U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Home R_X: The Health Benefits of Home Performance

A Review of the Current Evidence

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December 2016

NOTICE

Cover page photo captions (from top to bottom): 1. Caulk being used to seal cracks in a band joist insulation. Image courtesy of Building America Solution Center; 2. Outdoor unit for a ductless mini split heat pump. Image courtesy of Building America Solution Center; 3. High efficiency gas furnace. Image courtesy of Building America Solution Center; 4. A zero energy ready home in Hickory, NC. Image courtesy of Habitat for Humanity of Catawba Valley

Acknowledgements

We would like to thank the following people for contributing to this report, including David Lee, Eric Werling, Josh Olsen, and Madeline Salzman from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy; Michael Baechler from Pacific Northwest National Laboratory; Brett Singer from Lawrence Berkeley National Laboratory; David Rowson, Janise Palmer, Doug Anderson, and Chandler Von Schrader from the U.S. Environmental Protection Agency; Peter Ashley from the U.S. Department of Housing and Urban Development; Karen Hamilton from the New York State Energy Research and Development Authority; Will Baker from the Midwest Energy Efficiency Alliance; Brian Toll from Ecobeco; Charles Cormany from Efficiency First California; Asa Foss from the U.S. Green Building Council; Larry Zarker from the Building Performance Institute; Paul Francisco from the University of Illinois; Kevin Kennedy from Children's Mercy Hospitals and Clinics; Dr. Adam Weinstein from the University of Maryland/Shore Regional Health; Casey Murphy from ICF; Kevin Powell from the Redhorse Corporation; Courtney Moriarta and Bill Zwack from CSRA; Scott Pigg from Seventhwave, and Robert Johnson from Energetics. A special thank you is also in order to the DOE Building America program and the National Renewable Energy Laboratory for their essential help in making this report a reality. All errors and omissions are the sole responsibility of the authors.

Preface

This report was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE).

This report is being disseminated by DOE. As such, this document was prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554) and information quality guidelines issued by DOE. Though this report does not constitute "influential" information, as that term is defined in DOE's information quality guidelines or the Office of Management and Budget's Information Quality Bulletin for Peer Review, the report was reviewed both internally and externally prior to publication. This report has benefitted from review by the National Renewable Energy Laboratory and DOE's Building Technologies Office.

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Executive Summary

Background

The home performance industry supports whole-house solutions to improve home energy use and enhance indoor air quality and environmental conditions. Numerous studies have evaluated the effects of a range of residential energy efficiency and green renovation work on indoor environmental quality and occupant health. However, there has not been a systematic review of such studies to summarize current knowledge and identify research gaps.

Purpose

The purpose of this review is to address the question: what are the occupant health and indoor environmental outcomes resulting from energy efficiency or home performance upgrades, and how indoor environmental conditions can affect health? Home performance upgrades—defined as the systematic approach to improving the comfort, health, safety, energy efficiency, and durability of a home—ranges from work supported by many utilities and the Department of Energy's Weatherization Assistance Program (e.g., air sealing, insulation, lighting, properly functioning heating/cooling systems, assuring adequate ventilation) to additional work supported by DOE's Home Performance with ENERGY STAR (HPwES) and green renovations (e.g., ventilation upgrades, moisture control, window replacement, and allergen-reduction repairs). In all home repair and home performance work, there is some potential for unintended consequences and negative health outcomes due to improper design, inadequate installations, insufficient maintenance, and/or equipment failures. This review does not investigate the health outcomes related to these risks, nor does it assess the prevalence of home performance work that does not meet current industry best practices and standards.

Use and Audience

The results of this review can help guide future research, formulate work practices and work specifications, and delineate the opportunities for the home performance and energy efficiency sector to engage with those interested in population health and specific housing-related health risks. The primary audiences for this white paper are energy efficiency and home performance programs and funders, federal agency program staff and leadership, state and local energy efficiency and home performance program administrators, utilities, regulators, and home performance contractor networks. Healthcare stakeholders may also find the research of interest as they explore potential collaborations with energy efficiency, home performance, and green renovation partners.

Methods

An exhaustive literature review yielded over three million potentially eligible publications from the nation's main public health database (PubMed). After irrelevant entries and duplicates were eliminated, roughly 300 articles were reviewed in detail; of those remaining, close to 50 were analyzed to determine the strength of the study design, how large and statistically significant the health and environmental effects were, and other factors. These are all presented in a searchable spreadsheet and are summarized in the tables in the report.

