

Table 3-10. Variables Significantly Related[a] to $PM_{2.5}$
(n = 358 Visits, 176 Study/182 Comparison)

Variable	Overall (95% CI)	Study (95% CI)	Comparison (95% CI)	*P* Value[b]
Indoor $PM_{2.5}$ (GM) (µg/m³)	15.4 (14.1, 16.7)	13.3 (11.8, 15.1)	17.7 (15.8, 19.8)	.006
Indoor nicotine (GM) (µg/m³)	0.07 (0.06, 0.08)	0.06 (0.05, 0.08)	0.08 (0.06, 0.10)	.366
% visits to dwellings with musty odor observed more than a few times	5% (3%, 7%)	4% (1%, 7%)	6% (3%, 10%)	.374
% visits to dwellings located in Chicago	54% (49%, 60%)	60% (52%, 67%)	49% (42%, 57%)	.053

Key: µg/m³ = micrograms of dust per cubic meter of air; CI = confidence interval; GM = geometric mean; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

[a] Variable significantly related to $PM_{2.5}$ in multivariable modeling

[b] *P* value for the tests that the variable was different in study and comparison homes

3.4.4 Supplemental Analysis of Smoking and $PM_{2.5}$

Additional results are presented in Table 3-15, Table 3-16, Table 3-17, and Table 3-18.

Further analysis was conducted to explore whether ventilation in dwellings with more active smoking might perform differently than ventilation in dwellings with little or no smoking. Visits reporting less than 0.1 μg/m^3 of nicotine were classified as low-nicotine visits, with a low likelihood of active smoking during sampling (n = 269), while visits with 0.1 μg/m^3 or more of nicotine were classified as high-nicotine visits, with a higher chance of active smoking during sampling (n = 89).[116] The GM $PM_{2.5}$ level during low-nicotine visits was 12.8 μg/m^3, compared with 26.7 μg/m^3 during high-nicotine visits.

Mitigation

During low-nicotine visits, **study group** dwellings had $PM_{2.5}$ levels that were 25% lower than comparison group dwellings ($P = .003$). The effect size was equivalent to the effect of continuous ventilation as measured in the full model. When the resident reported **always or frequently using their on-demand bathroom exhaust when bathing**, similar $PM_{2.5}$ levels were seen across the two groups. When visits with frequent on-demand bathroom fan usage (n = 23 visits) were included with the study group homes, $PM_{2.5}$ levels were 28% lower than the remaining comparison group dwellings ($P < .001$).

During high-nicotine visits, study group dwellings had lower $PM_{2.5}$ levels than comparison group dwellings, but the difference was not statistically significant ($P = .390$). However, the **amount of bathroom exhaust** did matter ($P = .044$). Each 0.1 increase in ACH from the bathroom exhaust ventilation reduced $PM_{2.5}$ by 6%. As an example, dwellings where the bathroom fan air exchange rate was 0.5 ACH (the median for homes with continuous bathroom fans) had $PM_{2.5}$ levels that were 27% lower than dwellings with no continuous bathroom fan air exchange.

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[116] The 0.1 μg/m^3 cut point for classification as a low-or high-nicotine visit was primarily a function of the spread of the data and the laboratory detection limit. It also is supported by a study on the association of smoking behaviors and nicotine levels in multifamily housing. Although the paper did not specify a cut point, the data imply that homes with at least 0.1 μg/m^3 nicotine have a greater likelihood of an active smoker. See Kraev TA, Adamkiewicz G, Hammond SK, Spengler JD. Indoor concentrations of nicotine in low-income, multi-unit housing: associations with smoking behaviours and housing characteristics. *Tob Control*. 2009;18(6):438-444. doi:10.1136/tc.2009.029728.

Table 3-11. Variables Significantly Related to PM$_{2.5}$ (Low-Nicotine Homes)[a]
(n = 260 Visits, 141 Study/128 Comparison)

Variable	Overall (95% CI)	Study (95% CI)	Comparison (95% CI)	*P* Value[b]
Indoor PM$_{2.5}$ in homes with nicotine < 0.1 µg/m^3 (GM) (µg/m^3)	12.8 (11.8, 14.0)	11.3 (9.9, 12.8)	14.8 (13.2, 16.6)	.003
% visits to dwellings where bathroom fan used always/frequently	64% (58%, 69%)	100% (100%, 100%)	23% (16%, 31%)	<.001
% visits to dwellings with musty odor observed more than a few times	4% (2%, 7%)	4% (1%, 8%)	5% (1%, 8%)	.864
% visits to dwellings located in Chicago	54% (48%, 60%)	59% (51%, 67%)	49% (41%, 58%)	.113

Key: µg/m^3 = micrograms of dust per cubic meter of air; CI = confidence interval; GM = geometric mean; PM$_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

[a] Variable significantly related to PM$_{2.5}$ in multivariable modeling

[b] *P* value for the tests that the variable was different in study and comparison homes

Table 3-12. Variables Significantly Related to PM$_{2.5}$ (High-Nicotine Homes)[a]
(n = 89 Visits, 35 Study/54 Comparison)

Variable	Overall (95% CI)	Study (95% CI)	Comparison (95% CI)	*P* Value[b]
Indoor PM$_{2.5}$ in homes with nicotine = 0.1 µg/m^3 (GM) (µg/m^3)	26.7 (22.2, 32.0)	26.2 (19.8, 34.8)	27.0 (21.1, 34.5)	.689
Indoor nicotine (GM) (µg/m^3)	0.83 (0.62, 1.11)	1.07 (0.64, 1.80)	0.70 (0.50, 0.99)	.554
Mean bathroom exhaust ventilation (ACH)	0.17 (0.11, 0.23)	0.39 (0.28, 0.50)	0.02 (0.00, 0.04)	<.001
Mean number of occupants	2.1 (1.7, 2.4)	2.3 (1.5, 3.1)	1.9 (1.6, 2.3)	.352

Key: µg/m^3 = micrograms of dust per cubic meter of air; ACH = air changes per hour; CI = confidence interval; GM = geometric mean; PM$_{2.5}$ = micrograms of dust per cubic meter of air

[a] Variable significantly related to PM$_{2.5}$ in multivariable modeling

[b] *P* value for the tests that the variable was different in study and comparison homes

3.4.5 Interpretation of PM$_{2.5}$ Results

Mechanical ventilation was associated with lower PM$_{2.5}$ levels in study units than in comparison units. This supports a secondary hypothesis of this study — that homes with continuous mechanical ventilation would have lower levels of PM$_{2.5}$ than comparison group homes. Although the study's primary hypothesis was based on published simulation studies that estimated the impact of mechanical ventilation on NO_2 in homes with gas appliances, one of those simulations also reported that $PM_{2.5}$ levels would be reduced with increased air exchange and kitchen exhaust.

The type of cooking (e.g., frying and sauteing vs. boiling), as well as the duration of these activities, is more important to estimating $PM_{2.5}$ generation than the frequency of cooking. It is not surprising that the number of meals cooked was not associated with $PM_{2.5}$ levels. Even when homes with high nicotine levels were excluded, no cooking effect was seen. Evidence from prior studies suggests that cooking does contribute to $PM_{2.5}$ levels, even if this effect could not be quantified in this study.

For some other contaminants — such as NO_2 and CO — the main source of indoor generation was the kitchen, specifically the stove. $PM_{2.5}$ also is generated from other sources throughout a dwelling. For example, smoking produces $PM_{2.5}$ in the rooms in which it is occurring. Even in homes with low nicotine levels, use of cleaning products, use of candles, and infiltration of $PM_{2.5}$ from outdoors are likely to be sources of $PM_{2.5}$ in multiple rooms.

Given the diverse sources of $PM_{2.5}$, the finding that bathroom exhaust ventilation is effective at lowering $PM_{2.5}$ levels in both homes with high and low nicotine levels is logical because bathroom exhaust can ventilate the entire home. In high-nicotine homes, the amount of ventilation is important; the volume of air exchanged with continuous bathroom exhaust was significantly associated with indoor $PM_{2.5}$. In low-nicotine homes, the amount of ventilation across the study group homes was sufficient to see a statistically significant difference. Furthermore, in the low-nicotine homes, the use of on-demand bathroom ventilation yielded similar results as continuous ventilation. Nearly all comparison dwellings in this study offered the option for the resident to use the bathroom fan; however, only 19% of residents reported using them frequently.

In summary, homes with continuous mechanical ventilation had lower $PM_{2.5}$ levels than homes without continuous mechanical ventilation, and bathroom exhaust ventilation appeared to be the cause of the reductions. No observed benefit of kitchen exhaust ventilation was seen, likely because the indoor sources of $PM_{2.5}$ were not limited to the kitchen. The benefits of bathroom exhaust were observed across all housing.

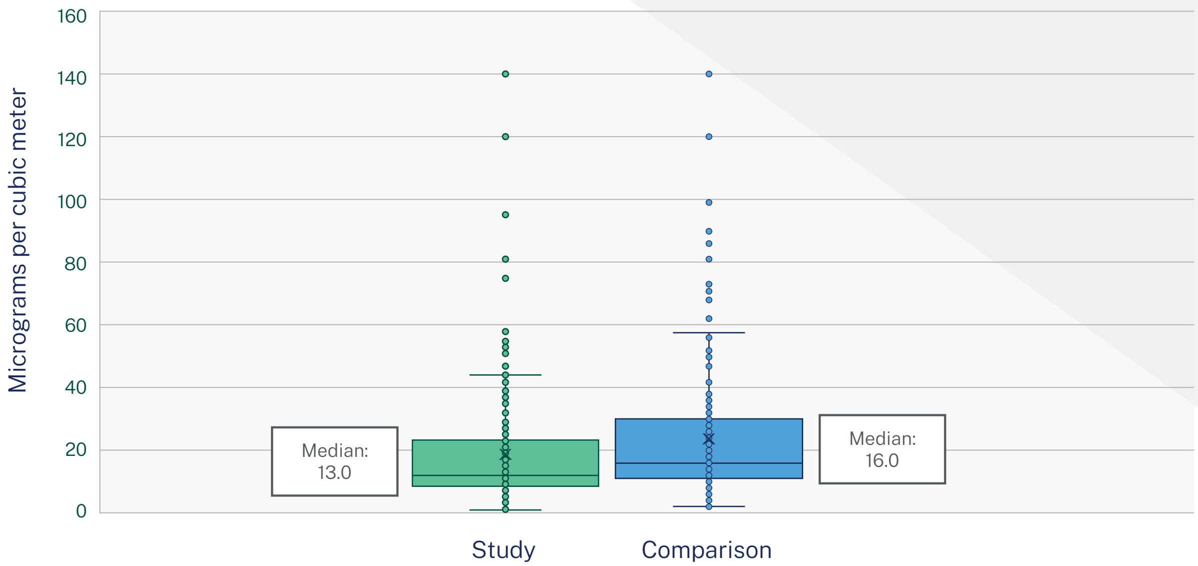

Figure 3-2. Particulate matter 2.5 micrometers or less in diameter ($PM_{2.5}$) levels by group — unadjusted data.

Interpretation: The top, middle, and bottom of each box are the 75th, 50th (median), and 25th percentiles, respectively. The interquartile range (IQR) is the difference between the 75th and 25th percentiles. The whiskers (vertical lines) extend from the ends of the box to the minimum value and maximum value that are within 1.5 times the IQR. Observations beyond 1.5 times IQR are considered outliers and are dots on the plot.

3.4.6 Detailed $PM_{2.5}$ Multivariable Results

Table 3-13. Predictors of Log Indoor $PM_{2.5}$ (µg/m³) — Study Group Forced Into Model (n = 358 Visits in 150 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	3.378 (3.197, 3.558)	<.001	3.316 (3.116, 3.515)	<.001
Study group (vs. comparison group)	−0.231 (−0.405, −0.057)	.009	−0.244 (−0.418, −0.070)	.006
Log nicotine (µg/m³)	0.209 (0.156, 0.261)	<.001	0.209 (0.157, 0.261)	<.001
Musty odor observed by resident more than a few times (vs. no)	0.316 (−0.025, 0.657)	.069	0.306 (−0.036, 0.647)	.110
Site: Chicago (vs. New York)			0.128 (−0.046, 0.301)	.149

Key: µg/m³ = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

Table 3-14. Predictors of Log Indoor $PM_{2.5}$ (µg/m^3) — All Ventilation Variables Eligible (n = 358 Visits in 150 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	3.401 (3.216, 3.586)	<.001	3.345 (3.139, 3.550)	<.001
Modified study group[a] (vs. comparison group)	−0.246 (−0.419, −0.073)	.005	−0.248 (−0.420, −0.076)	.005
Log nicotine (µg/m^3)	0.211 (0.159, 0.263)	<.001	0.211 (0.160, 0.263)	<.001
Musty odor observed by resident more than a few times (vs. no)	0.327 (−0.014, 0.668)	.060	0.320 (−0.021, 0.660)	.066
Site: Chicago (vs. New York)			0.108 (−0.065, 0.280)	.220

Key: µg/m^3 = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

[a] The modified study group includes five dwellings initially classified as comparison group units. These five dwellings have intermittent mechanical ventilation but were not designed as ASHRAE compliant.

Table 3-15. Predictors of Log Indoor $PM_{2.5}$ (µg/m^3) in Homes With Nicotine < 0.1 µg/m^3 — Study Group Forced Into Model (n = 269 Visits in 129 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	2.687 (2.550, 2.825)	<.001	2.602 (2.439, 2.765)	<.001
Study group (vs. comparison group)	−0.286 (−0.474, −0.097)	.003	−0.302 (−0.490, −0.115)	.002
Musty odor observed by resident more than a few times (vs. no)	0.359 (−0.048, 0.765)	.083	0.339 (−0.066, 0.745)	.099
Site: Chicago (vs. New York)			0.177 (−0.011, 0.365	.065

Key: µg/m^3 = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

Table 3-16. Predictors of Log Indoor $PM_{2.5}$ (µg/m^3) in Homes With Nicotine < 0.1 µg/m^3 — All Ventilation Variables Eligible (n = 269 Visits in 129 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	2.750 (2.595, 2.905)	<.001	2.667 (2.489, 2.845)	<.001
Bathroom fan used always/ frequently (vs. no)	−0.333 (−0.526, −0.141)	<.001	−0.343 (−0.534, −0.153)	<.001
Musty odor observed by resident more than a few times (vs. no)	0.379 (−0.026, 0.784)	.066	0.361 (−0.042, 0.765)	.079
Site: Chicago (vs. New York)			0.167 (−0.018, 0.353)	.077

Key: µg/m^3 = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

Table 3-17. Predictors of Log Indoor $PM_{2.5}$ (µg/m^3) in Homes With Nicotine ≥ 0.1 µg/m^3 — Study Group Forced Into Model (n = 89 Visits in 53 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	3.163 (2.853, 3.474)	<.001	3.223 (2.890, 3.555)	<.001
Study group (vs. comparison group)	−0.160 (−0.534, 0.214)	.390	−0.144 (−0.521, 0.233)	.443
Log nicotine (µg/m^3)	0.219 (0.087, 0.351)	.002	0.216 (0.084, 0.348)	.002
Number of occupants	0.102 (0.002, 0.206)	.054	0.127 (0.013, 0.241)	.030
Site: Chicago (vs. New York)			−0.218 (−0.618, 0.181)	.275

Key: µg/m^3 = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

Table 3-18. Predictors of Log Indoor $PM_{2.5}$ (μg/m^3) in Homes With Nicotine ≥ 0.1 μg/m^3 — All Ventilation Variables Eligible (n = 89 Visits in 53 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	3.203 (2.925, 3.480)	<.001	3.242 (2.941, 3.543)	<.001
Bathroom exhaust ventilation (air exchanges per hour)	−0.639 (−1.260, −0.018)	.044	−0.589 (−1.229, 0.050)	.070
Log nicotine (μg/m^3)	0.224 (0.098, 0.350)	<0.001	0.220 (0.093, 0.347)	.001
Number of occupants	0.108 (0.010, 0.207)	.033	0.126 (0.017, 0.235)	.024
Site: Chicago (vs. New York)			−0.159 (−0.548, 0.229)	.411

Key: μg/m^3 = micrograms of dust per cubic meter of air; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter

3.5 CO$_2$ Findings

3.5.1 Background

CO$_2$ is a gas primarily generated by the complete combustion of fossil fuels, as well as from respiration from animals and humans. Outdoor CO$_2$ levels form a baseline for indoor CO$_2$. As reported at the official U.S. CO$_2$ observatory in Hawaii, outdoor CO$_2$ levels in an area without many industrial sources are currently in the low 400 ppm. Outdoor CO$_2$ levels in urban areas on the mainland of the United States can be higher (on the order of 50 ppm more than rural areas). Outdoor levels vary depending on the time of year, with a peak during winter and spring, when energy generation from fossil fuel-burning power generation facilities is highest and absorption by vegetation is lowest, and a trough during summer and fall, when the opposite is true.

The main indoor sources of CO$_2$ are occupants (respiration) and combustion sources, such as gas stoves. Gas stoves can have complete combustion, which produces CO$_2$ and water vapor, and incomplete combustion, which produces CO, aldehydes, and soot and other combustion byproducts. Indoor CO$_2$ levels are moderated by the levels of natural and mechanical ventilation. The hypothesis in this study was that study group dwellings would have lower CO$_2$ levels than comparison dwellings.

3.5.2 Measured CO$_2$ Levels

In the STOVE study, the GM indoor CO$_2$ level of all readings (both the study and comparison groups) was 769 ppm overall — 825 ppm in Chicago and 709 ppm in New York. See **Figure 3-3** for box-and-whisker plots comparing study and comparison homes.

3.5.3 Results of Multivariable Modeling of CO_2

Variables significantly related to CO_2 are presented in **Table 3-19**. Detailed results related to CO_2 are presented in **Table 3-20** and **Table 3-21** in section **3.5.5, Detailed CO_2 Multivariable Results**.

Mitigation

Study group dwellings had CO_2 levels that were 13% lower than comparison group dwellings (adjusted study and comparison GMs were 719 ppm and 823 ppm, respectively; $P < .001$). This supports a secondary hypothesis of the study — that homes with continuous exhaust ventilation would have lower CO_2 levels than comparison group homes.

No significant difference was observed in CO_2 based on the location of the mechanical ventilation. Homes with kitchen exhaust ventilation did not perform differently than homes with only bathroom exhaust ventilation. Five comparison dwellings that had timed intermittent exhaust ventilation systems performed similarly to the dwellings in the study group and, when combined with the study group homes, had CO_2 levels that were 14% lower than the remaining comparison group dwellings ($P < .001$).

The effect of opening windows also was examined:

- Dwellings that **opened windows 4 or more hours per day** during the sampling period had indoor CO_2 levels that were 11–13% lower than dwellings that opened windows less than 4 hours per day ($P < .001$).