Forty studies as described by forty-four reports and peer-reviewed articles are presented in this paper. The studies were sorted into five categories:

1. *Base energy efficiency:* seven studies of energy efficiency programs that included at least two of the following three activities: insulation, air sealing, and heating improvements.
2. *Enhanced energy efficiency:* seven studies where the energy efficiency measures included air sealing, insulation, and heating upgrades and enhanced work to address moisture, ventilation, or other issues.

3. *Green renovation/construction:* nine studies of green renovation or new green construction that all included energy efficiency measures as a core component and also included practices such as enhanced ventilation, use of low-VOC (Volatile organic compounds) products, and resilient flooring options, and policies such as "no smoking" and use of integrated pest management.
4. *Ventilation:* eight studies that evaluated alternative ventilation strategies (e.g., exhaust only, heat recovery ventilators [HRVs]) to isolate their impact on resident health.
5. *Potential supplemental home performance services:* nine studies of three specific activities intended to improve indoor air quality which could be conducted by home performance contractors: (1) Stand alone in-room air filtration equipment, (2) gas-to-electric stove replacements, and (3) wood stove upgrades to cleaner burning wood stoves.

Results

Base energy efficiency work, such as work done under DOE's Weatherization Assistance Program, can also create healthier living environments. Health-related outcomes include improved general health, reductions in some asthma symptoms, fewer cases of hypertension and upper respiratory risks, and some improvements in indoor air quality contaminants. One New Zealand study showed significant healthcare savings when uninsulated homes received energy upgrades.

1. **Enhanced energy efficiency upgrades have been shown to reduce indoor air contaminants linked to chronic illnesses, control environmental contaminants (dust mites, mold/moisture) that can trigger respiratory symptoms, and improve symptoms of asthma and other respiratory health conditions.** The studies also found reductions in other indoor air pollutants and reported improvements in blood pressure and fatigue. One small study of low-income clients also showed a reduction in healthcare costs among U.S. residents. The enhanced practices most closely match common practices in the home performance industry.
2. **Green new construction research includes four studies that have documented observed reductions in healthcare utilization. Multiple studies of green renovation and new construction also found reductions in indoor air pollutants, other asthma triggers such as pests and mold, and, ultimately, asthma symptoms.** Although green building and maintenance practices are more extensive than the activities of most home performance contractors, this research offers information to frame the potential benefits of energy efficiency/home performance when coupled with other home renovations.
4. **Studies of enhanced ventilation strategies have documented reduced indoor air quality contaminants that have been linked with chronic illnesses or respiratory risks; fewer respiratory risks among people with asthma; and reduced allergens.** These studies offer promise for positive health benefits when whole house ventilation is incorporated into home performance measures.
5. **Several stand-alone home services/upgrades have been shown to improve occupant health and could be incorporated into home performance work specifications. These include: in-room HEPA (high-efficiency particulate air) air cleaners, replacement of gas stoves with electric stoves, and upgrades from older wood stoves to cleaner burning models.** These upgrades help to reduce respiratory risks by reducing air contaminants (e.g., nitrogen dioxide; fine particulate matter).

Additional studies are needed to build upon existing research that demonstrates improved indoor air quality and reported health symptoms to also document reductions in healthcare utilization -- the extent to which a given group uses particular healthcare services in a specified period, and/or costs. Among the gaps that should be filled:

- *More studies such as a Washington State evaluation of the impact on energy efficiency on Medicaid costs - but with larger populations and longer follow-up periods.* The study offers promising results that energy efficiency measures will improve the health of people with asthma and reduce the Medicaid costs associated with those households. With a larger study population and follow-up period that is more than a year, the effects of base energy efficiency as compared to enhanced energy efficiency can be observed. Such a study would benefit by assessing health outcomes and indoor environmental outcomes as well as healthcare utilization measures.
- *Additional studies focusing on clients with pre-existing health conditions to maximize the chances of observing an effect.* Studies of people with poorly controlled asthma, sensitivities to dust mites, or hypertension would appear to be the most fruitful.
- *Additional studies of market rate households.* Of the 11 studies of energy efficiency that considered health effects, nine of the studies focused on low-income households and did not provide sufficient evidence of the health benefit in market rate homes.
- *Additional studies focusing on prevalence and health impacts of radon, formaldehyde, and VOCs before and after home performance improvements.* These pollutants can have negative long-term health effects and can be difficult to test depending on location and duration of the test within the home, season, and external weather and air quality conditions.
- *Studies should include details about standards the energy or home performance/rehabilitation contractors followed.* With the emergence of compliance standards such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62 for ventilation and building performance work standards, researchers can now better define the scope of work assessed. This can help compare effects between studies. Furthermore, researchers should state what compliance testing was conducted to verify that the standards were achieved. It was presumed that future home performance services delivered for the purpose of verified health improvement would be compliant with industry-accepted standards and potentially third-party quality oversight such as what is offered in HPwES.

Conclusion

A strong foundation exists to “connect the dots,” making the case that energy efficiency measures can improve occupant health. Yet, for any combination of treatments and health outcomes (e.g., enhanced energy efficiency and hypertension), there may only be one or two studies demonstrating benefits. Such studies should be replicated to gain support from the healthcare community. For healthcare providers/insurers, they may also question whether self-reported improvements in health will result in changes in healthcare utilization. Although there will always be some early adopters, the healthcare field will likely need some of the research gaps filled before becoming invested in the benefit of home energy improvements or comprehensive services that include energy efficiency. For home performance contractors, the evidence that residents feel better, have fewer respiratory symptoms, and experience fewer headaches should be sufficient to help clients understand the potential added benefits of their work. The information in this report can help the *Health and Home Performance Initiative* prepare communication tools about energy efficiency and health. Although no one should use this research to guarantee health effects for any particular client, the evidence presented clearly demonstrates that population health benefits are real and valuable. Consumers should be educated that a properly conducted energy efficiency project will improve the indoor environment and likely improve occupant health.[a]

[a] Properly conducted energy efficiency projects positively impact indoor environmental quality with well-designed air sealing, insulation, and heating/cooling upgrades compliant with industry-accepted standards and quality assurance oversight.

Introduction

Residential energy efficiency and home performance work reduces energy use and can change the physical environment of homes by stabilizing temperatures, enhancing indoor air quality, and improving environmental conditions. Numerous studies have evaluated the effects of a range of residential energy efficiency and green renovation work on indoor environmental quality and occupant health. However, there has not been a systematic review of such studies to summarize current knowledge and identify research gaps. Some utilities and low-income weatherization programs have considered the effects of their work on outcomes beyond energy savings (i.e., non-energy benefits), but these analyses have often been broad in scope and not always focused on the impact on occupant health.

The Department of Energy (DOE) and its contractor, the National Renewable Energy Laboratory (NREL), have sponsored this literature review to describe what is currently known about the occupant health benefits resulting from residential energy efficiency or work that is consistent with home performance upgrades. Of particular interest are the occupant health impacts associated with work typically conducted by the home performance industry, such as: air sealing and insulation; properly-sized, selected, matched, and installed energy efficient heating, ventilation, and air conditioning (HVAC) systems; identification and correction of moisture problems; proper whole house and room ventilation; lighting; and additional services including the replacement of appliances; measurement and installation of whole house and room air filtration systems (e.g., air purifiers); and basic pest exclusion. The intent of this literature review is to examine research that assessed work that would not be expected to harm residents or the workers. Although the literature rarely offered details about the specific energy efficiency-related work practices and standards that were followed, we focused on research conducted in this century by researchers who hypothesized that there would be an improvement in occupant health and/or indoor environment outcomes from the energy efficiency or home performance work.

In all home performance and home performance work there is some potential for unintended consequences and negative health outcomes due to improper design, inadequate installations, insufficient maintenance, and/or equipment failures. This report does not investigate the health outcomes related to these risks. Nor does it assess the prevalence of such work that does not meet current industry best practices and standards or the risk that code or industry standards that inform the work specifications may themselves be inadequate or problematic. The goal of this review is to ask: What are the occupant health and indoor environmental outcomes resulting from energy efficiency or home performance upgrades, and how indoor environmental conditions can affect health?

DOE promotes and manages residential home performance and energy efficiency programs. Inherent in these programs is the principal of ensuring that the work "does no harm" to human health. Specifically, DOE, in coordination with the U.S. Environmental Protection Agency (EPA), offers the Home Performance with ENERGY STAR (HPwES) program. DOE also manages the Weatherization Assistance Program (WAP), which provides energy efficiency improvements to low-income families. Both HPwES and WAP promote the adoption of best practices for energy-efficiency and a healthy living environment. Under the HPwES program, activities are "designed to systematically enhance home performance for healthier and more comfortable living environments, enhanced durability of the homes' structures and systems, and improved energy savings for the homeowners" (DOE 2014).[1] The HPwES program recognizes that tightening a home without considering indoor air quality and moisture can lead to adverse outcomes for both the residents (e.g., sick building syndrome) and the building structure. DOE's Weatherization Program has clear standards and guidance to protect the health and safety of occupants.

Audience

The primary audience for this white paper is energy efficiency and home performance programs and those funding or supporting such work. The audience includes NREL/DOE and other federal agency program staff and leadership, state and local energy efficiency and home performance program administrators, utilities, and home performance contractor networks. While many program administrators recognize that energy efficiency work produces holistic benefits beyond energy reduction, benefits to occupant health are often not recognized or are undervalued by program administrators, regulatory agencies, contractors, and consumers. This paper was produced to help the home performance sector better understand the impact their work is having on occupant health and help them communicate these findings. Optimally, the findings will form a basis for discussions with other parties, including healthcare professionals, energy regulators, and evaluators who are all interested in the potential co-benefits of energy efficiency on health and healthcare utilization.