Models that considered both continuous and intermittent ventilation together offered a similar but slightly more nuanced finding about the effect of window usage on indoor CO_2 levels:

- Dwellings that **opened windows 4–12 hours per day** during the sampling period had indoor CO_2 levels that were 7–9% lower than dwellings that opened windows less than 4 hours per day ($P = .031$ and .099, without and with site as a control, respectively).
- Dwellings that **opened windows 12 or more hours per day** during the sampling period had indoor CO_2 levels that were 14–16% lower than dwellings that opened windows less than 4 hours per day ($P = .096$).

Table 3-19. Variables Significantly Related to Carbon Dioxide[a]
(n = 361 Visits, 174 Study/187 Comparison)

Variable	Overall (95% CI)	Study (95% CI)	Comparison (95% CI)	*P* Value[b]
Indoor CO_2 (GM) (ppm)	769 (746, 793)	715 (686, 745)	823 (789, 859)	<.001
% visits to dwellings where windows opened at least 4 hours per day (during sampling)	27% (22%, 31%)	22% (16%, 28%)	32% (25%, 38%)	.038
% visits to dwellings where windows opened at least 12 hours per day (during sampling)	16% (12%, 19%)	13% (8%, 18%)	18% (13%, 24%)	.148
% visits to dwellings where any meals cooked with stove (during sampling)	93% (90%, 95%)	93% (89%, 97%)	93% (89%, 96%)	.828
Mean number of meals cooked with stove (during sampling)	4.7 (4.3, 5.0)	4.4 (3.9, 5.0)	4.9 (4.3, 5.4)	.369
Mean number of occupants at least 5 years old	1.8 (1.7, 2.0)	1.8 (1.6, 2.0)	1.9 (1.7, 2.1)	.474
Season				.113
% visits during fall	20% (16%, 25%)	20% (14%, 25%)	21% (16%, 27%)	
% visits during spring	15% (11%, 19%)	11% (6%, 16%)	19% (13%, 24%)	
% visits during summer	35% (31%, 40%)	40% (33%, 48%)	31% (24%, 38%)	
% visits during winter	29% (24%, 34%)	29% (23%, 36%)	29% (22%, 35%)	
% visits to dwellings located in Chicago	54% (49%, 59%)	58% (51%, 65%)	50% (43%, 57%)	.114

Key: CI = confidence interval; CO_2 = carbon dioxide; GM = geometric mean; ppm = parts per million

[a] Variable significantly related to CO_2 in multivariable modeling

[b] *P* value for the tests that the variable was different in study and comparison homes

Sources of CO_2

Two sources were significantly associated with CO_2 levels:

- CO_2 increased 4–5% with each **additional occupant** who was 5 years of age or older (*P* value range = <.001–.007).
- **Gas stove usage** was associated with increased levels of CO_2. The effect was captured by two variables:
    - **Any meals cooked** with the stove during sampling (*P* value range = .035–.052)
    - **Number of meals cooked** with the stove during sampling (*P* value range = .011–.017)

Cooking one meal during the sampling period was associated with an 11–12% increase in CO_2 compared to no meals cooked, and each additional meal cooked during the 4-day sampling period increased CO_2 levels by an additional 1%. Thus, cooking an average of one meal per day was associated with a 16–17% increase in CO_2 when compared with a home with no meals cooked. Residents reported cooking an average of 4.4 meals per sampling period in study units and 4.9 meals per sampling period in comparison units.

Other Factors

EPA does not measure outdoor CO_2 levels at its ambient air testing sites, so the models could not control for it. However, indoor CO_2 did vary by **season**, with levels highest during winter and lowest during summer (*P* = .032), which matches seasonal patterns of outdoor CO_2 observed at other monitoring stations.[117]

Site Effect

As a final step of the modeling process, the **sampling site (Chicago or New York)** was tested as a possible factor. For CO_2, site was a marginally significant factor, with Chicago having 7% higher CO_2 levels than New York (*P* = .058). This does not necessarily mean that CO_2 levels are generally 7% higher in Chicago than New York. Instead, it might indicate that unmeasured characteristics of homes in Chicago and New York could be contributing to differences between the two sites.

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[117] Moore J, Jacobson AD. Seasonally varying contributions to urban CO_2 in the Chicago, Illinois, USA region: insights from a high-resolution CO_2 concentration and §13C record. *Elementa*. 2015; 3(000052). doi:10.12952/journal.elementa.000052

Adding site to the model helps control for these unexplained factors. Even after controlling for the site effect, no other variables were added or dropped from the models. Furthermore, the site effect did not change the effect sizes of any other significant factors meaningfully.

3.5.4 Interpretation of CO_2 Modeling

The use of mechanical ventilation was expected to lower indoor CO_2 levels and the STOVE study met this expectation. After controlling for other factors, CO_2 levels were about 13% lower in the study units (dwellings with continuous exhaust ventilation) when compared with comparison units that lacked continuous ventilation. In dwellings with continuous or intermittent exhaust ventilation, CO_2 levels were about 14% lower when compared with dwellings that lacked either continuous or intermittent ventilation.

Mechanical ventilation substantially reduces indoor CO_2 generated by cooking with a gas stove. Assuming that a dwelling with a gas stove that is not used has a baseline CO_2 level of 650 ppm,[118] the model used in this study shows that cooking one meal per day on the stove during a 4-day period would increase the CO_2 level to 775 ppm, all else being equal. Installing a continuous ventilation system in the same dwelling would reduce the CO_2 level to 680 ppm.

CO_2 levels often are used as a marker for how well-ventilated a dwelling is. In 2020, Canada Health proposed 1,000 ppm CO_2 as an indoor residential guidance level, although recent studies have identified health effects even at levels below 1,000 ppm.[119] The STOVE study found that, based on unadjusted data, 90% of visits to dwellings with continuous or intermittent mechanical ventilation had levels below 1,000 ppm, compared with 71% of visits to dwellings without such ventilation.

Use of windows also affected CO_2 levels. Dwellings where windows were reported to be open 4–12 hours per day during sampling had GM CO_2 levels that were 9% lower than dwellings where windows were open less than 4 hours per day. Dwellings that opened windows more than 12 hours per day had even greater reductions in CO_2: 16% less than dwellings with windows opened less than 4 hours per day. Window use

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[118] In this study, the GM of the average CO_2 level during visits when the gas stove was not used was 637 ppm.

[119] Health Canada. *Consultation: Proposed Residential Indoor Air Quality Guidelines for Carbon Dioxide*. Government of Canada. Updated October 29, 2020. Accessed November 8, 2021. https://www.canada.ca/en/health-canada/programs/consultation-residential-indoor-air-quality-guidelines-carbon-dioxide/document.html

is an effective method to improve indoor air quality for contaminants that have high indoor/outdoor ratios, such as CO_2 and formaldehyde. However, during periods of the year when heating or cooling is needed, it is a highly energy-inefficient method to reduce contaminant levels.

In summary, dwellings with continuous mechanical ventilation had lower CO_2 levels than dwellings without continuous mechanical ventilation, as was expected. Timed intermittent mechanical ventilation, although the sample size was small (five units), had a similar impact on CO_2 levels as continuous mechanical ventilation.

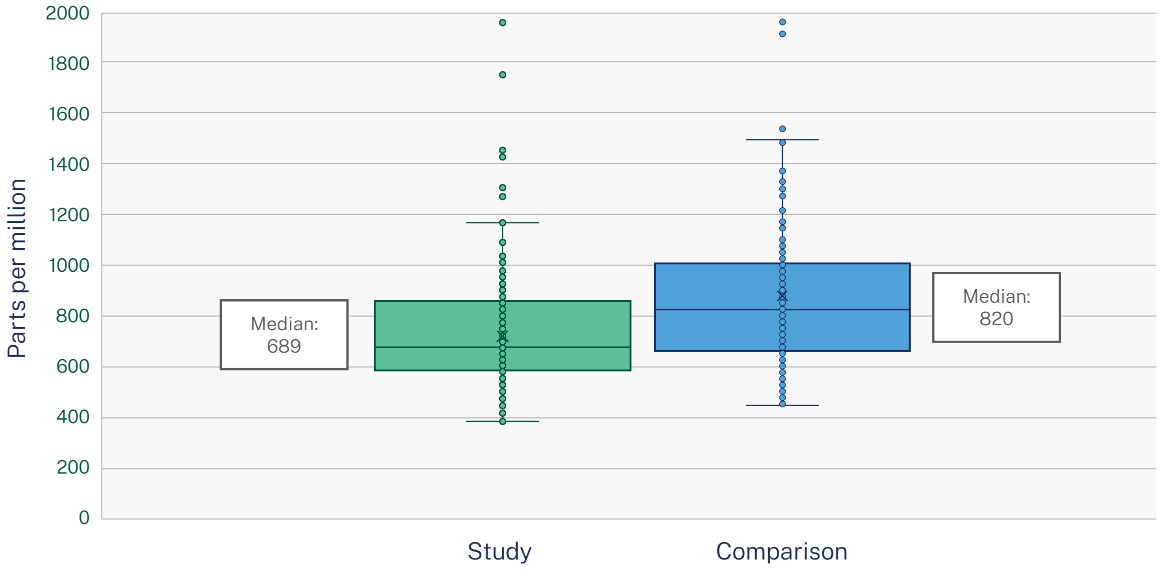

Figure 3-3. Carbon dioxide levels by group — unadjusted data.

Interpretation: The top, middle, and bottom of each box are the 75th, 50th (median), and 25th percentiles, respectively. The interquartile range (IQR) is the difference between the 75th and 25th percentiles. The whiskers (vertical lines) extend from the ends of the box to the minimum value and maximum value that are within 1.5 times the IQR. Observations beyond 1.5 times IQR are considered outliers and are dots on the plot.

3.5.5 Detailed CO_2 Multivariable Results

Table 3-20. Predictors of Log Carbon Dioxide (Parts Per Million) — Study Group Forced Into Model (n = 361 Visits in 150 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	6.518 (6.395, 6.641)	<.001	6.490 (6.364, 6.615)	<.001
Study group (vs. comparison group)	−0.136 (−0.202, −0.070)	<.001	−0.142 (−0.208, −0.077)	<.001
Window open ≥ 4 hours per day during sampling period (vs. no)	−0.142 (−0.205, −0.079)	<.001	−0.121 (−0.188, −0.054)	<.001
Cooked any meals (vs. no)	0.107 (−0.001, 0.216)	.052	0.114 (0.006, 0.222)	.039
Number of meals cooked	0.010 (0.002, 0.018)	.017	0.010 (0.002, 0.019)	.012
Season[a]		.032		.034
Winter (vs. fall)	0.048 (−0.021, 0.118)	.174	0.041 (−0.028, 0.111)	.244
Spring (vs. fall)	−0.003 (−0.087, 0.081)	.944	−0.012 (−0.096, 0.073)	.787
Summer (vs. fall)	−0.045 (−0.114, 0.023)	.191	−0.050 (−0.119, 0.018)	.147
Fall	0		0	
Number of occupants at least 5 years old	0.048 (0.023, 0.073)	<.001	0.039 (0.012, 0.065)	.004
Site: Chicago (vs. New York)			0.072 (−0.002, 0.147)	.058

[a] The *P* value from the overall test that predicted log carbon dioxide (CO_2) differs for at least one pair of seasons. CO_2 was lower for summer than winter for the models without and with site ($P = .003$ and .004, respectively), but other season comparisons were not significant.

Table 3-21. Predictors of Log Carbon Dioxide (Parts Per Million) — All Ventilation Variables Eligible (n = 361 Visits in 150 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	6.538 (6.416, 6.661)	<.001	6.512 (6.386, 6.638)	<.001
Modified study group[a] (vs. comparison)	−0.155 (−0.220, −0.091)	<.001	−0.157 (−0.221, −0.093)	<.001
Window open ≥ 4 hours per day during sampling period (vs. no)	−0.091 (−0.174, −0.009)	.031	−0.072 (−0.158, 0.014)	.099
Window open ≥ 12 hours per day during sampling period (vs. no)	−0.084 (−0.183, 0.015)	.096	−0.084 (−0.183, 0.015)	.096
Cooked any meals (vs. no)	0.110 (0.002, 0.217)	.045	0.116 (0.008, 0.223)	.035
Number of meals cooked	0.010 (0.002, 0.018)	.016	0.010 (0.002, 0.019)	.011
Season[b]		.031		.033
Winter (vs. fall)	0.045 (−0.024, 0.114)	.203	0.039 (−0.031, 0.108)	.274
Spring (vs. fall)	−0.010 (−0.093, 0.074)	.822	−0.017 (−0.101, 0.067)	.687
Summer (vs. fall)	−0.048 (−0.116, 0.020)	.164	−0.053 (−0.121, 0.015)	.127
Fall	0		0	
Number of occupants at least 5 years old	0.044 (0.020, 0.069)	<.001	0.036 (0.010, 0.062)	.007
Site: Chicago (vs. New York)			0.064 (−0.010, 0.138)	.088

[a] The modified study group includes five dwellings initially classified as comparison group units. These five dwellings have intermittent mechanical ventilation but were not designed as ASHRAE compliant.

[b] The *P* value from the overall test that predicted log carbon dioxide (CO_2) differs for at least one pair of seasons. CO_2 was lower for summer than winter for the models without and with site (*P* = .003 and .004, respectively), but other season comparisons were not significant.

3.6 CO Findings

3.6.1 Background

CO is a gas generated by the incomplete combustion of fuels. The most common sources of CO in outdoor air are vehicles that burn fossil fuels. Stationary fuel burning sources are a lesser contributor (10% or less of CO in outdoor air) but vary more by season. Outdoor CO levels tend to peak during winter and are lower during summer because fossil fuel use for heating and electricity varies. Gas stoves, unvented kerosene and gas space heaters, and gas-fired furnaces and water heaters are the main sources of CO in the indoor air. Combustion from tobacco smoking is another potential source of CO. EPA reports, “Average levels in homes without gas stoves vary from 0.5 to 5 parts per million (ppm). Levels near properly adjusted gas stoves are often 5 to 15 ppm and those near poorly adjusted stoves may be 30 ppm or higher.”[120]

When natural gas is burned completely, only water and CO_2 are produced. However, gas appliances do not achieve complete combustion. When the proper ratio of natural gas and oxygen from the surrounding air is present at the point of combustion, a minimal amount of CO may be generated. Inadequate air supply at the point of combustion, along with interactions between the flame and surfaces (e.g., the flame hitting a cool pan), causes the carbon in the natural gas to form CO instead of CO_2. Appliance technicians often can adjust or tune appliances to optimize the natural gas to oxygen ratio and reduce CO production. New gas appliances also are more likely to be properly tuned.

In addition to reducing CO generation at its sources, CO contamination can be reduced through better ventilation. Most furnaces and water heaters have flues that vent the combustion byproducts to the outdoors. However, few building code requirements require residential gas ranges and cooktops to vent to the outside. ASHRAE Standard 62.2 requires kitchen ventilation be vented to the exterior.

3.6.2 Measured CO Levels

The GM levels of CO were found to be quite low in both the study and comparison groups. The instrument used for indoor datalogging has a specified resolution of 0.5 ppm; more than 70% of all 96-hour mean indoor CO values fell below that level. Therefore, the maximum 15-minute arithmetic mean indoor CO value during each sampling period was used for analysis because, in this study, it proved to be a more reliable measure of indoor CO. This measure also is consistent with most CO exposure being episodic (e.g., during cooking), with a few peaks each day. In this report, the term indoor “CO maximum level” is used for the maximum 15-minute arithmetic mean indoor CO value.

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[120] *Carbon Monoxide’s Impact on Indoor Air Quality: Levels in Homes*. U.S. Environmental Protection Agency. Updated August 24, 2021. Accessed November 8, 2021. https://www.epa.gov/indoor-air-quality-iaq/carbon-monoxides-impact-indoor-air-quality

In the STOVE study, the maximum 15-minute GM indoor CO level was 2.5 ppm overall — 2.8 ppm in Chicago and 2.2 ppm in New York. No 15-minute peak result exceeded 42.6 ppm, and the 75th percentile result was 6.5 ppm. The GM outdoor CO level (as measured at EPA ambient air monitoring stations) was 0.2 ppm overall — 0.2 ppm in Chicago and 0.3 ppm in New York. See **Figure 3-4** for box-and-whisker plots comparing study and comparison homes.

3.6.3 Results of Multivariable Modeling of CO Maximum

Variables significantly related to CO are presented in **Table 3-22**. Detailed results related to CO are presented in **Table 3-23**, **Table 3-24**, and **Table 3-25** in section **3.6.5, Detailed CO (Maximum) Multivariable Results**.

Mitigation

When study group dwellings were compared with comparison group dwellings, controlling for all other significant factors, no study effect on CO maximum level was seen (adjusted study and comparison GMs were 2.3 ppm and 2.7 ppm, respectively; *P* = .324). The study effect remained nonsignificant when the analysis also controlled for the location of the dwellings (Chicago vs. New York) (*P* = .231).

However, study dwellings with **kitchen exhaust ventilation** had CO maximum levels that were 41–49% lower than study dwellings without kitchen exhaust ventilation (*P* = .011–.099). Twenty percent (20%) of visits to study dwellings were to units with kitchen exhaust ventilation. When the model includes the study effect, site effect, and kitchen exhaust effect, the model offers an indication of the relative impact of kitchen exhaust and bathroom exhaust[121] (see **Table 3-24**). Although the effect of bathroom exhaust ventilation was not significant for CO maximum levels (*P* = .515), study units with bathroom exhaust but *without* kitchen exhaust had CO maximum levels that were 11% lower than comparison units. Study units with bathroom exhaust and *with* kitchen exhaust had CO maximum levels that were 44% lower than comparison units.

Measures of window usage did not meet the statistical significance criterion for inclusion in the multivariable models. Use of windows was not associated with CO maximum levels.

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[121] In Table 3-24, the kitchen coefficient provides the effect size of kitchen exhaust and the study group coefficient provides the effect size from all other mechanical ventilation in the dwelling (i.e., the bathroom exhaust).

Sources of CO

Two sources of CO — outdoor mean CO and cooking with a gas stove — were significantly associated with CO maximum levels:

- **Log outdoor CO** (*P* < .001). Indoor CO maximum increased 8–9% for each 10% increase in outdoor mean CO.
- **Gas stove usage** as measured by number of meals cooked (*P* value range = .014–.024). Indoor CO maximum increased 20–22% for each additional meal cooked per day. In other words, a dwelling where eight meals were cooked on the stove during the 4-day sampling period had 20–22% higher CO maximum than a dwelling where four meals were cooked. There were 4.6 meals cooked (mean) per 4-day sampling period.

Site Effect

As a final step of the modeling process, the **sampling site (Chicago or New York)** was tested as a possible factor. For CO, site was a significant factor in the model with the study group variable included (*P* = .042), but site was not significant when kitchen exhaust ventilation was considered.

Study group dwellings in Chicago did not have exterior venting kitchen exhaust fans, but the majority of study dwellings in New York had such fans. When the kitchen exhaust variable is added to the models, the site coefficient is reduced greatly, and site is no longer significant (*P* = .269 and .323). The differences in the ventilation designs of the buildings enrolled in the two cities better explain the differences in CO levels than the generic site effect.