This paper is just one part of the *Health and Home Performance Initiative* of DOE. This paper will serve to advance the conversation among stakeholders concerning how the health benefits of home performance can be better articulated in policy and consumer messaging. The findings in this paper are presented for an audience with program or technical knowledge of home performance activities.

Focus Areas

This literature review focuses on the health impact resulting from activities that contractors in the energy efficiency and home performance market may routinely undertake. These contractors are trained to follow best practices to assure the quality of their work and take the health and safety of residents and workers into account. This review excluded case studies and other research findings about activities that are no longer common practice.

Literature reviews often find that there may only be a limited number of studies where the topic of interest (in this case, the effect of energy efficiency or home performance best practices on occupant health) was directly studied. Therefore, the reviewers looked for research that is closely related, so inferences about the effects can be drawn. The available research was subdivided into five categories, listed and described below.

1. Base Energy Efficiency
2. Enhanced Energy Efficiency
3. Green Renovation/Construction
4. Ventilation
5. Potential Supplemental Services
   a. Room air cleaners
   b. Stove replacement

Base Energy Efficiency includes research projects that included at least two of three core energy efficiency elements: air sealing, insulation, and heating upgrades. Studies that examined the effects of only adding heating or insulation to homes (common in Great Britain and New Zealand) were excluded. Some studies, such as the National Evaluation of the DOE Weatherization Assistance Program, included homes that received some exhaust ventilation, but were not required to meet current industry standards for ventilation.[2]

Enhanced Energy Efficiency includes research projects where the energy efficiency measures included air sealing, insulation, and heating upgrades and added work to address moisture, ventilation, or other issues. In some cases, additional services were provided to further improve the indoor environment such as air filtration and carpet removal to address allergens. This enhanced package is consistent with the whole building approach that is a core principle of HPwES.

Green Renovation/Construction is a separate area of study, but the core principles of green construction (energy efficiency, healthy environment, and sustainable materials) are consistent with the principles of HPwES and WAP. Green construction, like WAP and HPwES, takes a holistic approach to the home environment. However, green renovation and construction often include elements that go beyond the standard activities of home performance contractors, including use of low-polluting building materials, mold removal, carpet replacement, pest exclusion and integrated pest management, and smoke-free housing policies in multifamily buildings. These studies are included in this literature review because they all included energy efficiency measures, and they can be used to frame the potential benefits of energy efficiency/home performance when coupled with other home renovation.

At the outset of this project, there was interest in considering the effects of individual components of energy efficiency and home performance on health. We identified international studies that compared occupant health outcomes between homes with and without insulation or heating.[3] However, these comparisons were not considered relevant for the United States housing stock, because most U.S. homes have some level of heating and insulation; so the results would not be generalizable to this country. **Ventilation** was one area of research where the effects of a single component of energy efficiency or home performance could be evaluated. Several studies exist that compare alternative ventilation strategies as part of energy upgrades (e.g., exhaust only, heat recovery ventilators [HRVs]) to isolate their impact on resident health.

Potential Supplemental Home Performance Services includes research for three specific activities that have been studied independent of other renovation or construction work: (1) stand-alone in-room air filtration equipment, (2) gas-to-electric stove replacements, and (3) wood stove upgrades to cleaner-burning wood stoves. Each of these services seeks to improve indoor air quality and could be conducted by home performance contractors. This research was identified as part of the literature review process because it was considered potentially relevant to the home performance industry.

Anticipated Occupant Health Related Effects of Energy Efficiency

Energy efficiency measures are expected to improve occupant health through multiple pathways. The International Energy Agency (IEA, 2014) recently prepared an analysis of the multiple benefits of energy efficiency that summarized these pathways.[4] A modified version of their pathway analysis is presented in Table 1. All of the expected health effects are supported by research cited by IEA that supports these associations. Other housing and health outcomes may exist, but they were not cited in the IEA report.