Table 3-22. Variables Significantly Related to Carbon Monoxide[a]
(n = 359 Visits, 175 Study/184 Comparison)

Variable	Overall (95% CI)	Study (95% CI)	Comparison (95% CI)	*P* Value[b]
Indoor CO (15-minute maximum) (GM) (ppm)	2.5 (2.2, 2.9)	2.3 (1.9, 2.8)	2.8 (2.3, 3.4)	.256
Outdoor CO (GM) (ppm)	0.2 (0.2, 0.2)	0.2 (0.2, 0.2)	0.2 (0.2, 0.2)	.514
% visits to dwellings with kitchen exhaust ventilation (air changes per hour) greater than 0	13% (9%, 16%)	20% (14%, 26%)	6% (3%, 9%)	<.001
Mean number of meals cooked with stove (during sampling)	4.6 (4.2, 4.9)	4.4 (3.9, 4.9)	4.7 (4.1, 5.2)	.582
% visits to dwellings located in Chicago	55% (50%, 60%)	61% (53%, 68%)	49% (42%, 57%)	.035

Key: CI = confidence interval; CO = carbon monoxide; GM = geometric mean; ppm = parts per million

[a] Variable significantly related to CO in multivariable modeling

[b] *P* value for the tests that the variable was different in study and comparison homes

3.6.4 Interpretation of CO Results

Mechanical ventilation was associated with lower CO maximum levels when continuous kitchen exhaust ventilation was present. Other studies have found that greater use of gas stoves is associated with higher CO maximum levels.[122] The use of continuous kitchen exhaust likely helped prevent the CO gas emitted during cooking from reaching the living area where the sampling equipment was deployed, thus dampening the peak CO levels in the living area. Empirical data of the effect of kitchen exhaust and mechanical ventilation on CO is limited, but this study showed that such ventilation reduces potential exposure.

Indoor CO maximum is correlated highly with outdoor CO. Outdoor CO concentrations and indoor CO maximum levels both were higher during winter

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[122] Mullen N, Li J, Singer B. *Impact of Natural Gas Appliances on Pollutant Levels in California Homes*. Ernest Orlando Lawrence Berkeley National Laboratory; 2012. Accessed November 8, 2021. https://indoor.lbl.gov/publications/impact-natural-gas-appliances

and lower during summer. Although correlated with outdoor levels, CO largely is generated indoors when indoor combustion sources — such as gas stoves — are present. The ratios of indoor/outdoor CO maximum levels were fairly consistent by site and study group, except for the New York study units. Not controlling for other factors — such as number of meals cooked — the GM ratio of indoor/outdoor CO maximum was slightly higher in Chicago study units (11.2) than comparison units (8.9) but substantially lower in New York study units (4.7) than comparison units (9.4). Most study group dwellings in New York had continuous kitchen exhaust ventilation, while the Chicago study group units did not have this type of ventilation.

Although environmental tobacco smoke could be a source of CO, it would be expected that bathroom exhaust would help reduce CO generated in rooms other than the kitchen. However, none of the smoking variables were related to the variance in CO maximum levels across dwellings. Although smoking may contribute to CO levels, it might not have been distinguishable from the variation in CO produced by the gas stoves. A study found that in living rooms of homes without combustion appliances, smoking predicted CO levels exceeding 4 ppm, but in homes with combustion appliances, this relationship was not observed because CO levels were just as likely to exceed 4 ppm with or without smoking.[123] Further research is needed to better understand whether bathroom exhaust ventilation has a greater impact in homes with smoking but without combustion appliances.

In summary, this study offers evidence that the use of continuous kitchen exhaust ventilation can have a significant effect on lowering CO maximum levels in the living space. It should be further noted that no homes approached the level that WHO has identified as an indoor air guidance level for a 15-minute sample (87 ppm). The highest CO maximum level recorded in this study was less than half of that level (43 ppm).

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[123] Cox BD, Whichelow MJ. Carbon monoxide levels in the breath of smokers and nonsmokers: effect of domestic heating systems. *J Epidemiol Community Health.* 1985;39(1):75-78. doi:10.1136/jech.39.1.75

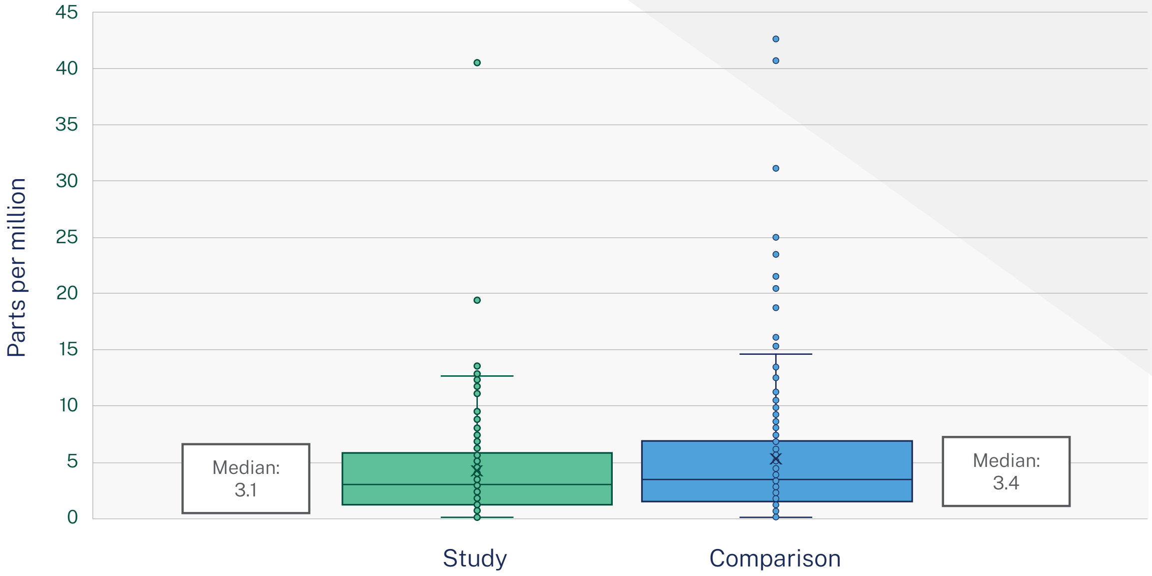

Figure 3-4. Carbon monoxide levels, 15-minute maximum by group — unadjusted data.

Interpretation: The top, middle, and bottom of each box are the 75th, 50th (median), and 25th percentiles, respectively. The interquartile range (IQR) is the difference between the 75th and 25th percentiles. The whiskers (vertical lines) extend from the ends of the box to the minimum value and maximum value that are within 1.5 times the IQR. Observations beyond 1.5 times IQR are considered outliers and are dots on the plot.

3.6.5 Detailed CO Maximum Multivariable Results

Table 3-23. Predictors of Log Maximum Carbon Monoxide (Parts Per Million) — Study Group Forced Into Model (n = 359 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	1.968 (1.223, 2.713)	<.001	1.903 (1.158, 2.649)	<.001
Study group (vs. comparison group)	−0.168 (−0.504, 0.167)	.324	−0.202 (−0.535, 0.130)	.231
Log outdoor mean CO (ppm)	0.811 (0.341, 1.281)	<.001	0.897 (0.419, 1.375)	<.001
Number of meals cooked	0.045 (0.006, 0.084)	.024	0.049 (0.010, 0.087)	.015
Site: Chicago (vs. New York)			0.352 (0.012, 0.692)	.042

Key: CO = carbon monoxide; ppm = parts per million

Table 3-24. Predictors of Log Maximum Carbon Monoxide (Parts Per Million) — Study Group With Kitchen Exhaust Eligible (n = 359 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	2.055 (1.309, 2.801)	<.001	1.998 (1.245, 2.751)	<.001
Study group (vs. comparison group)	−0.072 (−0.410, 0.267)	.677	−0.115 (−0.461, 0.232)	.515
Kitchen exhaust ventilation (air exchanges per hour) greater than 0 (vs. no)	−0.609 (−1.110, −0.108)	.018	−0.469 (−1.028, 0.090)	.099
Log outdoor mean CO (ppm)	0.854 (0.383, 1.326)	<.001	0.897 (0.419, 1.375)	<.001
Number of meals cooked	0.047 (0.008, 0.086)	.018	0.049 (0.010, 0.087)	.014
Site: Chicago (vs. New York)			0.212 (−0.165, 0.589)	.269

Key: CO = carbon monoxide; ppm = parts per million

Table 3-25. Predictors of Log Maximum Carbon Monoxide (Parts Per Million) — All Ventilation Variables Eligible (n = 359 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	2.028 (1.293, 2.763)	<.001	1.965 (1.219, 2.711)	<.001
Kitchen exhaust ventilation (air exchanges per hour) greater than 0 (vs. no)	−0.634 (−1.120, −0.148)	.011	−0.525 (−1.057, 0.006)	.053
Log outdoor mean CO (ppm)	0.858 (0.388, 1.329)	<.001	0.898 (0.421, 1.376)	<.001
Number of meals cooked	0.047 (0.009, 0.086)	.017	0.049 (0.010, 0.088)	.014
Site: Chicago (vs. New York)			0.185 (−0.183, 0.552)	.323

Key: CO = carbon monoxide; ppm = parts per million

3.7 Formaldehyde Findings

3.7.1 Background

Formaldehyde is a gas that is generated by multiple sources. Building and consumer products are considered the primary sources of formaldehyde in residential spaces. Formaldehyde is added to building products as a resin and binder. As relative humidity and temperatures rise, so can formaldehyde levels, through a process known as "off-gassing." In indoor environments with low air exchange or ventilation, the released formaldehyde can accumulate in the air. Other consumer products — such as cosmetics, cleaning products, and air fresheners — also can release formaldehyde directly or can release other VOCs that chemically react to form formaldehyde. Tobacco smoking and cooking with a gas stove are other sources of formaldehyde.

In outdoor ambient air, formaldehyde is generated primarily when hydrocarbons — such as compounds found in vehicular emissions — react with other compounds (mainly O_3). Formaldehyde also can be generated directly from incomplete combustion from fossil fuels, such as gas appliances in indoor spaces and vehicular emissions outdoors.

Indoor levels are generally higher than outdoor levels, but levels and ratios vary. One study in New York City found that during winter, GM indoor levels were 9.7 ppb and outdoor levels were 1.7 ppb (average indoor/outdoor ratio = 7). During summer, GM indoor levels were 16.7 ppb and outdoor levels were 4.2 ppb (average indoor/outdoor ratio = 3).[124] Average indoor formaldehyde levels have been declining because regulations have resulted in reduced formaldehyde use in building products and other consumer products.

Increased air exchange, in theory, can have the short-term effect of increasing off-gassing and indoor formaldehyde levels, but most studies find an inverse relationship between air exchange and formaldehyde. Tighter homes often have lower air exchange rates and, therefore, may tend to have higher formaldehyde levels, whereas increased natural and mechanical ventilation generally reduces formaldehyde levels.

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[124] Kinney PL, Chillrud SN, Ramstrom S, Ross J, Spengler JD. Exposures to multiple air toxics in New York City. *Environ Health Perspect*. 2002;110 Suppl 4(Suppl 4):539-546. doi:10.1289/ehp.02110s4539

3.7.2 Measured Formaldehyde Levels

In the STOVE study, the GM indoor formaldehyde level was 16.7 ppb overall (both study and comparison dwellings) — 15.7 ppb in study units and 17.8 ppb in comparison units. GM formaldehyde levels were 18.2 ppb in Chicago and 15.1 ppb in New York. See **Figure 3-5** for box-and-whisker plots comparing study and comparison homes.

3.7.3 Results of Multivariable Modeling of Formaldehyde

Variables significantly related to formaldehyde are presented in **Table 3-26**. Detailed results related to formaldehyde are presented in **Table 3-27**, **Table 3-28**, and **Table 3-29** in section **3.7.5, Detailed Formaldehyde Multivariable Results**.

Mitigation

Study group dwellings had formaldehyde levels that were 9–10% lower than comparison group dwellings (adjusted study and comparison GMs were 15.9 ppb and 17.5 ppb, respectively; *P* = .082; *P* = .045 when controlling also for site). This matched a secondary hypothesis of the study — that the use of continuous ventilation would be related to lower formaldehyde levels.

When the location of ventilation was taken into account, study dwellings with **kitchen exhaust ventilation** had formaldehyde levels that were 23–29% lower than study dwellings without kitchen exhaust ventilation (*P* < .001–.010). Twenty-one percent (21%) of visits to study dwellings were to units with kitchen exhaust ventilation. When the model includes the study effect, site effect, and kitchen exhaust effect, the model provides an indication of the relative impact of kitchen exhaust and bathroom exhaust[125] (see **Table 3-28**). Although bathroom exhaust ventilation had no significant effect on formaldehyde levels (*P* = .270), study units with bathroom exhaust but *without* kitchen exhaust had formaldehyde levels that were 6% lower than comparison units. Study units *with* bathroom exhaust and with kitchen exhaust had formaldehyde levels that were 25% lower than comparison units.

Analysis of natural ventilation also showed significant results:

- Dwellings that **opened windows up to 12 hours per day** during the sampling period had indoor formaldehyde levels that were 11–16% lower than dwellings that did not open windows (*P* value range = <.001–.017).

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[125] In Table 3-28, the kitchen coefficient provides the effect size of kitchen exhaust and the study group coefficient provides the effect size from all other mechanical ventilation in the dwelling (i.e., the bathroom exhaust).

- Dwellings that **opened windows 12 or more hours per day** during the sampling period had indoor formaldehyde levels that were 20–25% lower than dwellings that did not open windows (marginally significant: P value range = .086–.090). Windows were opened for 12 or more hours per day during 16% of visits.

Sources of Formaldehyde

No variables representing potential sources of formaldehyde (cooking or smoking) were significant in the models.

Other Factors

Indoor **relative humidity** and **temperature** are positively correlated with indoor formaldehyde ($P < .001$ for both). Prior research has found that higher relative humidity and temperatures promote formaldehyde off-gassing from building products.[126] In addition, because indoor relative humidity and temperatures were associated with seasons in this study and outdoor formaldehyde levels vary by **season**, the relative humidity and temperature variables are likely to partially capture the outdoor formaldehyde effect. Formaldehyde is not a pollutant monitored by EPA, so the model could not control for it. Season was marginally significant in the base study model (see **Table 3-27**: $P = .065$) and significant in the models with kitchen exhaust included (see **Table 3-28** and **Table 3-29**: P value range = .028–.045), serving to modify the relative humidity and temperature levels. Controlling for other factors and taking into account seasonal mean levels of indoor temperature and relative humidity, indoor formaldehyde was 45–49% higher during summer than during winter.

Site Effect

As a final step of the modeling process, the **sampling site (Chicago or New York)** was tested as a possible factor. For formaldehyde, site was a significant factor with the study effect (see **Table 3-27** and **Table 3-28**: P value range = .001–.042) and marginally significant without the study effect included (see **Table 3-29**: $P = .062$. Chicago had higher formaldehyde levels than New York. When site is included, all variables remain significant in the model, and no additional variables emerged as significant.

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[126] Murphy MW, Lando JF, Kieszak SM, et al. Formaldehyde levels in FEMA-supplied travel trailers, park models, and mobile homes in Louisiana and Mississippi. *Indoor Air*. 2013;23(2):134-141. doi:10.1111/j.1600-0668.2012.00800.x

Table 3-26. Variables Significantly Related to Formaldehyde[a]
(n = 370 Visits, 184 Study/186 Comparison)

Variable	Overall (95% CI)	Study (95% CI)	Comparison (95% CI)	*P* Value[b]
Formaldehyde (GM) (ppb)	16.7 (15.9, 17.6)	15.7 (14.6, 16.8)	17.8 (16.7, 19.0)	.032
% visits to dwellings with kitchen exhaust ventilation (air changes per hour) greater than 0	13% (10%, 16%)	21% (15%, 27%)	5% (2%, 9%)	<.001
% visits to dwellings where windows were opened (during sampling)	48% (43%, 53%)	44% (37%, 51%)	52% (44%, 59%)	.144
% visits to dwellings where windows opened at least 12 hours per day (during sampling)	16% (12%, 20%)	14% (9%, 19%)	18% (12%, 23%)	.344
Average indoor relative humidity (%) (during sampling)	43 (41, 44)	42 (40, 44)	43 (41, 45)	.312
Average indoor temp (°F) (during sampling)	76 (75, 76)	76 (75, 76)	76 (76, 77)	.330
Season				.336
% visits during fall	20% (16%, 24%)	20% (14%, 25%)	20% (14%, 26%)	
% visits during spring	14% (11%, 18%)	11% (7%, 16%)	17% (12%, 23%)	
% visits during summer	37% (32%, 42%)	40% (33%, 47%)	33% (27%, 40%)	
% visits during winter	29% (25%, 34%)	29% (22%, 35%)	30% (23%, 36%)	
% visits to dwellings located in Chicago	54% (49%, 59%)	58% (51%, 65%)	49% (42%, 57%)	.094

Key: CI = confidence interval; GM = geometric mean; ppb = parts per billion

[a] Variable significantly related to formaldehyde in multivariable modeling

[b] *P* value for the tests that the variable was different in study and comparison homes

3.7.4 Interpretation of Formaldehyde Results

Mechanical ventilation was associated with reduced levels of formaldehyde in the study homes. This supports prior research[127] that describes the benefits of mechanical ventilation[128] on indoor formaldehyde levels. Earlier research has not always been consistent on this finding, however, with at least one study[129] observing no relationship between air exchange rates and formaldehyde concentrations. Kitchen exhaust ventilation is recommended commonly for addressing cooking emissions, but limited research exists on the relationship between kitchen exhaust and formaldehyde levels. One study[130] reported that a self-report of having kitchen exhaust ventilation was related to lower formaldehyde levels, whereas another study[131] found that such a self-report was associated with higher formaldehyde levels. The STOVE study showed kitchen and bathroom exhaust ventilation both resulted in lower formaldehyde levels, with most of the effect attributed to the kitchen exhaust. This suggests that the source of formaldehyde in these green renovated properties might have been localized primarily to the kitchen, which allowed kitchen exhaust to help prevent formaldehyde from reaching the main living area, where the samplers were deployed.

No significant association was seen between the number of meals cooked and formaldehyde. However, the number of meals cooked with a gas stove may not be the best measure to estimate the amount of formaldehyde generated from cooking. A study by the National Institute of Standards and Technology[132] found that cooking with the gas burner set on high emitted low levels of formaldehyde, while cooking with the gas burner set on low (simmering) emitted higher levels of formaldehyde. At high temperatures, the formaldehyde is consumed by the flame as quickly as it is formed, but at lower temperatures, less formaldehyde is consumed, allowing it to accumulate in the air. For example, cooking on low with a frying pan on one burner produced 20 times the level of formaldehyde as cooking on high. Using burners on low is a fairly

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[127] Sherman MH, Hodgson AT. Formaldehyde as a basis for residential ventilation rates. *Indoor Air*. 2004;14(1):2-8. doi:10.1046/j.1600-0668.2003.00188.x

[128] Hult E, Willem H, Price P, et al. *Formaldehyde and Acetaldehyde Exposure Mitigation in US Residences: In-Home Measurements of Ventilation Control and Source Control*. Ernest Orlando Lawrence Berkeley National Laboratory; 2014. Accessed November 8, 2021. https://escholarship.org/uc/item/53d887k8

[129] Hun DE, Corsi RL, Morandi MT, Siegel JA. Formaldehyde in residences: long-term indoor concentrations and influencing factors. *Indoor Air*. 2010;20(3):196-203. doi:10.1111/j.1600-0668.2010.00644.x

[130] Stock TH, Mendez SR. A survey of typical exposures to formaldehyde in Houston area residences. *Am Ind Hyg Assoc J*. 1985;46(6):313-317. doi:10.1080/15298668591394888

[131] Gilbert NL, Gauvin D, Guay M, et al. Housing characteristics and indoor concentrations of nitrogen dioxide and formaldehyde in Quebec City, Canada. *Environ Res*. 2006;102(1):1-8. doi:10.1016/j.envres.2006.02.007

[132] Poppendieck D, Gong M. *Simmering Sauces! Elevated Formaldehyde Concentrations from Gas Stove Burners*. National Institute of Standards and Technology. Accessed November 8, 2021. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=926006

common practice when cooking, so it is reasonable to expect that cooking would be a source of formaldehyde in kitchens.

The STOVE study did not collect information systematically about possible sources of formaldehyde from building and consumer products in the dwellings. Because these sources can be highly influential contributors to indoor formaldehyde levels, the lack of this information is a limitation. At the study design stage, it was assumed that because all properties underwent green renovations, pressed wood products — such as cabinets — either were replaced with low-formaldehyde cabinets or had been in place long enough that any formaldehyde in the products had off-gassed substantially. However, it is possible that formaldehyde from other sources (e.g., building products, cleaners, glues) was a source of variation in formaldehyde levels between dwellings.

The importance of kitchen exhaust also may be related to non-building products in the kitchen. During summer, when window usage is highest, ambient O_3 can enter dwelling spaces easily. Research on indoor sources of formaldehyde has identified O_3 reactions with cooking oil byproducts and VOCs emitted from cleaning products as potential sources of formaldehyde in homes.[133]

Formaldehyde is not an outdoor contaminant that EPA monitors, so the models could not directly control for outdoor sources of formaldehyde. Outdoor formaldehyde generally is in the 2–4 ppb range and is not considered to be a major contributor to indoor formaldehyde levels. However, a strong seasonal pattern exists, with indoor formaldehyde levels highest during summer and lowest during winter. Three factors were tested in the STOVE study models to control for this seasonal variation: indoor relative humidity, indoor temperature, and sampling season. Relative humidity and temperature are correlated with season and also have been found to be related to changes in the amount of off-gassing of formaldehyde from building products. Indoor relative humidity, temperature, and sampling season all were significant in the models, but it is unclear if the relationship between relative humidity/temperature and off-gassing can be decoupled from the relationship between relative humidity/temperature/season

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[133] Salthammer T, Mentese S, Marutzky R. Formaldehyde in the indoor environment. *Chem. Rev.* 2010;110(4):2536-2572. doi:10.1021/cr800399g

and outdoor formaldehyde. Although the source of formaldehyde cannot be identified from the models, seasonal variation can be estimated when estimating ventilation effects. This is important because more visits to study units occurred during summer (40%) than visits to comparison units (33%), while fewer visits to study units occurred during spring (11%) than visits to comparison units (17%).

Window usage appears to be effective at reducing formaldehyde levels in homes. In fact, opening windows for more than 12 hours per day can provide reductions in formaldehyde on the same order as mechanical kitchen exhaust ventilation. However, limitations exist to window usage. Opening windows can be a security or noise concern at certain properties, and opening windows on cold days or on hot days when air conditioning is in use can be energy inefficient. In contrast, mechanical ventilation offers building management the opportunity to adjust the air exchange rate to optimize ventilation to improve indoor air quality while managing the energy penalty.

In summary, mechanical ventilation can be an effective form of mitigation for formaldehyde generation. This study adds new evidence that the use of continuous kitchen exhaust ventilation can have a significant effect on lowering formaldehyde levels.

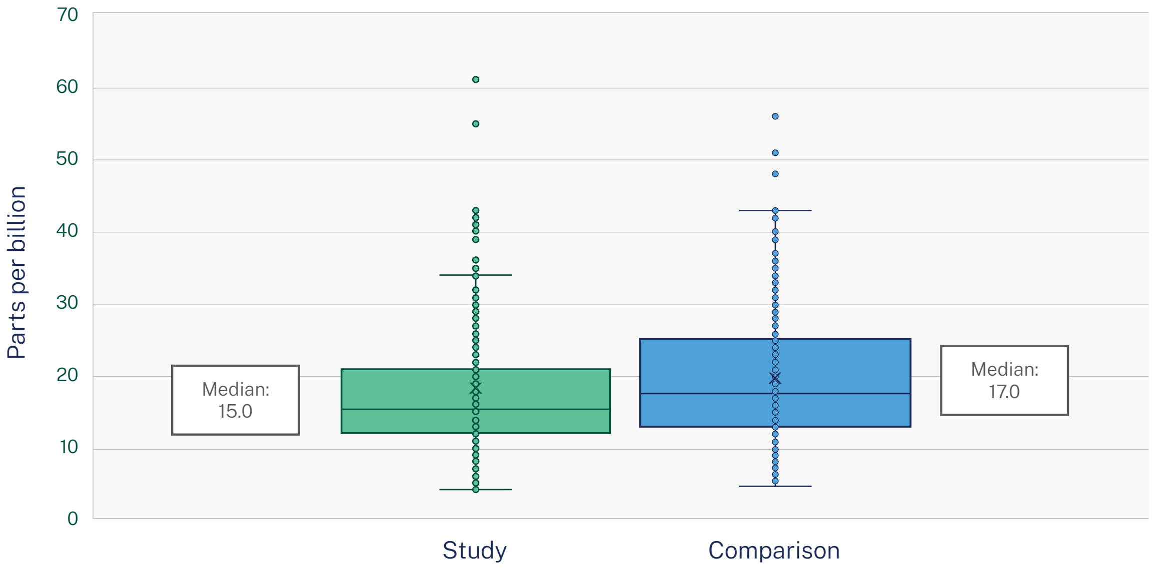

Figure 3-5. Formaldehyde levels by group — unadjusted data.

Interpretation: The top, middle, and bottom of each box are the 75th, 50th (median), and 25th percentiles, respectively. The interquartile range (IQR) is the difference between the 75th and 25th percentiles. The whiskers (vertical lines) extend from the ends of the box to the minimum value and maximum value that are within 1.5 times the IQR. Observations beyond 1.5 times IQR are considered outliers and are dots on the plot.

3.7.5 Detailed Formaldehyde Multivariable Results

Table 3-27. Predictors of Log Formaldehyde (Parts Per Billion) — Study Group Forced Into Model (n = 370 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	0.913 (0.086, 1.740)	.031	0.390 (−0.484, 1.263)	.380
Study group (vs. comparison group)	−0.097 (−0.206, 0.012)	.082	−0.108 (−0.213, −0.002)	.045
Window open ≥ 12 hours per day during sampling period (vs. no)	−0.107 (−0.229, 0.015)	.086	−0.105 (−0.226, 0.016)	.089
Window open at all during sampling period (vs. no)	−0.177 (−0.270, −0.084)	<.001	−0.129 (−0.226, −0.032)	.010
Season[a]		.065		.063
Winter (vs. fall)	0.166 (0.042, 0.290)	.009	0.162 (0.038, 0.286)	.011
Spring (vs. fall)	0.107 (−0.023, 0.238)	.106	0.092 (−0.039, 0.222)	.167
Summer (vs. fall)	−0.020 (−0.142, 0.103)	.753	−0.037 (−0.160, 0.085)	.551
Fall	0		0	
Average indoor relative humidity (%)	0.019 (0.014, 0.024)	<.001	0.019 (0.014, 0.023)	<.001
Average indoor temperature (°F)	0.016 (0.005, 0.026)	.003	0.021 (0.011, 0.032)	<.001
Site: Chicago (vs. New York)			0.201 (0.080, 0.321)	.001

[a] Season modifies the effects of temperature and relative humidity. When seasonal mean levels for temperature and relative humidity are considered, formaldehyde is higher during summer and lower during winter.

Table 3-28. Predictors of Log Formaldehyde (Parts Per Billion) — Study Group With Kitchen Exhaust Eligible (n = 370 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	0.731 (−0.089, 1.552)	.080	0.413 (−0.456, 1.283)	.349
Study group (vs. comparison group)	−0.041 (−0.150, 0.068)	.464	−0.061 (−0.170, 0.048)	.270
Kitchen exhaust ventilation (air exchanges per hour) greater than 0 (vs. no)	−0.297 (−0.457, −0.136)	<.001	−0.227 (−0.398, −0.055)	.010
Window open ≥ 12 hours per day during sampling period (vs. no)	−0.105 (−0.226, 0.016)	.088	−0.104 (−0.225, 0.016)	.090
Window open at all during sampling period (vs. no)	−0.148 (−0.241, −0.054)	.002	−0.121 (−0.219, −0.024)	.014
Season[a]		.043		.045
Winter (vs. fall)	0.171 (0.048, 0.295)	.007	0.168 (0.044, 0.291)	.008
Spring (vs. fall)	0.101 (−0.029, 0.231)	.127	0.092 (−0.039, 0.222)	.167
Summer (vs. fall)	−0.038 (−0.160, 0.084)	.541	−0.046 (−0.168, 0.076)	.458
Fall	0		0	
Average indoor relative humidity (%)	0.019 (0.015, 0.024)	<.001	0.019 (0.015, 0.024)	<.001
Average indoor temperature (°F)	0.018 (0.008, 0.028)	<.001	0.021 (0.011, 0.032)	<.001
Site: Chicago (vs. New York)			0.134 (0.005, 0.264)	.042

[a] Season modifies the effects of temperature and relative humidity. When seasonal mean levels for temperature and relative humidity are considered, formaldehyde is higher during summer and lower during winter.

Table 3-29. Predictors of Log Formaldehyde (Parts Per Billion) — Study Group With Kitchen Exhaust Eligible (n = 370 Visits in 151 Homes)

Variable	Model Without Site		Model With Site	
	Coefficient	*P* Value	Coefficient	*P* Value
Intercept	0.671 (−0.133, 1.476)	.101	0.357 (−0.507, 1.220)	.415
Kitchen exhaust ventilation (air exchanges per hour) greater than 0 (vs. no)	−0.313 (−0.467, −0.160)	<.001	−0.258 (−0.421, −0.095)	.002
Window open ≥ 12 hours per day during sampling period (vs. no)	−0.105 (−0.226, 0.016)	.088	−0.104 (−0.225, 0.016)	.090
Window open at all during sampling period (vs. no)	−0.105 (−0.226, 0.016)	.003	−0.119 (−0.216, −0.022)	.017
Window open at all during sampling period (vs. no)	−0.144 (−0.237, −0.051)	.002	−0.121 (−0.219, −0.024)	.014
Season[a]		.031		.028
Winter (vs. fall)	0.176 (0.053, 0.298)	.005	0.174 (0.051, 0.297)	.006
Spring (vs. fall)	0.105 (−0.024, 0.234)	.111	0.098 (−0.031, 0.228)	.136
Summer (vs. fall)	−0.044 (−0.165, 0.077)	.476	−0.054 (−0.175, 0.067	.381
Fall	0		0	
Average indoor relative humidity (%)	0.020 (0.015, 0.024)	<.001	0.020 (0.015, 0.024)	<.001
Average indoor temperature (°F)	0.018 (0.008, 0.028)	<.001	0.021 (0.011, 0.032)	<.001
Site: Chicago (vs. New York)			0.121 (−0.006, 0.249)	.042

[a] Season modifies the effects of temperature and relative humidity. When seasonal mean levels for temperature and relative humidity are considered, formaldehyde is higher during summer and lower during winter.

3.8 Assessing the Effect of Study Group on Contaminants by Adjusting for Multiple Comparisons

When hypotheses are closely related, the probability that one of the hypotheses could appear “significant” — when in fact this observed difference could be due to chance alone — increases. This is called the multiple comparisons problem, and it can suggest that an intervention has an effect on an outcome when it did not. This study generated discussion about whether there was one hypothesis encompassing five contaminants or five separate hypotheses. Although consensus does not exist across branches of research on how to make such a determination, a statistical method was applied to control for the potential problem of multiple comparisons.

The study hypothesized that the five contaminant levels would be lower in study homes than in comparison homes. The Holm-Bonferroni method was used to adjust for the five contaminant comparisons (see **Table 3-30**). The study group had lower GM levels than the comparison group for CO_2 and $PM_{2.5}$ ($P = .002$ and $P = .018$, respectively). The groups were not significantly different for NO_2 or CO ($P = .836$ and $P = .511$, respectively). The two groups were marginally different for formaldehyde ($P = .097$). Although the *P* values were lower after adjusting for multiple comparisons, the statistical classifications (significant, marginally significant, and not significant) did not change.

In short, the conclusions remained unchanged after adjusting the *P* values for multiple comparisons (see **Table 3-30**).

Table 3-30. Assessing Model-Adjusted Effects of Study Group on Contaminants Using Holm-Bonferroni Method to Account for Multiple Comparisons

Variable	Study (95% CI)	Comparison (95% CI)	*P* Value[a]
NO_2 (ppb)	25.6 (23.5, 27.8)	25.3 (23.3, 27.4)	.836
$PM_{2.5}$ (µg/m³)	13.2 (11.4, 15.3)	17.7 (15.3, 20.4)	.018
CO_2 (ppm)	716 (677, 756)	819 (778, 863)	.002
CO (ppm)	2.3 (1.8, 2.9)	2.8 (2.2, 3.5)	.511
Formaldehyde (ppb)	15.6 (14.4, 17.0)	17.7 (16.3, 19.2)	.097

Key: µg/m³ = micrograms of dust per cubic meter of air; CI = confidence interval; CO = carbon monoxide; CO_2 = carbon dioxide; GM = geometric mean; NO_2 = nitrogen dioxide; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter; ppb = parts per billion; ppm = parts per million

[a] Holm-Bonferroni multiple comparison *P* values

3.9 Health Interview Findings

When the original *Healthy Homes, Happy Kids* study was designed, the hypothesis was that children with poorly or not well-controlled asthma or a recent unscheduled visit to the emergency room, hospital, or urgent care center for asthma, living in an apartment that was renovated to a green standard would have better health after the renovation than before. The study was designed with a control arm of unrenovated homes where renovations would be completed after the study period. To observe a significant difference in health and health care utilization, a power calculation determined that a final sample of 711 children was needed. At the time the study was redesigned, the focus of the study changed from directly measuring the health of the participants to measuring the indoor air quality as an upstream factor that predicts resident health. The sample size for the redesigned study was based on the ability to see a statistically significant difference in the NO_2 levels between the study and comparison groups. Residents who were enrolled into the redesigned study were not required to have a pre-existing health condition, such as asthma. When preparing the data collection tools for the study, a decision was made to retain an abbreviated version of the health questionnaire with the hope that differences in health effects might be observed between the study and control arms, even if the sample size would make it unlikely to see statistically significant outcomes.

One hundred sixty-eight (168) adult respondents in 160 homes completed the heath interview questionnaire. They provided information about themselves and a total of 70 children in residence. Four of the questions asked whether the respondent or child currently had a specific health condition or had been diagnosed with such a condition. None of these conditions were likely to be caused by the intervention. Therefore, an unadjusted test of statistical significance was used to assess whether either arm of the study was likely to have residents with these conditions (see **Table 3-31**). Two of the health interview findings that achieved statistical significance between the study and comparison groups were (1) Has the participant ever been diagnosed with asthma? And (2) Does the participant currently have asthma? Participants who enrolled in the study group were more likely to have asthma. Participants were not asked to provide information on when they were diagnosed, however, so it is unknown whether diagnosis occurred before or after living in the renovated dwelling.

Thirteen (13) of the health questions were more likely to be affected by the intervention. The Holm-Bonferroni method was used to test the hypothesis that the study group has better health than the comparison group while adjusting for the thirteen health outcome comparisons (see **Table 3-32**). No significant differences ($P = 1.0$) were observed between groups for the 13 health outcomes.

Unlike the original design, all data collection for the redesigned study was conducted after renovation had occurred. It is not possible, therefore, to observe if resident health improved after renovation. The health differences between the study group and comparison group are inconclusive. As discussed in the **Introduction** section, a body of research documents the impact of indoor air contaminants on health. Although the health interview was administered with the expectation of seeing an effect despite a small sample size, the data were too limited to observe significant effects or even nonsignificant trends. These limitations are described further in the **Discussion** section.

Table 3-31. Selected Health Conditions of Study Participants

Variable	Study (95% CI)	Comparison (95% CI)	*P* Value
Ever diagnosed with asthma (all ages)	33% (109)	21% (129)	.042
Currently has asthma (all ages)	29% (109)	17% (126)	.020
Adult currently has emphysema	1% (73)	3% (89)	.414
Adult currently has chronic obstructive pulmonary disease	5% (75)	4% (90)	.791

Key: n = number of participants

Table 3-32. Selected Health Outcomes of Study Participants

Health Outcome	Study Group (n)	Comparison Group (n)
Child general health (excellent/very good vs. good/fair/poor)	68% (31)	77% (39)
Adult general health (excellent/very good vs. good/fair/poor)	31% (78)	24% (90)
In last 4 weeks, has physical or emotional health interfered with social activities (adult)? (> a little)	31% (78)	32% (90)
False/mostly false that adult is as healthy as anyone they know	31% (78)	29% (90)
Is adult health worse than 1 year ago?	19% (78)	21% (90)
Is adult health better than 1 year ago?	31% (78)	39% (90)
Adult physical health score (SF-36), 0–100, with 100 as the best possible score (mean)	45.4 (78)	45.6 (85)
Adult mental health score (SF-36), 0–100, with 100 as the best possible score (mean)	52.3 (78)	51.2 (85)
Adult perceived stress score (PSS-4), 0–16, with 0 as the best possible score (mean)	4.5 (76)	4.9 (89)
Health outcomes of 32 study group residents and 21 comparison group residents with current asthma		
Poorly controlled asthma — child	63% (8)	100% (4)
Poorly controlled asthma — adult	67% (24)	53% (17)
In last 3 months, were you at the emergency department or hospitalized for asthma?	25% (32)	10% (21)
In last 30 days, did you use inhaler for an asthma attack more than 4 times?	19% (32)	25% (20)

Key: n = number of participants; PSS = Perceived Stress Scale; SF-36 = 36-Item Short Form Survey Instrument for Adults

Note: Holm-Bonferroni multiple comparison adjustment applied for 13 health outcome comparisons. For all results, *P* = 1.0.