Table 1: Overview of impacts of improved energy efficiency on health and well-being

Energy Efficiency Measure	Primary Housing Effect	Secondary Housing Effect	Expected Health Outcomes
Insulation	Heating/cooling retained within dwelling	• Comfortable indoor temperatures • Lower indoor relative humidity • Reduced allergens	• Reduced deaths due to temperature extremes • Reduced symptoms of respiratory disease
Air Sealing			
Improved Heating Systems	Heating provided to whole dwelling	• Comfortable indoor temperatures • Reduced gases and particulates • Increased usable living space	• Reduced deaths due to cold • Reduced symptoms of respiratory disease • Reduced stress and infectious disease
	Cleaner burning heating systems		
	Combustion by-products properly vented to outdoors		
Improved Cooking Systems	Cleaner-burning cooking systems	• Reduced gases and particulates	• Reduced symptoms of respiratory disease • Reduced risk of cancer
	Combustion by-products properly vented to outdoors		
Improved Ventilation	Increased air flow within dwelling	• Reduced gases and particulates • Reduced dampness • Reduced mold	• Reduced symptoms of respiratory disease • Reduced risk of cancer • Reduced symptoms of cardiovascular disease • Reduced arthritis • Reduced depression

Adapted from Table 4.1 of the International Energy Agency report: Capturing the Multiple Benefits of Energy Efficiency.

Health-Related Outcome Measures

This literature review examines the effects of energy efficiency activities on **occupant health**. Health outcomes are commonly measured based on occupant self-reports through the use of validated health questionnaires. Validated questionnaires are tools that have been tested to demonstrate that interviewees will provide similar responses when their health conditions are similar. Self-reported health has been shown to be a good predictor of clinical health. In some studies, the researchers identified an at-risk population as the focus of the study (e.g., children with asthma, adults with hypertension) and some empirical health measures (e.g., lung function, blood pressure) were also measured.

Most of the studies looked at health effects over a one- to two-year window after the energy efficiency measures were installed. This time frame was often selected to maximize the time to observe changes in health while recognizing the resource limitations of research budgets. This time frame also minimizes the time when other changes in the home may be done that might confound the results of the intervention. A limitation for the analysis is that studies often did not share common health outcome measures, so it is not possible to report whether a given condition changed in all homes studied.

We identified some studies where researchers also considered the impact of the work on either **healthcare utilization** (e.g., visits to the emergency department) or **healthcare costs**. Capturing healthcare costs in some countries, such as the United States, can be challenging because multiple healthcare plans/insurers are involved, and it is difficult to obtain consistent data. Government data such as U.S. Medicaid outcomes and studies of national healthcare costs in Great Britain have been used for such outcome measures.

We also identified studies that collected **indoor environmental outcome** data. Environmental data were reported in three formats: self-reported observations from residents, observations from professional assessors, and empirical data from air sampling, settled dust allergens, and/or data loggers (temperature/humidity). Indoor environmental findings included:

- Occupant comfort: These metrics included temperature and relative humidity or the resident's assessment of their comfort. Most of the studies considered were conducted in cooler climates with the objective of increasing indoor winter temperatures while keeping humidity levels in a range that is neither too dry nor damp.
- Non-airborne biological contaminants[5]: These metrics included indoor allergens (pet and pest-based allergens, molds), mold/musty smells/dampness, and evidence of pests. All of these factors are known triggers of respiratory health symptoms (e.g., asthma attacks, wheezing). The presence of pests can also lead to pesticide exposure that can have negative effects on resident health.
- Metrics of airborne physical and chemical contaminants:
    - Particulate matter (PM or $PM_{2.5}$): fine particles from exterior sources including cars, trucks, heating oil and other fuel burning, and power plants and interior sources, including cooking, tobacco smoke, burning candles, fireplaces, or wood stoves
    - Formaldehyde/volatile organic compounds (VOCs): chemicals that off-gas from building and household products
    - Phthalates: another form of chemical that off-gases from products
    - Nitrogen dioxide (NO_2) and carbon monoxide (CO): by-product of combustion found in both indoor and outdoor air
    - Radon: naturally occurring radioactive gas that can enter homes from the ground
    - Carbon dioxide (CO_2): by-product of breathing. CO_2 levels can be a marker for poorer air quality and inadequate fresh air supply, although recent studies have also shown that people perform tasks less well in higher CO_2 environments

Several of these indoor air contaminants can increase respiratory risks including asthma ($PM_{2.5}$, formaldehyde, NO_2) and trigger eye, nose, and throat irritation; headaches; and loss of coordination and nausea. Radon and some VOCs have been shown to elevate human cancer risks.

Energy efficiency measures as well as green construction can address these hazards through source control (e.g. avoiding the use of products with VOCs), exclusion measures (barriers or pressure differentials to keep out radon and outdoor air pollutants), improvements to indoor combustion systems, and better ventilation (ventilation of combustion appliances, spot ventilation to reduce pollutants in specific rooms such as bathrooms and kitchens, and whole-dwelling ventilation to introduce more fresh air).