4 Discussion

4.1 Ventilation and Air Contaminants

The STOVE study results mark a significant contribution to the existing evidence base, demonstrating that improved mechanical ventilation in affordable homes rehabilitated using green building practices has many indoor air quality and potential health benefits. Although previous studies have supported the idea that green building practices improve indoor air quality and health (reviewed in **Appendix A**), the STOVE study is among the first to focus specifically on ventilation. Improving ventilation to meet the ASHRAE Standard 62.2 during a rehabilitation project can be complicated and difficult to implement depending on building construction, existing design, and project budgets. The results of this study provide evidence that supports broader adoption of mechanical ventilation through new resources and policy changes that address the complexity and cost of improving ventilation in such projects. (See section **5.2, Ventilation**, for more details.)

Table 4-1 and **Table 4-2** summarize the air contaminant and ventilation results of the STOVE study. Levels of four of the five contaminants improved substantially with mechanical ventilation. The improvement in $PM_{2.5}$ was the most important because of $PM_{2.5}$'s substantial and widespread threats to public health and documented negative health outcomes, such as asthma, COPD, heart and cardiovascular problems, cognitive difficulties, and other health issues. This improvement was seen in units with continuous whole-house mechanical ventilation delivered from bathroom exhaust.

Table 4-1. Contaminant Trends in the STOVE Study

Contaminant	Geometric Mean		95% Confidence Interval		Adjusted Effect — Study Group vs. Comparison Group	Guidance Level
	Study Group	Comparison Group	Study Group	Comparison Group		
Nitrogen dioxide (ppb)	25.6	25.3	24.0–27.4	23.7–27.0	NS	21[a]
$PM_{2.5}$ (µg/m^3)	13.3	17.7	11.8–15.1	15.8–19.8	−21%	See note[b]
Carbon dioxide (ppm)	715	823	685–745	789–859	−13%	1,000[c]
Carbon monoxide (15-minute maximum) (ppm)	2.3	2.8	1.9–2.8	2.3–3.4	−25%*	87[d]
Formaldehyde (ppb)	15.7	17.8	14.6–16.8	16.7–19.0	−44%*	7–80[d]

Key: µg/m^3 = micrograms of dust per cubic meter of air; NS = not significant; ppb = parts per billion; $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter; ppm = parts per million

* observed effect of continuous kitchen and bathroom exhaust vs. comparison dwelling, controlling for other factors

[a] WHO Guidelines for Indoor Air Pollutants. World Health Organization. 2010. Accessed November 8, 2021. https://www.euro.who.int/__data/assets/pdf_file/0009/128169/e94535.pdf

[b] EPA has a 12 µg/m^3 annual outdoor limit and a 35 µg/m^3 for $PM_{2.5}$ daily outdoor limit. EPA National Ambient Air Quality Standards. U.S. Environmental Protection Agency. Updated February 10, 2021. Accessed November 8, 2021. https://www.epa.gov/criteria-air-pollutants/naaqs-table

[c] *Residential Indoor Air Quality Guidelines: Carbon Dioxide*. Health Canada; March 2021. Accessed November 8, 2021. https://www.canada.ca/en/health-canada/services/publications/healthy-living/residential-indoor-air-quality-guidelines-carbon-dioxide.html

[d] California Office of Environmental Health Hazard Assessment (7 ppb) and WHO (80 ppb). *OEHHA Acute, 8-hour and Chronic Reference Exposure Level (REL) Summary*. California Office of Environmental Health Hazard Assessment. November 4, 2019. Accessed November 8, 2021. https://oehha.ca.gov/air/general-info/oehha-acute-8-hour-and-chronic-reference-exposure-level-rel-summary. WHO (Ibid.)

Table 4-2. Raw Unadjusted Geometric Mean Results by Ventilation Group and Sampling Site

	Number of Visits	Percent Exhaust Measured[a]	Mean Total ACH[b]	Mean Exhaust ACH[c]	Mean Kitchen ACH[d]	GM CO_2	GM $PM_{2.5}$	GM NO_2	GM CO Max	GM Formaldehyde[e]
New York	176					709	14.4	27.6	2.2	15.1
Units with CIMV[f]	93	66%	0.61	0.61	0.38	641	11.4	26.2	1.3	13.7
Units without CIMV	83	NA	0	0	0	789	18.6	29.1	3.8	16.9
Chicago	203					825	16.2	23.8	2.8	18.2
Units with CIMV[g]	108					774	15.6	25.2	3.0	17.6
Apartment units	50	82%	0.49	0.53	0	799	13.5	27.0	2.2	17.3
Townhome units	58	95%	0.61	0.61	0	753	17.6	23.3	3.9	17.9
Units without CIMV	95					884	17.0	22.3	2.6	19.0
Apartment units	84	NA	0	0	0	918	16.9	22.3	2.5	20.2
Townhome units	11	NA	0.41	0	0	655	17.5	21.9	3.6	11.4
TOTAL	379					769	15.4	25.5	2.5	16.7

Key: ACH = air changes per hour; CIMV = continuous (or intermittent) mechanical ventilation; CO = carbon monoxide (parts per million); CO_2 = carbon dioxide (parts per million); GM = geometric mean; NO_2 = nitrogen dioxide (parts per billion); $PM_{2.5}$ = particulate matter 2.5 micrometers or less in diameter (micrograms of dust per cubic meter of air)

[a] Percent of visits to a study unit where exhaust could be measured

[b] Total ACH from outdoor air, including exhaust air exchange and building leakage

[c] Dwelling unit ACH delivered from outdoor air associated with bathroom and kitchen exhaust (measured units only)

[d] Dwelling unit ACH delivered from outdoor air associated with kitchen exhaust only (measured units only)

[e] Formaldehyde is measured in ppb

[f] Rooftop fans were ducted to 100% of bathrooms and 85% of kitchens in measured units

[g] Bathroom exhaust fans

4.1.1 Impact of Continuous Mechanical Ventilation and Location of Ventilation

The effect of continuous mechanical ventilation that complies with the whole-house ASHRAE ventilation requirement matched the expectations of the research team for $PM_{2.5}$, CO_2, CO, and formaldehyde. The levels of these contaminants generally are lower outdoors than they are inside homes with gas stoves as shown in the **Results** section. The exhaust ventilation that was present in the study group dwellings extracted air from the dwelling, and that air was replaced by outdoor air that entered the building through gaps in the building envelope. The use of continuous ventilation that was engineered for each dwelling was critical to generating the effects the study observed. In the comparison dwellings, indoor air also was diluted by the outdoor air through window openings, use of resident-operated ventilation, or air exchange through gaps in the envelope, but the levels of air exchange were lower than in the study group dwellings. All comparison group units except townhomes had effectively zero air exchanges from outdoor air. Townhomes received an infiltration credit when calculating ASHRAE compliance for the study, as specified in the ASHRAE standard due to their configuration. In addition, air exchange would be minimal in the comparison group homes during periods when the occupant did not open windows or operate ventilation fans.

For CO and formaldehyde, the location of the continuous exhaust ventilation also proved to be important. When a contaminant source is primarily in a single room (e.g., a gas stove in the kitchen), extracting the air from that room before it migrates throughout the living space is important to reduce occupant exposure. CO and formaldehyde levels were significantly lower in the primary living space in dwellings with kitchen exhaust ventilation than in homes without such ventilation. Dwellings with only continuous bathroom exhaust ventilation had small but nonsignificant improvements in CO and formaldehyde levels compared with dwellings without continuous exhaust ventilation. Because ventilation systems should be designed to address multiple contaminants in the indoor environment, these findings support the need to install continuous exhaust ventilation in both kitchens and bathrooms in order to maximize improvements in $PM_{2.5}$, CO_2, formaldehyde, and CO. Although this study did not include homes without gas stoves, electric stoves also can produce elevated levels of $PM_{2.5}$, so kitchen exhaust ventilation might be important to improve indoor air quality in homes with electric stoves as well.

4.1.2 Observations About Intermittent Ventilation

This study examined the effect of ventilation that was designed to be compliant with ASHRAE Standard 62.2. Five dwellings were placed in the comparison group because they were not designed for this standard, yet they performed similarly to the study group units. These dwellings had exhaust ventilation that was set on a timer to operate at a set exhaust rate intermittently throughout the day. While this method of ventilation design is compliant with the ASHRAE whole-house ventilation requirement, the remainder of the study homes were designed to be compliant with ASHRAE through continuous rather than intermittent exhaust. When these five dwellings were included with the study group units (and excluded from the comparison group units), the combined effect on $PM_{2.5}$ and CO_2 was slightly larger than the original study group/comparison group differential. Although these dwellings represent a small sample, this finding suggests that further research should be conducted on intermittent ventilation strategies.

4.1.3 Ventilation Effects on NO_2

In section **3.3, NO_2 Findings**, the unexpected null results of the studied ventilation on NO_2 levels are discussed. The study lacks evidence to explain empirically why the main hypothesis was not proven. However, some possible reasons to explain the null results are presented to assist future research in this area.

First, the assumption that outdoor NO_2 levels would be substantially lower than indoor NO_2 levels in dwellings with gas stoves might not be correct in certain dense urban communities with high levels of traffic. This is especially true during winter when more combustion activities (e.g., power plant usage) create additional NO_2, temperature inversions keep NO_2 closer to the ground, and less ultraviolet light is present to break down NO_2. If outdoor levels are not substantially lower than indoor levels, ventilation will not be able to reduce the indoor NO_2 levels.

Second, these same dense communities with high traffic volume can have higher levels of O_3 and oxides during summer. The use of windows in warm weather can allow for the infiltration of these oxides into the indoor environment, where they can mix with NO from gas stoves to produce NO_2. Although NO_2 is lower indoors during summer than during winter, it was not as low in this study as would be expected based on outdoor NO_2 levels. Because NO_2 is an unstable gas that reacts with other oxides, ventilation does not appear in this study to have a fixed dilution effect in communities with higher levels of those oxides. Further research is needed on the effects of ventilation on indoor NO_2 in communities with outdoor air pollution.

4.1.4 Other Methods to Improve Indoor Air Quality

This study's results support the installation and maintenance of continuous mechanical ventilation that complies with the whole-house ASHRAE ventilation requirement as an effective means of improving indoor air quality, but mechanical ventilation is only one of several tools that can be used to improve resident health outcomes. Outdoor air quality plays an important role in indoor air quality, so enforcing existing outdoor air quality standards should remain a high priority for our nation's policymakers. Indoor source control also is an important factor. Replacing gas stoves with electric or induction stoves would reduce the sources of all of the contaminants in this study, especially NO_2 and CO. Generation of electricity from non-carbon sources like wind and solar at the community level also would help reduce greenhouse gas emissions. Other contaminant sources — such as environmental tobacco smoke and consumer and building products containing formaldehyde (and other VOCs) — should be reduced through education, policies, and practices that discourage or ban their use. Although source control must be advanced, some contaminants cannot be eliminated, such as CO_2 from exhaled breath and $PM_{2.5}$ from routine cooking and cleaning. As buildings are made tighter to conserve energy and address climate disruption, efforts to maintain healthy indoor environments through mechanical ventilation must be undertaken.

4.2 Study Strengths and Limitations

4.2.1 Measurement Strategy

Among this study's strengths was that the study measured five contaminants. Measuring more than one contaminant improved the prospect of more fully understanding the impact of mechanical ventilation. The sources and factors contributing to contaminant levels differ, and as a result, the effect that mechanical ventilation had on each contaminant was found to differ. Had the study considered only the effects on NO_2 levels, the conclusions about ventilation effectiveness would have been very different. For example, if the study had not examined CO or formaldehyde, the importance of kitchen exhaust ventilation would have been overlooked.

Although the decision to assess five contaminants proved beneficial for the study, widening the focus to span multiple contaminants did bring some tradeoffs. All five contaminants had been associated with the use of gas stoves in prior studies, but gas stove usage was not the only source of these contaminants. The study did capture information about smoking and outdoor sources, when available. However, to maintain a reasonable data collection burden on the participants, information about type of cooking was not collected. Previous studies have documented that $PM_{2.5}$ is related mostly to cooking itself (frying vs. baking) and less on fuel combustion. Formaldehyde generation depends on the temperature of combustion. Formaldehyde also can be emitted into indoor air from building and consumer products, but limited data (e.g., use of an air freshener) were collected on these sources to minimize participant reporting burden. Additionally, the study assumed that emissions from building products would be low because green rehabilitation standards require the use of low-VOC products; therefore, data collection on these sources was not conducted. Future studies should examine closely the indoor sources of these contaminants of interest and impact of ventilation because the sources vary.

Another tradeoff in assessing five contaminants was that samples were collected only in the living area. Although this was done to reduce the burden on the participants and contain study costs, it created some limitations. To better understand the sources and pathways of contaminants within a dwelling, samples also could have been collected in the kitchen and bedrooms of the home. For example, kitchen exhaust ventilation ducted to the exterior was associated with lower CO and formaldehyde, suggesting that the kitchen was a substantial source of those contaminants. For CO, the assumption of the kitchen as a substantial source is supported by the study's modeling, which found that the gas stove and outdoor sources were significantly associated with indoor CO levels. For formaldehyde, the analytical support is weaker given that no specific source of formaldehyde was identified in the models. In each of these cases, collecting data from the kitchen and bedroom would have improved the strength of the study's findings.

Inclusion of nicotine measurements was another strength of this study. Although agreements to not smoke during the sampling period were made with occupants, they were only partially effective. Nicotine sampling enabled analyses to control for the confounding influence of smoking.

One study limitation was that additional contaminants that are known to have negative health consequences — such as black carbon, semi-volatile organic compounds, radon, mold, pesticide residues, ultrafine particles, and others — were not measured. The study also did not measure substances that can react with NO_2, such as O_3 and VOCs; data on these substances might have indicated why NO_2 levels did not improve.

Finally, the study did not include samples collected immediately outside each dwelling unit due to weather, structural, and security considerations. However, to address this limitation, the research team acquired EPA and other outdoor air sampling data for some contaminants, even though these were a distance away from the units in the study. The outdoor air data were particularly important in explaining indoor NO_2 levels because the outdoor data showed higher-than-expected NO_2 levels.

4.2.2 Focus on Affordable Housing Green Rehabilitation

A unique contribution of the STOVE study is that it focused on the effects of mechanical ventilation in existing affordable housing, whereas previous studies focused on ventilation in newly constructed affordable housing. Newly constructed affordable housing offers many more options for installing mechanical ventilation and fewer related cost constraints compared to the rehabilitation of existing housing. Construction of new affordable housing, while desperately needed, is limited to at best 1% of the new housing stock each year; therefore, it is critically important to ensure a safe and healthful environment in existing properties that will continue to be in service for decades to come.

The Criteria provides guidance for promoting a safe and healthful environment in existing affordable housing properties through moderate or substantial rehab. This study provides important evidence that not only confirms the importance of including ventilation-related components in the Criteria, but also prompts recommendations that can further the adoption of mechanical ventilation in both substantial and moderate rehab in affordable housing properties, which are discussed in section **5.3, Recommendations**). Currently, the Criteria requires mechanical ventilation for substantial rehabilitation and new construction but only recommends it for moderate rehabilitation. Because the properties included in the STOVE study all underwent moderate green rehabilitation within 8 years before the start of data collection at the property, the improved indoor air quality in the study group has important implications for the Criteria's recommendations for moderate green rehabilitation. The results of this study suggest that these recommendations should be reviewed.

While the STOVE study's focus on existing affordable housing makes its findings particularly relevant for the field, conducting a research study within the context of the affordable housing ecosystem also offers important lessons for future researchers. Recruiting both properties and residents for the study proved more challenging than expected. The relationships between affordable housing property owners and their residents influenced the study's efforts to recruit and enroll participants. In the study's early years, some housing owners expressed reluctance to participate because of perceived liability around housing conditions and concerns about how the study would impact their relationship with residents. These and other insights are detailed in two reports published to highlight the lessons learned through the design and implementation of the study: *Measuring the Impact of Affordable Housing Interventions: Strategies for Study Design and Implementation*,[134] published in 2017, and *Overcoming Challenges in Housing-Based Research: Insights from a Longitudinal Study*,[135] published in 2020.

In short, the strong ties created between the property owners, property management staff, study participants, and researchers was a strength of the study. Without them, the STOVE study would not have come to fruition.

4.2.3 Ventilation Design and Performance

Another strength of this study was that multiple measurements of ventilation were considered. For example, the research team did not rely only on whether the building was designed to meet ASHRAE Standard 62.2; compliance was confirmed through dwelling performance (ventilation) tests (see the **Methods** section). This was an important aspect of the study — building systems do not always operate as designed, particularly as they age. Although the requirement that buildings meet ASHRAE Standard 62.2 was ultimately beneficial for the research, it created limitations by narrowing the pool of eligible properties. Fewer properties complied with the ASHRAE standard than initially expected, creating challenges and timeline delays in the study's implementation.

The requirement that buildings meet the ASHRAE standard also facilitated a process of coordination with developers to confirm property eligibility that

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[134] *Measuring the Impact of Affordable Housing Interventions: Strategies for Study Design and Implementation*. Enterprise Community Partners; April 2017. https://www.enterprisecommunity.org/resources/measuring-impact-affordable-housing-interventions

[135] Eilers L, De Scisciolo S. *Overcoming Challenges in Housing-Based Research: Insights from a Longitudinal Study*. Enterprise Community Partners, The JPB Foundation, National Center for Healthy Housing; November 2020. Accessed November 8, 2021. https://www.enterprisecommunity.org/resources/overcoming-challenges-housing-based-research

provided additional feedback regarding implementation of the standard. In discussions with the developers, the research team learned that ASHRAE Standard 62.2 is not as well-known or understood as originally anticipated and is perceived as costly to implement in affordable housing rehabs.[136] Developers interested in mechanical ventilation must include it in their construction scopes, which are reviewed as part of the financing process, creating a possible barrier to implementation. In a stakeholder engagement session, one developer remarked, “We applied for additional funding in our budget to install ventilation, but we were rejected.” Together with perception of high cost, the ASHRAE standard’s complexity is notable, suggesting the need for simplification and additional funding for ventilation (see section **5.3, Recommendations**).

Although all study units were required to meet the ASHRAE standard, one limitation of the study was the extent of variability in ventilation design and performance among units. All the units in the study group had continuous bathroom exhaust that was designed to ventilate the entire unit. The units in the comparison group either had no bathroom exhaust or, if they did, the bathroom exhaust was not continuous. Some of the dwellings in New York also had kitchen exhaust ducted to the exterior, but in the Chicago study group units, the kitchen fans were recirculating and not ducted to the exterior. Performance measurements showed variability between the design parameters and the actual airflow. Another limitation was that this study was conducted post-rehabilitation, therefore it was not possible to collect pre-rehabilitation data.

This variability in performance was likely associated with at least two key factors: inadequate maintenance and the difficulty in adequately designing airflows in multifamily buildings, which can be complex. Ventilation testing in the STOVE study showed that some bathroom exhausts were not functioning. Other tests showed that even when fans were rated to move air at 50 cfm, they sometimes had lower airflows, likely because of longer duct runs and the associated increased static pressure that was not fully accounted for in the design. Longer duct runs might require higher flow rates to overcome the additional resistance caused by the longer duct runs. These both support recommendations for better maintenance and

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[136] *Measuring the Impact of Affordable Housing Interventions: Strategies for Study Design and Implementation*. Enterprise Community Partners; April 2017. https://www.enterprisecommunity.org/resources/measuring-impact-affordable-housing-interventions

improved design. As another example of the variability in ventilation performance, a few of the study group units had ventilation levels that were twice as high as those required by ASHRAE (usually because two bathrooms in a single unit were exhausting continuously, when only one was needed given the size of the unit).

Additionally, the STOVE study was characterized by study group units that used exhaust-only ventilation. The exhaust-only option tends to put the unit under negative pressure, making back-drafting and combustion spillage from chimneys and flues more likely, unless care is taken. In this study, there was no evidence that back-drafting occurred in any of the dwellings. Ventilation designs that rely on bathroom exhaust to ventilate an entire dwelling unit might also introduce more variability and be less effective because a single bathroom exhaust fan might not be able to ventilate an entire apartment. However, this type of bathroom exhaust ventilation is one of the most common means of achieving ASHRAE compliance.

Although a strength of the study was relying on actual quantified air exchange rates, not design intent, limitations included the inevitable variability in performance across building ventilation systems and that exhaust-only ventilation systems were included in the study properties. Despite this limitation, the exhaust-only ventilation systems included in the study reflect the most common system present in the affordable housing stock. Future research should examine whether supply-only designs (units with a planned outdoor air supply and no exhaust) or balanced designs (units with both supply and exhaust) perform better than exhaust-only designs. In addition, future research could examine whether exhaust ventilation from bathrooms and kitchens or a combination of both is effective in providing whole-house ventilation.

Of course, ventilation does not occur only through the mechanical systems. Another study strength was the collection of data on window and door usage. These variables proved to be an important addition to mechanical ventilation data.

4.2.4 Retention and Randomization

Many longitudinal studies suffer from high attrition rates over time, a well-known source of bias. Retention rates under 50% are common in housing studies. One of this study's strengths was its ability to keep participants engaged during the course of home visits conducted during an 8-month period, resulting in a 66–74% retention rate. This helped to minimize bias and also was important in understanding the influence of different seasons on the contaminants measured.

Despite the high retention rates, some limitations did exist. Retention is influenced by participant compensation. Although post office money orders were used to compensate participants for their time, several participants found them difficult to cash, and some may have left the study because of this. Other residents relocated during the study period, and the new residents were ineligible for the study (the research protocols required that residents lived in their homes at least 4 months before the first study visit). These and other factors affected retention rates.

Another limitation was that the study and comparison groups could not be randomized. At the time of enrollment, each building already had been renovated with a common ventilation system throughout the building, and the participants were residing in their dwellings. Although it would have been ideal to be able to compare two groups within the same building so that factors like outdoor air quality, dwelling size, and the building's smoking policy would be the same, this was not possible. The lack of randomization resulted in some intercorrelated factors that could not be considered independently in analysis. For example, all dwellings with kitchen exhaust ventilation were in four- to six-story New York buildings, while study group units without kitchen exhaust ventilation tended to be in buildings with fewer than four stories in Chicago. The effects of kitchen exhaust ventilation could not be separated easily from other unique characteristics of those buildings.

4.2.5 Multidisciplinary Team

The STOVE research team and its National Advisory Council had diverse expertise. Members included physicians, engineers, exposure scientists, statisticians, epidemiologists, industrial hygienists, community-based research experts, managers, ventilation experts, quality assurance and data management professionals, and an affordable housing provider. Students were trained to reliably carry out complex data collection tasks, including conducting recruitment and thoughtful informed consent, collecting samples, interviewing participants, identifying building deficiencies, scheduling and coordinating visits, and maintaining security. Students also were able to conduct some of their own research, including Ph.D. and master's theses and capstone projects.

Building managers, affordable housing developers and owners, and community organizers also contributed to the study. Without their support and cooperation, the study would not have been possible. However, the study design did not include compensation for these individuals. This lack of compensation might have hampered the ability to identify candidate buildings and enrolling participants and may have introduced a source of bias to the study. Residents also were an important part of the study team, contributing to the research through their participation and, in some cases, helping to recruit additional residents in their building. The strengths and limitations of coordinating such a large and diverse multidisciplinary team are highlighted in two reports summarizing lessons learned from this study.[137,138]

4.2.6 Multiple Institutional Review Boards

Three IRBs were involved in this study: the central IRB (Advarra), one in New York (Mount Sinai), and one in Chicago (University of Illinois Chicago). With limited experience in the ethical considerations of housing research, the IRBs sometimes treated the study as though it were a drug trial or a clinical study, which occasionally led to minor delays. Nonetheless, all three IRBs ultimately approved the project as a minimal risk study, the main risk being accidental breach of confidentiality, which did not occur. Ideally, improved coordination among the IRBs would have saved time and avoided duplication; however, each IRB chose to retain its own authority.

4.2.7 Air Sampling Methods

All air sampling methods performed reasonably well. Out of the total 1,895 air samples collected, only 45, or 2.4%, were lost or excluded due to quality control issues. The excluded samples included 8 NO_2 results, 11 $PM_{2.5}$ results, 12 CO_2 results, 10 CO results, and 4 formaldehyde results.

Although the measurement of multiple contaminants was a strength of the study, two of the sampling methods performed less reliably than the others. Despite a small level of field sample loss, all sampling devices performed within the norm for environmental sampling studies and did not impact the study findings. The $PM_{2.5}$

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[137] *Measuring the Impact of Affordable Housing Interventions: Strategies for Study Design and Implementation. Enterprise Community Partners*; April 2017. https://www.enterprisecommunity.org/resources/measuring-impact-affordable-housing-interventions

[138] Eilers L, De Scisciolo S. *Overcoming Challenges in Housing-Based Research: Insights from a Longitudinal Study*. Enterprise Community Partners, The JPB Foundation, National Center for Healthy Housing; November 2020. Accessed November 8, 2021. https://www.enterprisecommunity.org/resources/overcoming-challenges-housing-based-research

samplers used a pump to draw air through a filtered impactor. This method has the advantage of producing gravimetric results rather than particle counts, making its results more comparable to EPA standards. A limitation, however, was that a few study participants thought the pumps were too noisy, despite the pumps being enclosed in a sound-deadening jacket. In addition, the pumps sometimes failed and required repair or replacement. In some cases, the problems occurred during transport (e.g., wires became loose), and the field data collector was unable to start the sampler while in the home. Data collectors were trained to carry an extra pump so that the $PM_{2.5}$ tests could be carried out concurrently with other sampling.

The analytical laboratory played an especially important role in providing equipment repairs and supplies and analytical advice; a strength of this study was the collaboration between laboratory and field personnel. Nevertheless, the pumps were designed to operate at lower flow rates during a single work shift, not a 4-day sampling period at a higher flow rate. This did not affect the collection of particulate matter when running, but it did result in the premature stoppage of pumps during a small percentage of visits. During 8 of the 379 visits (2%), the $PM_{2.5}$ sampler stopped operating less than 24 hours into the sampling process; the data had to be excluded. This level of field sample loss is within the norm for environmental sampling studies; nonetheless, researchers considering the use of this equipment should consider its limitations and possible alternatives.

Another sampling method that performed less reliably was the datalogger used to take CO readings. Unlike the CO_2 datalogger, the CO datalogger did not have a method to alert the operator of low battery capacity. With experience, field data collectors learned to anticipate battery length and replace the special-order batteries before they stopped in the field. During 10 of the 379 visits (3%), the CO logger stopped operating less than 24 hours into the sampling process; the data had to be excluded. The CO_2 datalogger did not experience similar problems with stoppage during sampling; only one of the CO_2 dataloggers failed to collect at least 24 hours of data.

During 15 of the 379 visits (4%), the $PM_{2.5}$ pump or the CO datalogger provided readings for more than 24 hours but stopped before the conclusion of the 4-day sampling period. Although the 4-day sampling period was intended to help ensure the samples were representative of both weekend and weekday living patterns, our analysis found that results collected for at least 24 hours were comparable to a full 96-hour sample and, therefore, could be retained for statistical modeling.

The passive samplers for NO_2, formaldehyde, and nicotine, along with the CO_2 datalogger, all proved to be reliable and relatively simple to operate. Fewer than 11 of these samples (3%) had extreme values that resulted in exclusion from statistical analyses. The extreme passive sampler values might be associated with a failure to open and close the samplers correctly or with laboratory analytical error. These failures were rare and not considered a concern for the study. Specifically, it appears unlikely that the difference in NO_2 sampler design, operation, and laboratory analysis explained the observation that NO_2 levels did not improve, unlike the other contaminants.

4.2.8 Self-Reported Health Interviews

The study's inability to observe significant self-reported general, physical, and mental health improvements directly through health interviews underscores the importance of the many factors that contribute to overall well-being. Although the evidence is clear that improved indoor air quality improves health, documenting health gains within this study proved to be a limitation for a number of reasons. The STOVE study was not designed and powered to see changes in health outcomes. More importantly, no baseline health data had been collected before the renovations were completed. The greatest impact of improved indoor air quality likely would be seen in participants with an existing respiratory condition, but fewer than 25 participants in each of the study and comparison groups had a respiratory condition. Although the interview instrument was drawn from several well-known and validated sources and was carefully administered, it may be inherently limited by a participant's subjectivity and other innate or external contributing factors to health. Clinical health indicators also have limitations, such as access and confidentiality concerns. Future research can help uncover more reliable health status indicators. Modeling future health outcomes associated with improved indoor air quality should be part of future studies.

4.2.9 Costs and Benefits

Although it is beyond the scope of this study to monetize costs and benefits of improved ventilation and air quality, the economic benefits are likely to be substantial. One study[139] found that for each incremental reduction of 1 µg/m^3 in outdoor concentrations of particulate matter, nearly $350 million would be generated annually in economic benefits for the United States.[140] The STOVE study showed a reduction in indoor $PM_{2.5}$ of about 20% (a reduction of 4 µg/m^3 for the average dwelling in this study) due to improved ventilation, when controlling for other factors. Reductions in CO_2, CO, and formaldehyde also would be expected to produce additional economic benefits. Further research is needed to monetize both the benefits and the costs associated with indoor air improvements.

A 2017 study conducted for Enterprise suggested that the incremental cost of installing green rehabilitation and continuous mechanical ventilation is highly variable due to the diversity in building types, sizes, and designs. That study examined 10 building typologies in three cities: Chicago, New York City, and San Francisco. The draft report estimated that the incremental cost of installing ASHRAE-compliant ventilation ranged from $0 (where it was already a code requirement) to $530 (where bathroom fans were installed) to $2,756 per dwelling (where rooftop fans also were installed). Although this cost may seem prohibitive in certain cases, even the highest cost estimate represents only 33% of the total incremental costs of including green features in a rehabilitation and approximately 5% of total construction costs. The analysis found that construction changes that positively impacted health accounted for more than 75% of the total incremental costs for meeting the green standard. It is important to keep in mind that most of those health improvements have benefits in non-health areas as well, from energy savings to comfort improvements to cleaner manufacturing processes.

Affordable housing developers operate on very limited budgets, and additional costs above those required for minimum code compliance can be prohibitive. Providing additional financing to cover the cost of mechanical ventilation, particularly in rehabilitation projects, likely would lead to more widespread adoption of ASHRAE Standard 62.2–compliant ventilation with the scope of work, leading to improved indoor air quality and better resident health outcomes. It is

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[139] Williams AM, Phaneuf DJ, Barrett MA, Su JG. Short-term impact of $PM_{2.5}$ on contemporaneous asthma medication use: behavior and the value of pollution reductions. *Proc Natl Acad Sci U S A*. 2019;116 (12) 5246-5253. doi:10.1073/pnas.1805647115

[140] The study was based on changes in $PM_{2.5}$ in outdoor air only; was limited to asthma outcomes; did not include the costs and benefits of installing, maintaining, and operating ventilation systems; did not include the benefits of improved ventilation on structural durability, such as less rot and mold; and did consider discount rates (i.e., the present value of future money).

worth noting that market forces alone are unlikely to meet this need because housing markets have traditionally been unable to monetize the benefits of housing-based health interventions, such as ventilation. While the market might be able to determine a value for certain physical improvements — for example, the cost of replacing a roof — computing the costs and benefits of health investments is far more complex. Furthermore, the benefits of improved health from better quality housing do not necessarily accrue to building owners. Ultimately, the failure to make investments in health-promoting housing transfers the avoided housing cost to the health care sector in the form of increased medical costs stemming from avoidable housing-related illnesses.

4.2.10 Study Design Flexibility

An earlier version of the STOVE study involved the use of additional clinically based methods and metrics, such as spirometry and nitric oxide in exhaled breath. It also included enrollment criteria that required participants to have poorly controlled asthma (this was thought to increase the chances of detecting a statistically significant improvement in health outcomes). The spirometry and exhaled breath measurements proved to be too complex and unreliable in a home setting, and the team was unable to find enough participants who met the “poorly controlled asthma” criterion in properties soon to be renovated according to green criteria. As a result, the study was redesigned to focus on the effect of mechanical ventilation on indoor air quality. The support of the study’s primary funder, The JPB Foundation, and the National Advisory Council were tremendous assets and provided the flexibility and scientific expertise necessary to enable the study to be completely redesigned and implemented.

4.2.11 The COVID-19 Pandemic

Of the many challenges that occurred during the implementation of this study, perhaps none was greater than the unforeseen COVID-19 pandemic, which arose during data collection after the Phase 1 and 2 environmental sampling visits had been conducted. The study team was nimble and adapted the study protocols to ensure that both participants and researchers were protected during the Phase 3 visits. This involved enabling the participants to play a greater role in deploying the air samplers, taking social distancing precautions, and adhering to other procedures explained more fully in **Appendix C, COVID-19 Protocol Modification**.

Participants reported that they were grateful for the researchers' concerns and diligence in completing data collection during the pandemic.

4.2.12 Stakeholder Outreach

The study team engaged housing and resident stakeholders separately at the conclusion of the study in a series of virtual sessions to provide information, share findings, and collect feedback.

Two virtual information sessions were offered to owners and property managers of the buildings participating in the study. During these sessions, the research team shared the study's findings and engaged attendees in a dialogue about the importance of mechanical ventilation and the difficulties associated with its installation as part of rehabilitation projects. For example, one housing provider shared that their organization sought to incorporate ventilation into the rehabilitation of one of their properties but was denied by the funder because the funder believed this element of the scope to be cost prohibitive. Housing providers emphasized in their comments during the sessions that the study is valuable to communicate why ventilation matters and that additional research would help to further advance this work. One key theme that emerged was the need to advocate for financial incentives and other resources to support continuous mechanical ventilation in all rehabilitation projects. Another theme was the need to further study the financial costs and benefits to installing continuous mechanical ventilation in all rehabilitation projects to help justify the costs of this work and to support advocacy efforts. Housing providers also emphasized the need for educational materials to share with residents to communicate the importance of ventilation in their homes and how to properly use ventilation to maximize potential health benefits. The housing providers also expressed an interest in communicating this information alongside other key aspects of property awareness (or "house rules") that similarly affect resident health, such as no-smoking policies.

The study team also held virtual information sessions for all residents of the buildings that were part of the study, regardless of whether the residents participated in the study. Three sessions were offered: two in English and one in Spanish. The sessions provided residents with information about indoor air contaminants, summarized the study's findings, offered tips for using ventilation and improving indoor air quality, and gathered resident feedback on the study's findings. During the sessions, residents responded positively to the information presented and expressed enthusiasm in putting the information into practice by using the strategies presented to improve indoor air quality. These strategies included using a kitchen fan when cooking and switching on a fan's "boost" mode when available. Multiple residents shared that after engaging with the study team, they contacted their building operator to have a maintenance check performed on their fans. In at least one case, this resulted in the building owner fixing a fan that was not operational. Echoing feedback from property owners, residents also commented that it would be valuable for building owners to share information with all residents about the benefits of ventilation and how to optimally use their ventilation systems. Most residents participating in the information sessions were not fully aware of the benefits of ventilation or how to use ventilation in their home before participating in the study or attending the session.

The feedback gained through these stakeholder engagement sessions underscores the importance of advocacy and education to support the proper design, installation, maintenance, and occupant use of mechanical ventilation.

5 Conclusions

5.1 Green Criteria, Indoor Air Quality, and Health

This study was conducted to help answer the question of whether improved ventilation in multifamily dwellings, designed to meet the Enterprise Green Communities Criteria or an equivalent, results in improved indoor air quality and, ultimately, better health outcomes. Those who have low incomes across the United States and around the world suffer disproportionately from poor health associated with poorly constructed and substandard housing with inadequate ventilation (in many cases those are made of a disproportionate number of Black and Latino households). Green building standards offer promise in rehabilitating housing to support good health through improved ventilation and other means. These measures result in better indoor air quality and less exposure to potentially toxic substances.

The results of this study showed large and statistically significant improvements in levels of four of the five contaminants studied, when comparing dwellings with continuous mechanical ventilation designed to meet the requirements of ASHRAE Standard 62.2 and those without such ventilation. Specifically, $PM_{2.5}$ and CO_2 were found at much lower concentrations in homes with continuous mechanical ventilation systems. CO and formaldehyde had lower concentrations in homes with continuous mechanical ventilation in both the kitchen and bathroom. In general, exposures should be kept as low as possible. Together, these improvements would be expected to result in better health outcomes for the residents.

5.2 Ventilation

The improvements in contaminant levels in the study group homes occurred because these homes had an average total air exchange rate of about 0.6 ACH due to the bathroom exhaust and kitchen exhaust, if present. The comparison group homes, which did not have continuous mechanical ventilation, had an air exchange rate close to zero (assuming little or no infiltration from cracks, crevices, doors, and windows). The mechanical ventilation diluted the indoor contaminants with outdoor air to achieve the improvements, although some of the replacement air also could have come from other units in the building or its hallways and common areas.

An important exception to the overall conclusion of this study was that NO_2 levels remained essentially the same between the study and comparison groups. Although further research is needed, two of the reasons might include that the outdoor air had high NO_2 levels (particularly in some seasons and in large cities with high traffic) and that NO_2 reacts with other contaminants. Ventilation generally relies on good quality air replacing the exhausted air. In other words, poor outdoor air quality will adversely affect indoor air quality, especially for NO_2.

Ventilation also frequently is considered to be expensive, particularly in rehabilitation of existing buildings. Installing new ductwork in existing buildings that were not designed for such ductwork is difficult and can be expensive. Also, the air that replaces the exhausted air must be heated, cooled, and humidified or dehumidified. The high cost of implementing ventilation improvements is one reason why the Criteria requires compliance with ASHRAE Standard 62.2 only in the context of substantial rehabilitation and new construction, not in moderate rehabilitation. Typically, renovation budgets are higher for substantial rehabilitation.

Other technical challenges in achieving better ventilation include the prospect of creating too much negative pressure within a unit, potentially causing unplanned backward airflows in chimneys and flues. The results from this study show that at the exhaust rates measured, air quality is improved, not degraded, even when using limited continuous bathroom exhaust.