This report considers studies that examine environmental outcomes with and without assessments of health effects. Studies of the effects of energy efficiency on indoor air quality can be used to draw inferences about potential health effects based on other research on the relationships between air pollutant exposures and health effects. These studies are also critical when anticipated health outcomes, such as cancer incidence, cannot be observed through one- to two-year follow-up studies with relatively small population sizes. Documentation of reductions in known or suspected carcinogens in the indoor environment are good markers for potential health benefits in the future.

Summary of the Literature Review Search Process

Given the diversity in the housing, energy efficiency, home performance, and allied programs and industries, the number of potentially relevant publications is very large. A number of screening steps were used to enable the review process to be done comprehensively and efficiently. First, PubMed.gov, the nation's authoritative public health database (managed by the U.S. National Library of Medicine, a division of the National Institutes of Health), was queried using keywords (shown in Appendix A), resulting in a total of 3,667,665 publications. Second, keywords were combined, and filters were applied, such as limiting results to human studies and for some keywords with a large number of results, limiting the time frame to studies completed within the past five years. Third, duplicates were removed. Fourth, the titles of the publications were examined to remove clearly irrelevant publications. For example, the publications found using the keywords "home performance" all involved assessment of nursing homes, many of the publications using the keywords "ventilation" yielded studies associated with ventilating patients in hospitals (instead of structural ventilation), and the term "housing" yielded toxicological studies of animal cage design. Finally, we contacted knowledgeable experts to determine if other publications not indexed in PubMed were relevant. Three hundred eight articles remained. Following a review of abstracts, 40 studies as reported in 44 papers were identified to be directly relevant. These papers were read and results were summarized in a searchable matrix, which was adapted from the Guide to Community Prevention Services.[6]

Overview

This review summarizes the findings of relevant studies and characterizes the strength of the evidence. There is a large body of information discussing why energy efficiency measures should improve resident health, but questions remain about what empirical studies exist to support these theories. This report considers what is known about the effects of energy efficiency on the indoor environment, resident health, and healthcare utilization. In addition, the literature review identifies gaps in the literature that if filled would yield stronger justification for consumer messaging, regulatory and statutory policy, and private investment encouraging greater adoption of home performance services.

Research Findings

Base Energy Efficiency

Base energy efficiency is defined as energy efficiency activities that include at least two of the following three activities: insulation, air sealing, and heating improvements. In some cases, exhaust ventilation was installed, although it was not a requirement for this category of work. We selected studies in which all of the work was performed in this century because a review of program guidance suggests that by that point, most program managers had been exposed to information that over-tightening homes without proper ventilation could lead to indoor air problems. The programs sought to tighten homes to a level where a healthy indoor environment could be maintained through natural or mechanical ventilation. Although there was some concern that the air sealing and insulation could increase levels of some indoor pollutants and moisture, programs expected that these activities would be a net benefit to the residents. Research evaluated the hypothesis that overall health, respiratory health, and possibly cardiovascular health would improve following base energy efficiency activities.

Seven studies were classified as base energy efficiency studies (Table 2A). The studies include two as part of the Evaluation of the U.S. Weatherization Assistance Program targeting low-income residents,[7,8] a separate study of low-income energy efficiency activities in the United States[9], a New Zealand study of insulation/air sealing,[10] and three studies of energy efficiency upgrades in Great Britain.[11,12,13,14] Most of the homes in the studies were located in cooler and damper northern climates.

Studies largely confirm that base energy efficiency programs can improve resident comfort. However, there is insufficient evidence to conclude that indoor air quality improved. The studies documented that homes were, on average, warmer and drier after work. In one study[15], the average temperature and humidity levels remained the same, but fuel costs declined. In addition to finding lower relative humidity and condensation, two studies[16,17] observed fewer homes with mold after work. Tests of the indoor air were not commonly part of the studies, because improving indoor air quality was not an objective of most of the programs studied. In two of the studies[18,19] where indoor air was tested, the levels of gases and particulates did not change significantly from before work to after work. In one study,[20] average formaldehyde and radon levels increased after work, suggesting that natural ventilation was not sufficient in some cases.

Studies document a trend toward better occupant health and reduced respiratory risks after base energy work. Residents reported their general health improved in four[21,22,23,24] of the six studies. These same four studies asked residents about non-lower respiratory tract health outcomes and found an improvement on some area of health including fewer colds, sinus infections, or headaches; and reduced blood pressure or other cardiovascular conditions. Lower respiratory tract symptoms (e.g., asthma symptoms, overall respiratory score wheeze, chronic obstructive pulmonary disease [COPD] respiratory score) improved in three[25,26,27] of the six studies and were mixed in a fourth[28] (less bronchitis, mixed asthma outcomes). In general, residents reported feeling better after the work was complete, and those improvements were associated with improved upper and lower respiratory health and cardiovascular health due to improvements in hypertension, which is a precursor to heart disease.