Finally, the study showed that ventilation was quite variable. Some units that were designed to comply with the ASHRAE standard had less ventilation than required by the standard, but others had more than required. Despite this variability, the results clearly show that relying on unplanned building leakage to ventilate homes, which was the case for the comparison group units, does not lead to better indoor air quality.

5.3 Recommendations

5.3.1 Systems Interventions

Adopt ASHRAE Standard 62.2 Requirements

Mechanical ventilation and full compliance with ASHRAE Standard 62.2 should be included in moderate and substantial rehabilitation in green building standards and certification programs, in other local building codes, and in federal and state requirements for subsidies and tax credits. The STOVE study found significantly lower concentrations of indoor air contaminants in homes with mechanical ventilation that met the ASHRAE standard than in those without such ventilation. Lower levels of indoor air contaminants will contribute to better health outcomes for residents and should be incentivized throughout the affordable housing industry.

Provide Financing for Ventilation

Housing improvement budgets should include the costs of installing mechanical ventilation. Ideally, this could mean a separate line item for mechanical ventilation in housing rehabilitation financing programs to ensure that costs are fully covered, which would incentivize the adoption of mechanical ventilation in rehabilitation construction scopes. This recommendation addresses financing issues raised by developers during the course of the study as they sought to include ventilation improvements within their moderate rehab project.

Simplify ASHRAE Standard 62.2

ASHRAE Standard 62.2 is complex, with numerous and nuanced credits, such as an infiltration credit. Although there are sound reasons for such complexity, it poses a significant barrier. Many of the owners, developers, and engineers contacted by the research team as part of this study did not fully understand the requirement of the standard or know if their units complied. ASHRAE should consider ways to simplify its standard.

Establish Indoor Air Quality Standards

Like many studies before it, the STOVE study showed a linkage between outdoor and indoor air quality. Since the passage of the Clean Air Act in 1963, outdoor air pollution has been regulated, yet no enforceable standards exist in the United States for indoor residential air. The growing body of evidence that indoor air pollutant levels often exceed the limits on outdoor levels calls for regulatory action. Congress should amend the Clean Air Act or otherwise authorize EPA to establish and enforce such standards. Consensus bodies should be established in the interim to develop recommended standards for indoor residential air.

The absence of legally enforceable indoor air standards and the presence of such standards for outdoor air seems incongruous given the two are related to each other so clearly, supporting a recommendation that indoor air standards be adopted. At the same time, actions to reduce outdoor pollutant levels must continue to be pursued. Without indoor residential air standards, no incentive exists to adopt systems like mechanical ventilation that can result in lower contaminant levels, nor is it possible to determine whether such systems are reducing exposure to levels that are not harmful to human health. For example, this study observed large reductions in $PM_{2.5}$ levels, which appear very meaningful based on prior research. The relevance of the findings could be enhanced if it were possible to show that homes with continuous ventilation were more likely to have $PM_{2.5}$ levels below a consensus threshold than homes without such ventilation.

5.3.2 Building Interventions

Eliminate or Reduce Indoor Contaminant Sources and Replace Gas Stoves With Electric

Ventilation alone cannot be expected to reduce all exposures, as demonstrated by this study's NO_2 results. If sources of pollutants both indoors and outdoors can be eliminated or reduced, indoor air quality will improve. Some sources cannot be eliminated, such as CO_2 from human respiration. However, other sources are amenable to elimination; gas stoves are one example. Although some contaminants still will be emitted during the cooking process, the products of combustion can be eliminated. Electrification is increasingly emerging as an important strategy in reducing greenhouse gas emissions. Gas stoves should be eliminated and replaced by low-polluting cooking methods, such as electric or induction stoves. This recommendation is supported by the findings of this study and others indicating that stoves and frequency of cooking were sources of air contaminants.

Adopt Smoke-Free Housing Policies

Another source of contamination is tobacco smoke. Smoke-free policies have gained increased acceptance in recent years and now are required in public housing supported by HUD and are increasingly common in affordable housing properties. The results of this study, however, show that smoking remains a major source of contamination. Smoke-free policies, together with the necessary support to help residents stop smoking, should be adopted more broadly. This recommendation is supported by the study's finding that smoking was an important source of air contaminants and is a known detriment to human health.

Install Mechanical Ventilation Systems and Improve Maintenance of Existing Ones

Mechanical ventilation should be installed when possible. Where mechanical ventilation exists, it should be properly maintained. Some of the fans in the STOVE study appeared to not function at the time of testing. Maintenance personnel should be trained on how to inspect and replace nonfunctioning systems and how to set airflow rates. This recommendation is supported by the wide variation in airflow rates measured by the ventilation tests conducted for the STOVE study and field personnel observations that some fans did not appear to function properly, indicating a lack of proper maintenance.

5.3.3 Education

Educate Occupants Who Already Have Mechanical Ventilation

The importance of ventilation should be explained to building residents, and they should be encouraged to report a nonfunctioning bathroom or kitchen exhaust fan to their property managers. Leasing agents or property managers should point out fan switches and explain why residents should not attempt to override continuous fans and should use manually operated kitchen and bathroom exhaust fans. During a resident engagement session, one participant suggested that building owners consider posting information in the lobby to remind residents of how and when they should use their exhaust fans. Some residents also thought the fan was on when it actually was not; a simple label on the switch would help mitigate this. ASHRAE Standard 62.2 states, "Controls shall include text or an icon indicating the system's function."[141]

Provide Technical Assistance

Technical assistance should be provided to building owners, property managers, developers, financing institutions, and others seeking to improve ventilation. Although it certainly is true that cost is a barrier to adoption of ventilation system installation, the complications related to achieving compliance also pose a barrier.

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[141] *ANSI/ASHRAE Standard 62.2-2019: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. ASHRAE. Accessed November 8, 2021. https://www.ashrae.org/technical-resources/standards-and-guidelines/read-only-versions-of-ashrae-standards

Stakeholder engagement conducted during the course of the study indicates that building owners and financing agencies have many questions about including continuous, ASHRAE-compliant mechanical ventilation in multifamily affordable housing rehabilitation. Some building owners and financing agencies question whether a ventilation system will offer benefits beyond what might be achieved from opening windows. Even further, the systems must be installed and maintained properly to deliver those benefits, yet the study found that the systems were not always functioning properly. Affordable housing intermediaries like Enterprise should partner with ASHRAE and multifamily energy-efficiency experts to develop additional training resources targeted to the audiences listed above to explain the value of continuous mechanical ventilation, describe how these systems can be installed and maintained properly, and promote widespread adoption.

Invest in Public Education and Marketing

High-quality housing often is presented to the public as an amenity. Additional messaging tools are needed to convey the importance of green housing criteria and efficient, effective ventilation and to promote widespread adoption of ventilation standards. As long as the public is uninformed about how the built environment can affect indoor air quality and their health, it will remain challenging to convince owners and financiers of multifamily affordable housing to justify an investment in better indoor air quality management strategies like ventilation. Currently, one of the largest adopters of the ASHRAE Standard 62.2 for existing housing is the U.S. Department of Energy's Weatherization Assistance Program. The standard was adopted only after an evaluation of the program documented that energy-efficiency efforts — such as closing gaps in the building envelope — resulted in increased indoor air contamination. Requiring adequate mechanical ventilation was the best solution to avoid worsening indoor air quality while fulfilling the program's mission to reduce the energy cost burden on lower-income clients. Attendees at the STOVE study's post-study resident engagement sessions said they wished they knew more about their indoor environment and what they could do about it. Environmental justice begins with awareness and advocacy.

5.4 Research Needs

The STOVE study has shown the need for further research to advance our understanding of indoor air chemistry, ventilation, and improved health.

First, studies that examine indoor air chemical reactions and how such reactions can influence health clearly are needed for NO_2, as well as other contaminants. The study's main hypothesis anticipated improvements in NO_2 levels, which were not observed. This occurred even though the mechanism that was expected to reduce indoor NO_2 in the study group dwellings was observed: air exchange rates were higher in study group dwellings than in comparison group dwellings, and during at least some seasons, particularly summer, NO_2 levels outdoors were substantially lower than indoors. For a stable, nonreactive gas like CO_2, the increased mixing of outdoor air with indoor air in the study group dwellings resulted in a meaningful and statistically significant reduction in indoor CO_2, compared with the comparison group dwellings. The same was not true for NO_2. Although this study lacks empirical evidence to conclude that indoor chemical reactions played a role in the unexpected results, prior research on how O_3 and VOCs can react with NO and NO_2 suggest that this may have been a factor. Further work is needed in housing with gas stoves and varying levels of ventilation that is situated in communities with higher levels of outdoor pollution.

Second, improvements in air quality sensors and the capability to link them to automated ventilation systems to address episodic exposures could reduce the cost of operating ventilation, because the system might not need to be run continuously. Since EPA's convening of the Apps and Sensors for Air Pollution Workshop in 2012 to discuss emerging opportunities around low-cost air quality sensors, sensors measuring oxides of nitrogen, O_3, sulfur dioxide, CO_2, CO, and particulate matter have been incorporated into consumer-grade products to assess indoor air quality and outdoor air pollution. This work has advanced research into sensor-based demand-control ventilation, which has been explored as a way to reduce indoor air contaminants while managing peak residential energy demand.[142] Results from research focused on in-home environmental sensors tied to heating, ventilating, and air conditioning (HVAC) controls are promising and warrant further investigation. Improved sensors also could help to produce more stable estimates by measuring air quality over longer time periods, as well as inform about emerging contaminants and how they affect indoor air quality. Additionally, sensors potentially could be used in ways that enable occupants to take action to improve their own air quality. This should be an area of investigation for future

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[142] Fisk WJ, De Almeida AT. *Sensor-based demand-controlled ventilation: a review. Energy and Buildings*. 1998;29(1):35-45.

research. Future research ideally should include larger and longer-term studies, with randomization to the extent feasible.

Finally, research is needed on how housing studies can better engage the public and potential participants in their design and implementation, including around participant enrollment. The STOVE study lacked community and participant perspectives during the research design phase and experienced difficulties in identifying candidate buildings and encouraging occupants to enroll as participants in the study. Future research would benefit from exploring ways to best engage these stakeholders to ensure that studies more directly respond to community needs and are seen as a priority by key stakeholders. Future studies also would benefit from research that explores reasons why participants choose to engage in research, actions that are needed to build trust and encourage participation, and barriers that make potential participants reluctant to join. This future research would build on the observations and lessons learned by the STOVE study team.[143,144]

5.5 Summary

The STOVE project offered a unique opportunity to investigate how ventilation improves indoor air quality. The study's findings highlight the importance of mechanical ventilation in reducing levels of common indoor air contaminants. Given the health risks posed by these contaminants, mechanical ventilation must be prioritized during housing rehabilitation, and budgets must be adequate to cover the costs of installation and maintenance. Resident education also should be prioritized by building managers to ensure that occupants understand the importance of using their kitchen and bathroom fans and are encouraged to report those that are not operating properly.

This study provided insights into how green affordable housing can improve the built environment and, by extension, resident health through practices that support housing sustainability, resiliency, and equity. For years, the issues of affordable

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[143] *Measuring the Impact of Affordable Housing Interventions: Strategies for Study Design and Implementation*. Enterprise Community Partners; April 2017. https://www.enterprisecommunity.org/resources/measuring-impact-affordable-housing-interventions

[144] Eilers L, De Scisciolo S. *Overcoming Challenges in Housing-Based Research: Insights from a Longitudinal Study*. Enterprise Community Partners, The JPB Foundation, National Center for Healthy Housing; November 2020. Accessed November 8, 2021. https://www.enterprisecommunity.org/resources/overcoming-challenges-housing-based-research

housing, affordable energy, the environment, and health have been addressed in a siloed manner. The green affordable housing and healthy homes movements of recent decades have highlighted the need to tackle these issues systematically rather than as independent problems.

This study’s findings also support existing green housing practices, such as requiring continuous mechanical ventilation that complies with the whole-house ASHRAE ventilation requirement in new and substantially rehabbed housing and encouraging smoke-free policies. This report encourages policymakers to consider what incentives or mandates are needed to reduce the use of gas appliances in housing, as well as what investments are needed to allow the current ventilation requirements to be expanded to all rehabilitation projects. Taken together, an enhanced combination of green housing policies, and the funding to support it, will offer better housing quality, a reduced energy burden, a more sustainable environment, and healthier residents.

Appendices

Appendix A: Literature Review of Green Healthy Housing Studies

Overview

A literature review of the health benefits associated with residential green construction, including both new construction and rehabilitation of existing housing, was conducted as part of the *Healthy Homes, Happy Kids study*. With the redesign of the original study to focus on the effects of mechanical ventilation on indoor air quality, this literature review was updated to include studies on ventilation in the context of weatherization and energy efficiency.

Studies of New Green Construction

One of the most robust studies on new green construction is the Breathe-Easy home study,[1] which used a quasi-experimental design to compare the asthma outcomes of two groups of children and adolescents with asthma living in households with low incomes. The groups included 34 participants who moved into new construction and a local matched cohort of 68 participants who had received a previous asthma-control intervention. Both groups received in-home asthma education. The new homes featured a building envelope with air-and moisture-tight construction beyond code to ensure that the air and moisture entering the home was controlled tightly with sealed rigid insulation; mats and shoe storage at the entry to minimize the entry of contaminants into the homes; landscaping to minimize outdoor asthma triggers in yards; outdoor spaces using plants with low allergen ratings; integrated pest management; and low-volatile organic compound (VOC) and nontoxic interior furnishings and materials, including flooring with no polyvinyl chloride (PVC) and low-emission adhesives. The upgraded ventilation system included an energy recovery component and high-efficiency particulate air (HEPA) filtration (i.e., Minimum Efficiency Reporting Value [MERV] 15) of both outdoor and indoor air and provided 270 cubic feet per minute (cfm) of fresh and filtered air (up to 105 cfm of fresh air). The heating system was a hydronic radiant baseboard system that minimizes dust circulating in the air. Local exhaust ventilation was used in all bathroom, utility, and kitchen areas and was vented directly to the outside. Results showed that asthma symptom-free days increased from a mean of 8.6 days per 2 weeks in their old homes to 12.4 days per 2 weeks after 1 year. The proportion

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[1] Takaro TK, Krieger J, Song L, Sharify D, Beaudet N. The Breathe-Easy Home: the impact of asthma-friendly home construction on clinical outcomes and trigger exposure. *Am J Public Health*. 2011;101(1):55-62. doi:10.2105/AJPH.2010.300008

of residents with an urgent asthma-related clinical visit in the previous 3 months decreased from 62% to 21%, and caretakers' quality of life increased significantly. The study analyzed allergens in settled dust, which showed a significant sustained reduction, but it did not measure other air contaminants. Exposures to mold, rodents, and moisture also were reduced significantly.

Another study of new green construction[2] employed a prospective telephone-administered questionnaire in new-home occupants to compare general and respiratory health at occupancy and 1 year later in two groups. The study group consisted of 52 R-2000 (a Canadian designation) homes (128 occupants) built to preset and certified criteria for energy-efficient ventilation and construction practices. The control group was 53 new homes (149 occupants) built in the same year and in the same geographic area and price range but without the energy conservation measures. Analyzed by household, respiratory symptom scores improved significantly over the year of occupancy. In comparison with the control homes, occupants of the study group homes reported more improvement in throat irritation ($P < .004$), cough ($P < .002$), fatigue ($P < .009$), and irritability ($P < .002$). The study's authors note that some of these improvements may be due to slightly higher smoking and asthma rates in the control homes, although the control group did have lower rates of hay fever and allergies. The number of people with asthma was too few to draw conclusions, and the study did not include air sampling. The authors recommended an extension of this pilot study be conducted to determine if these perceived health benefits are reproducible or relate to objective indoor air quality measures.

Another study of public or subsidized housing new construction in Chicago[3] compared health before and after families moved into new green healthy housing. It also compared health with a control group in traditionally repaired housing and employed a mixed-method study design (n = 325 dwellings with 803 individuals). The study used self-reported health status via structured interview, visual assessment of housing condition, indoor air sampling, and Medicaid expenditure and diagnostic data. The results showed that housing conditions and self-reported physical and mental health improved significantly in the green healthy housing

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[2] Leech JA, Raizenne M, Gusdorf J. Health in occupants of energy efficient new homes. *Indoor Air*. 2004;14(3):169-173. doi:10.1111/j.1600-0668.2004.00212.x

[3] Jacobs DE, Ahonen E, Dixon SL, et al. Moving into green healthy housing. *J Public Health Manag Pract*. 2015;21(4):345-354. doi:10.1097/PHH.0000000000000047

study group, compared with both the control group and the study group before relocation. Hay fever, headaches, sinusitis, angina, and respiratory allergy also improved significantly. As compared to the control homes, adults in the study homes reported significantly better mental health measures for sadness ($P < .001$), nervousness ($P < .001$), restlessness ($P < .001$), hopelessness ($P = .031$), and “everything being an effort” ($P = .007$). They also reported significantly better mental health measures when compared to their previous public housing ($P < .001$, $P < .001$, $P < .001$, $P = .001$, and $P = .026$, respectively).

Asthma severity was measured by self-reported lost school and work days and disturbed sleep, and symptoms improved significantly, as did sadness, nervousness, restlessness, and child behavior. The percentage of control group children who required urgent care for asthma during the previous year was much higher than that of study group children (60% vs. 39%; $P = .029$) and was marginally significant for adults (49% vs. 40%; $P = .094$). Study group children with asthma also had significantly lower frequencies of asthma symptoms, difficulty staying asleep, and use of a prescription inhaler to stop an asthma attack than control group children with asthma ($P = .020$, $P = .043$, and $P = .014$, respectively). For children and adults with asthma, relatively more people reported that their asthma was better, rather than the same or worse, in their current home versus their previous home ($P < .001$ for both children and adults).

Air sampling measurements for carbon dioxide (CO_2), particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$), carbon monoxide, formaldehyde, and VOCs were not significantly different between the two groups, possibly because the control group dwellings were found to have more small gaps in the building envelope (i.e., were “leakier”) than the study group dwellings. Medicaid data in this exploratory study were inconclusive and inconsistent with self-reported health outcomes and visual assessment data on housing quality, but they hold promise for future investigation. One limitation of this study was that randomization was not feasible. Ventilation rates could not be measured in the two groups, and allergens in settled dust also were not measured. Possible sources of bias in the Medicaid data include older age in the study group, changes in Medicaid eligibility over time, controlling for Medicaid costs in an urban area, and the increased stress associated with relocation, even if the move is into better housing.

A study[4] of Leadership in Energy and Environmental Design (LEED) Platinum-certified green housing new construction in New York City had participants complete a home-based respiratory health questionnaire before moving into the new dwellings. Follow-up occurred at 6, 12, and 18 months post-move. A home-based educational module was delivered on indoor environmental interventions to avoid asthma triggers. A pretest was given before the module, and a post-test was given 9 months later, including an evaluation of behavioral practice changes. The results showed statistically significant decreases in continuous daily respiratory symptoms ($P < .001$), asthma symptoms disrupting sleep in the past month ($P = .028$), and urgent visits to a health care professional for asthma in the past 3 months ($P = .038$). Clinically relevant outcomes included fewer days with asthma symptoms; asthma episodes; days of work, school, or day care missed; and emergency department visits. Education changes from pretest to post-test included increased knowledge about dust mites, roaches, mold, and chemical irritants ($P = .007$). Common behavioral changes included use of hypoallergenic mattress covers, use of green cleaning products, and elimination of bedroom carpets. This study's limitations included the absence of a control or comparison group, the absence of a doctor's diagnosis of asthma, and a small sample size (n = 18 households). The study was able to retain 78% of those enrolled.

Another study of new green housing construction[5] showed that indoor air quality is an important predictor of health, especially in populations with low incomes. In two successive years, the study conducted environmental sampling, home inspections, and health questionnaires with families in green and conventional (control) dwellings in two public housing developments. A subset of participants was followed as they relocated from conventional to green housing or from conventional to conventional housing. Measurements included $PM_{2.5}$, formaldehyde, nitrogen dioxide (NO_2), nicotine, CO_2, and air exchange rate (AER) during a 7-day sampling period coincident with the administration of the interview. Results showed 57%, 65%, and 93% lower concentrations of $PM_{2.5}$, NO_2, and nicotine (respectively) in green versus control homes, all of which were statistically significant ($P = .032$, $P < .001$, and $P = .003$, respectively). Fewer reports

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[4] Garland E, Steenburgh ET, Sanchez SH, et al. Impact of LEED-certified affordable housing on asthma in the South Bronx. *Prog Community Health Partnersh*. 2013; 7(1):29-37. doi:10.1353/cpr.2013.0010

[5] Colton MD, MacNaughton P, Vallarino J, et al. Indoor air quality in green vs. conventional multifamily low-income housing. *Environ Sci Technol*. 2014;48(14):7833-7841. doi:10.1021/es501489u

of mold, pests, inadequate ventilation, and stuffiness were made. Differences in formaldehyde and CO_2 were not statistically significant. The AER was marginally lower in green buildings ($P = .109$). Participants in green homes experienced 47% fewer "sick building syndrome" symptoms ($P < .010$). After controlling for temperature, no significant difference in AER between the two groups existed, although the control group did demonstrate a wider range in AER values. Researchers suggested that some differences could be associated with switching from gas to electric stoves in the study group.

Another research study[6] used pollutant measurements, home inspections, diagnostic testing, and occupant surveys to assess indoor air quality in 24 new or deeply retrofitted homes designed to be high-performance green buildings in California. Although the mechanically vented homes were six times as airtight as nonmechanically ventilated homes (medians of 1.1 and 6.1 air changes per hour (ACH) at 50 pascals; n = 11 and n = 8, respectively), their use of mechanical ventilation systems and possibly window operation meant their median AERs were almost the same (0.30 vs. 0.32 per hour; n = 8 and n = 8, respectively). Pollutant levels also were similar in vented and unvented homes. The researchers observed that occupant behavior was important, with cooking exhaust systems being used inconsistently or suffering from design flaws. Ambient NO_2 standards were exceeded or nearly exceeded in four homes that either used gas ranges with standing pilots or were passive house-style homes that used gas cooking burners without venting range hoods. Homes without active particle filtration had particle count concentrations approximately double those in homes with enhanced filtration. The majority of homes reported using low-emitting materials; consistent with this, formaldehyde levels were approximately half those in conventional, new California homes built before 2008. Emissions of ultrafine particles (with diameters < 100 nanometers) were dramatically lower on induction electric cooktops, compared with either gas or resistance electric models. These results indicate that high-performance homes can achieve acceptable and even exceptional indoor air quality by providing adequate general mechanical ventilation, using low-emitting materials, providing mechanical particle filtration, incorporating well-designed exhaust ventilation for kitchens and bathrooms,

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[6] Less B, Mullen NA, Singer BC, Walker IS. Indoor air quality in 24 California residences designed as high-performance green homes. *Science and Technology for the Built Environment.* 2015; 21(1):14-24. doi:10.1080/10789669.2014.961850

and educating occupants to use the kitchen and bathroom ventilation. The chief limitation of this study was the absence of a control or comparison group.

Studies of Green Housing Rehabilitation

A study of green housing rehabilitation in Minnesota[7] investigated resident health and building performance outcomes at baseline and 1 year after the rehabilitation of affordable housing using the Enterprise Green Communities Criteria (the Criteria). Health outcomes were assessed via structured interview, and healthy homes training was provided to all participants. Other data included measured ventilation, CO_2, and radon. Results showed that adults reported statistically significant improvements in overall general health, asthma, and non-asthma respiratory problems. Adults also reported that their children's overall health improved, but this was not statistically significant. Significant improvements were seen in non-asthma respiratory problems, such as sinusitis, hay fever, and bronchitis. Post-renovation building performance testing indicated that the building envelope was tightened and that local exhaust fans performed well. New mechanical ventilation was installed (compared with no ventilation previously), with fresh air being supplied at 70% of the minimum ventilation rates established by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) Standard 62.2. Radon was less than 4 picocuries per liter of air following mitigation, and the annual average indoor CO_2 level was 982 parts per million. Energy use was reduced by 45% during the 1-year post-renovation period. Limitations of the study included difficulty in retrofitting existing buildings to add mechanical ventilation systems when they previously had none. Despite best efforts, full compliance with ASHRAE Standard 62.2 could not be achieved in this study. Another limitation was the absence of clinical metrics of health. The study also relied on recall for baseline self-reported health status due to construction-related impediments.

Two studies examined health effects specifically among elderly individuals in green rehabilitated housing. The first consisted of a study[8] of public housing that used questions from the Medicare Health Outcomes Survey to interview residents

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[7] Breysse J, Jacobs DE, Weber W, et al. Health outcomes and green renovation of affordable housing. *Public Health Rep*. 2011;126(Suppl 1):64-75. doi:10.1177/00333549111260S110

[8] Breysse J, Dixon SL, Jacobs DE, Lopez J, Weber W. Self-reported health outcomes associated with green-renovated public housing among primarily elderly residents. *J Public Health Manag Pract*. 2015;21(4):355-367. doi:10.1097/PHH.0000000000000199

at baseline and 1 year after green renovation of a 101 unit building. This study compared self-reported mental and physical health outcomes of two groups of residents (all-ages group: median, 66 years, n = 40; elder group: median, 72 years, n = 22), with outcomes for two same-aged low-income Minnesota comparison groups taken from Medicare Health Outcomes Survey participants (n = 40 and 572, respectively). The green renovations included building envelope restoration; new heating, electrical, and ventilation systems; air sealing; new insulation and exterior cladding; window replacement; installation of ENERGY STAR® fixtures and appliances; asbestos and mold abatement; apartment gut retrofits; use of low-VOC and moisture-resistant materials; exercise enhancements (e.g., walking trails); and a no-smoking policy indoors. Results showed that the all-ages study group's mental health improved significantly more than the all-ages comparison group's mental health, on the basis of the mean number of good mental health days in the past month ($P = .026$) and the mean mental health component score ($P = .023$). Sixteen percent (16%) less all-ages study group participants versus 8% more all-ages comparison group participants reported falls ($P = .055$). The elder study group's 9% improvement in general physical health was not statistically significantly better than the elder comparison group's decline (6%; $P = .094$). Significantly fewer individuals in the all-ages study group than in the all-ages comparison group reported smoke in their dwellings because of tobacco products (20% vs. 0%; $P = .005$), likely reflecting the new no-smoking policy. The authors concluded that green healthy housing renovation results in improved mental and general physical health, prevented falls, and reduced exposure to tobacco smoke. Limitations in the study included the inability to fully control for disability status in both the study and comparison groups and the inability to control for seasonal effects and housing condition in the comparison group. Finally, the introduction of a no-smoking policy following the renovation likely had some unmeasured influence on health outcomes.

The second study of elderly individuals in green renovated housing[9] examined (1) whether health and economic circumstances make elderly individuals vulnerable to indoor environmental conditions and (2) if green energy retrofits in affordable housing for older adults can improve indoor climatic conditions (e.g., temperature, humidity, air infiltration) and whether such improvements correspond

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[9] Ahrentzen S, Erickson J, Fonseca E. Thermal and health outcomes of energy efficiency retrofits of homes of older adults. *Indoor Air*. 2016;26(4):582-593. doi:10.1111/ina.12239

with improved health and comfort of residents. The housing improvements included replacement of interior cabinetry, flooring, and paint with materials that had low or no VOCs. Fifty-seven (57) residents from 53 apartment dwellings participated in both baseline (pre-renovation) and 1-year post-renovation data collection trials. Environmental measures included temperature, relative humidity (RH), and air infiltration. Health measures included general health, emotional distress, and sleep. Four questions addressed residents' perceptions of temperature quality. Results demonstrated a 19% reduction in energy consumption following the retrofit and a significant stabilization of unit temperature from pre-retrofit to 1 year post-retrofit. Reductions in an apartment's temperature extremes of 27.2°C (81°F) and above also corresponded with improvement in the occupant's reported health during the same time period, although the reductions did not correspond with the occupant's perceptions of thermal comfort. A companion study[10] of the same housing development reported other health and environmental improvements and measured indoor formaldehyde levels before the building retrofit, which routinely exceeded reference exposure limits. In the long-term follow-up sampling, indoor formaldehyde decreased for the entire study population by a statistically significant margin. Indoor levels of particulate matter were dominated by fine particles and showed a statistically significant decrease in the long-term follow-up sampling within certain resident subpopulations (i.e., residents who reported smoking, residents who had resided longer at the apartment complex). A main weakness of this study was the absence of a control or comparison group.

Another study[11] employed discrete event simulation modeling to assess green home improvements on asthma-related outcomes and environmental factors. This study focused on evaluating the impact of building interventions on indoor environmental quality and pediatric asthma health care use and compared intervention costs to health care costs and energy savings. The effect of environmental factors, medication compliance, seasonality, and medical history on pollutant concentrations indoors and asthma outcomes in affordable multifamily housing was simulated by estimating health care use and costs at baseline and

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[10] Frey SE, Destaillats H, Cohn S, Ahrentzen S, Fraser MP. The effects of an energy efficiency retrofit on indoor air quality. *Indoor Air*. 2015; 25(2):210-219. doi:10.1111/ina.12134

[11] Fabian MP, Adamkiewicz G, Stout NK, Sandel M, Levy JI. A simulation model of building intervention impacts on indoor environmental quality, pediatric asthma, and costs. *J Allergy Clin Immunol*. 2014;133(1):77-84. doi:10.1016/j.jaci.2013.06.003

subsequent to interventions, then comparing health care costs to energy savings and intervention costs. Results showed that simulated interventions — such as integrated pest management and repairing kitchen exhaust fans — led to 7–12% reductions in serious asthma events, with 1–3-year payback periods. The authors concluded that weatherization efforts targeted solely toward tightening a building envelope led to 20% more serious asthma events; however, bundling weatherization efforts with repair of kitchen exhaust fans and elimination of indoor sources (e.g., gas stoves, smokers) mitigated this effect. Limitations inherent in the model included that only one suitable study of the relationships between lung function and asthma outcomes was published at the time of analysis, limiting the generalizability of results to populations outside of Boston public housing. Another limitation was the simplification in classifying patients with persistent asthma for medication assignment solely based on lung function values, whereas asthma classification is far more complex.

A study[12] of green rehabilitated housing in Washington, D.C., examined self-reported resident physical and mental health via structured health interviews, allergens in settled dust, and building conditions at baseline and 1-year follow-up in an affordable housing development being renovated in accordance with green healthy housing improvements that comply with both the Criteria and LEED Gold certification. Results showed that self-reported general health in adults significantly improved, from 59% to 67% ($P = .026$), with large statistically significant improvements in water and dampness problems, cockroaches and rodents, and pesticide use. Median cockroach (Bla g1) and mouse (Mus m1) allergen dust loadings showed large and statistically significant reductions from baseline to 3 months post-intervention, and these reductions were sustained at 1 year (both $P < .05$). Energy and water cost savings were 16% and 54%, respectively. The chief limitations of this study included the absence of a control or comparison group and the inability to measure air contaminants.

Studies of Ventilation and Weatherization

Although weatherization (i.e., energy retrofits, residential energy-efficiency improvements) is not considered “green” by definition, weatherization and associated ventilation improvements are a key component of most green standards, including the Criteria. Therefore, some of the more recent studies are included here.

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[12] Jacobs DE, Breysse J, Dixon SL, et al. Health and housing outcomes from green renovation of low-income housing in Washington, D.C. *J Environ Health*. 2014;76(7):8-60.

A randomized trial[13] showed how compliance with ASHRAE Standard 62-1989 (n = 39 single-family houses) and ASHRAE Standard 62.2-2010 (n = 42 single-family houses) influenced ventilation rates, moisture balance, indoor air quality, and self-reported physical and mental health outcomes. None of the homes in the ASHRAE Standard 62-1989 group received mechanical ventilation, whereas all homes in the ASHRAE Standard 62.2-2010 group did. In the ASHRAE Standard 62.2-2010 homes, average total airflow was nearly twice as high (79 cfm vs. 39 cfm), and VOCs, formaldehyde, and CO_2 all were reduced significantly. Humidity in the ASHRAE Standard 62.2-2010 group was only about half that of the ASHRAE Standard 62-1989 group, using the moisture balance metric. Radon levels increased in the basement but declined on the first floor living space in ASHRAE Standard 62.2-2010 homes. Using a standardized structured health interview, children in each group reported fewer headaches, less eczema, and fewer skin allergies after weatherization, and adults showed improvements in psychological distress. The study did not target homes of children with asthma, and no change in asthma was observed. The study showed that indoor air quality and health improve when weatherization is accompanied by an ASHRAE residential ventilation standard and that compliance with ASHRAE Standard 62.2-2010 led to greater improvements in certain outcomes, compared with ASHRAE Standard 62-1989. The study's main limitations were the inability to characterize sources of air contaminants and a limited follow-up period (6 months).

A small study of 49 homes[14] investigated three groups of homes: Medicaid-insured homes that received U.S. Department of Housing and Urban Development Healthy Homes interventions only, homes that received U.S. Department of Energy (DOE) Weatherization Assistance Program (WAP) interventions only, and homes that received DOE Weatherization Plus Health interventions. Comparing pre-and post-intervention data for the three study groups revealed that both weatherization (e.g., air sealing, insulation, heating equipment installation and maintenance) and healthy housing interventions (e.g., flooring replacement, ventilation, dust mite mattress and pillow covers, education) reduced asthma triggers. All three groups had decreased moisture and mold and improved thermal comfort. Caregivers

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[13] Francisco PW, Jacobs DE, Targos L, et al. Ventilation, indoor air quality and health in homes undergoing weatherization. *Indoor Air*. 2017;27(2):463-477. doi:10.1111/ina.12325

[14] Rose E, Hawkins B, Tonn, B, Paton D, Shah L. Exploring potential impacts of weatherization and healthy homes interventions on asthma-related Medicaid claims and costs in a small cohort in Washington state. Oak Ridge National Laboratory, Env Sciences Division; 2015. ORNL/TM-2015-213.

reported child health improvement. All households within the Weatherization Plus Health group, 94% of the Healthy Homes–only group, and 64% of the WAP-only group reported children in their care "could run and play longer" post-intervention. A statistically significant decrease of $421 was observed in annualized asthma-related Medicaid costs for all of the study groups combined. The average number of Medicaid claims paid also decreased significantly within the Weatherization Plus Health and WAP-only groups, by 0.42 and 0.91 claims per month, respectively. This study was not published in the peer-reviewed literature and did not report statistical significance for some outcomes.

An Austrian study[15] compared two groups of apartment buildings, one with lower energy use and mechanical ventilation (n = 62 buildings) and another with only "passive" ventilation (n = 61 buildings). Health outcomes were not measured, but results demonstrated improvements in levels of formaldehyde, radon, RH, and CO_2, suggesting that buildings with lower energy use and mechanical ventilation do not have poorer indoor air quality.

A randomized controlled trial[16] investigating the effect of improved home ventilation on ACH, indoor air contaminants, and asthma symptoms in children studied 83 asthmatic children during a 2-year period who lived in buildings with low ventilation rates (less than 0.3 ACH). The children were randomized into a group that received installation of either a heat recovery ventilator (HRV) or energy recovery ventilator (ERV) and those that did not. The homes that received the improved ventilation had an increase of 0.15 ACH on average. A variety of chemical parameters (e.g., CO_2, VOCs, semi-volatile organic compounds, NO_2, formaldehyde), biologic parameters (e.g., settling, airborne mold spores, house dust mite allergens), and physical parameters (e.g., temperature, RH, $PM_{2.5}$, building envelope air tightness, ventilation rate) were measured during summer, fall, and winter. During the fall and winter seasons, significant increases were seen in the mean ventilation rate in the homes of the intervention group, and a statistically significant reduction in the mean was recorded for formaldehyde, airborne mold spores, toluene, styrene, limonene, and a-pinene concentrations. Although no

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[15] Wallner P, Munoz U, Tappler P, et al. Indoor environmental quality in mechanically ventilated, energy-efficient buildings vs. conventional buildings. *Int J Environ Res Public Health*. 2015;12(11):14132-14147. doi:10.3390/ijerph121114132

[16] Lajoie P, Aubin D, Gingras V, et al. The IVAIRE project — a randomized controlled study of the impact of ventilation on indoor air quality and the respiratory symptoms of asthmatic children in single family homes. *Indoor Air.* 2015;25(6):582-597. doi:10.1111/ina.12181

significant group difference was observed in the number of days with asthma symptoms per 2-week period, a significant decrease was seen in the intervention group in the proportion of children who experienced any wheezing (one or more episodes) and those with four or more episodes in the 12-month period. This study indicates that improved ventilation reduces air contaminants and may prevent wheezing. The authors observed that because of a lack of statistical power, a larger study is needed. The limitations in this study included the inability to control for differences in medication across the two groups, improvement in both groups (perhaps due to the Hawthorne effect), and asthma in the study group at baseline possibly being more severe.

Another randomized controlled trial[17] of ventilation and asthma examined a tailored package of housing improvements providing adequate ventilation and temperature, following inspection by a housing officer. Ventilation improvements consisted of an HRV that increased fresh air supply to bedrooms. The study included 192 children with asthma aged 5–14 years, identified from general practice physician records. At baseline and after 4 and 12 months, parents reported their child's asthma-specific and generic quality of life and days off from school. The asthma scores for the study showed a statistically significant improvement at 12 months. The generic quality-of-life scale reported that physical problems were reduced significantly at 4 months, but results at 12 months did not indicate statistical significance ($P = .061$). The improvement in psychosocial quality of life at 12 months also was not statistically significant. Parent-reported school attendance improved, but not significantly. The authors concluded that the installation of a ventilation system, and central heating where necessary, in the homes of children with moderate to severe asthma improves their parent-reported respiratory health and quality of life. Limitations of this study included the inability to collect air quality or allergen data.

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[17] Woodfine L, Neal RD, Bruce N, et al. Enhancing ventilation in homes of children with asthma: Pragmatic randomised controlled trial. *Br J Gen Pract.* 2011;61(592):e724-e732. doi:10.3399/bjgp11X606636

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