One study observed a reduction in healthcare utilization among those with respiratory risks. The New Zealand study[29] that included over 4,000 individuals found that people with respiratory diseases whose homes were improved were 38% less likely to be admitted to hospitals in the 12 months after work than people with those diseases in homes that were not improved. In the treated homes, hours of extreme low temperatures were reduced, and relative humidity and condensation declined along with observations of mold. The study found that changes in hospital admissions for non-respiratory reasons were not statistically significant. A study[30] of the Weatherization Assistance Program found that after controlling for non-energy factors, use of emergency departments for asthma fell six fold following weatherization. Three other studies[31,32,33] investigated changes in healthcare utilization, but no other study observed a difference between the intervention group and the control group. In two of these studies,[34,35] the hospital admission data were not segregated by admission type. Because energy efficiency is more likely to have an effect on healthcare utilization for respiratory problems in the short term, the inability to separate out effects by reason of admission could conceal the impact of energy efficiency.

Implications and Research Gaps

The research supports the theory that in the short term, energy efficiency measures are most likely to have an effect on reducing symptoms of lower respiratory tract diseases such as asthma. **However, additional U.S. studies are needed to make a compelling case that base energy efficient work conducted to the current standard of care will reduce healthcare utilization and costs, particularly for occupants with asthma or other respiratory diseases.**

The Evaluation of the Weatherization Assistance Program was a large robust study[36] with over 1,468 baseline health surveys and 828 follow-up surveys, but only 99 people provided information about their asthma both before and one year after energy efficiency work. In the treatment arm of the study (47 people), emergency department visits for asthma in the past year declined 60% (from five visits to two), but given the small sample size, the effect was not large enough to be statistically significant. The number of study participants with asthma in future studies will need to be large enough to have the statistical power to observe reductions in healthcare utilization.

Follow-up periods of less than a year can limit the observation of improvements in health if there is insufficient time for the body to react to the changes in the indoor environment. Outcomes can also be affected by seasonal patterns for some diseases. For example, hospital admissions for asthma are greater in certain seasons.[37] Studies should be designed to account for these seasonal patterns by testing in similar seasons and using comparison groups to control for seasonal changes.

Indoor air quality did not significantly change in two of the three studies in this analysis where testing was conducted, suggesting that base energy efficiency can be achieved without adversely affecting indoor air quality. However, only half of the studies classified as base energy efficiency studies tested the indoor air quality. One of the studies[38] found that, in the absence of mandatory mechanical ventilation, some levels of indoor pollutants can increase after energy efficiency work. **Added studies of energy work should include indoor air quality testing when possible as it is a valuable component of research into the health impacts, particularly for pollutants such as formaldehyde and radon that might not affect occupant health for many years.**

Base energy efficiency work continues to be practiced today, and the findings support the contention that energy efficiency measures can improve the general health of occupants. One study from New Zealand [39] found that base energy efficiency is associated with fewer hospital admissions for respiratory health problems and the Evaluation of the U.S. Weatherization Assistance Program[40] showed potential respiratory hospital reductions among people with asthma. Creating a warmer, drier indoor environment with potentially less mold can make residents feel better and reduce the symptoms of respiratory disease as well as other health condition.

Table 2A: Base Residential Energy Efficiency Studies Summary of Work Performed

Study, Lead Author, Date of Publication, and Country Study Population		Energy Efficiency Activities					
		Insulation	Air Sealing	Heating Repair/ Replacement	Window/Door Replacement	Exhaust Ventilation	Other
Energy Efficiency and COPD (Osman et al. 2010) 178 adults	GB	✓		✓			
Watcombe Housing Study (Barton et al. 2007) (Richardson et al. 2006) 119 homes; 45 individuals with asthma	GB	✓		✓	✓	✓	Roofing repair
Insulation and Health (Howden-Chapman et al. 2007) 1128 homes; 3,312 individuals	NZ	✓	✓				
Scottish Central Heating Programme (Walker et al. 2009) 2,365 homes	GB	✓	✓	✓			Smoke/carbon monoxide alarms
US Weatherization Assistance Program (Pigg et al. 2014) 514 homes (Tonn et al. 2014) 828 occupants, 99 with pre-/post- asthma reports	US	✓	✓	✓*		✓*	
Watts-to-Wellbeing Study (Wilson et al. 2014) 248 homes	US	✓	✓	✓*	✓*	✓*	

✓ Energy efficiency activity considered

* Installed in some dwellings.

GB: Great Britain; NZ: New Zealand; US: United States

Table 2B: Health-Related Effects of Base Residential Energy Efficiency Measures by Study

Author and Date of Publication	Health-Related Outcomes						
	Healthcare Utilization	General Health/ Wellness	Lower Respiratory Health/Asthma	Upper Respiratory and Other Health	Comfort (Temperature/ Relative Humidity)	Indoor Air Pollutants	Other
Osman (2010)	~	~	⊕		~		
Barton (2007) Richardson (2006)	~	~			⊕	~ (PM)	
Howden-Chapman (2007)	⊕	⊕	⊕	⊕ (cold/flu)	⊕		⊕ (mold)
Walker (2009)	~	⊕	~	⊕ (heart disease/ hypertension)/- (nasal allergies)	⊕		
Pigg (2014a)					⊖	⊕ (formaldehyde, radon)	
Tonn (2014)	⊕	⊕	~	⊕	⊕		⊕ (mold, musty smells,pests)
Wilson (2014)		⊕	⊕/⊖	⊕(sinus infection, hypertension)	⊕	~	

⊕Positive (improved) effect; ⊖Negative (worse) effect; ⊕/⊖ Positive and negative effects;
~Effect tested but result not statistically significant at $p<0.05$
Fields in gray were not part of the study design; Fields in green highlight positive results

Enhanced Energy Efficiency

Home performance contractors and other programs offer services that go beyond base energy efficiency measures. Additional services may include whole-dwelling ventilation, dehumidification, other moisture control, pest exclusion, radon control, and other healthy homes services. HPwES contractors recognize that when homes are tightened to maximize energy efficiency, mechanical ventilation may need to be introduced to maintain/enhance indoor environmental quality and maximize comfort. Such work may also be an opportunity to improve health associated with the indoor environment by reducing exposure to molds, pests, and indoor pollutants.

These enhanced activities are intended to extend the benefits of base energy efficiency by improving indoor air quality through better ventilation and reducing moisture and pest problems with exclusion measures. With fewer pollutants and irritants in the air and less mold and allergens in the indoor environment, resident health was expected to be better. This is especially true for residents with an existing lower respiratory condition such as asthma or COPD.

Seven studies met the criteria for enhanced energy efficiency measures (Table 3A). The studies included two studies conducted in the Seattle, Washington, metro area of the health effects of weatherization plus health-related home repairs compared to (a) home healthcare activities[41] and (b) weatherization only and healthy homes repairs only.[42] Other studies included a study in Canada comparing health outcomes of occupants of new highly energy-efficient homes to standard new homes,[43] a Swiss study of energy-efficient homes built 20-26 years ago compared to standard homes built in the same era,[44] an Austrian study of homes built to Passive House standards compared to conventional homes,[45] and a British study of homes retrofitted with energy-efficient measures that included whole-house ventilation compared to untreated homes.[46] A seventh study compared various energy efficiency measures including whole-house ventilation on indoor air quality in California multifamily dwellings.[47]

Three of the studies[48,49,50] were specifically designed to examine the effects of the measures on an individual within each home with an existing health condition: Two of these studies[51,52] examined the effects on children with asthma, while one[53] looked at the impact of the work on adults with high blood pressure. Another of the studies[54] looked at the impact of the measures on children with asthma, but the study was not designed to specifically enroll children with asthma.

Enhanced energy efficiency resulted in improvements in indoor environmental quality. Three of the studies[55,56,57] in this category tested indoor air quality, one[58] tested dust allergens, and two[59,60] others used observational measures to consider changes in the indoor environment. The results were generally positive, with lower levels of airborne mold, particulate matter, VOCs, and radon in the treated homes than in the comparison homes. Formaldehyde levels were also lower in two studies,[61,62] although the levels increased in one of three multifamily buildings in the California study.[63] The researchers conducting the latter study could not identify a reason for the increase.

The Swiss study[64] supported the hypothesis that mechanical ventilation and moisture controls can result in lower levels of dust mites (which depend on adequate moisture for growth) and mold. Both Washington State studies[65,66] also found fewer self-reports of mold/dampness after the enhanced energy efficiency measures were completed. Both dust mites and mold are known triggers of lower respiratory tract problems.

Asthma and other lower respiratory problems improved for residents in homes that received enhanced energy packages. The King County (WA) Study[67] and the study[68] of Canadian high-performance building standards focused on the effects of the enhanced energy efficiency measures on residents with asthma. Both studies observed reductions in asthma symptoms that were significantly better than changes in control homes. The findings show that the energy efficiency measures can have observable positive impact when residents with existing respiratory health conditions are examined. The Swiss study[69] was not able to observe a difference in respiratory symptoms between residents in the treated and untreated homes, but it did show that residents living in homes with higher dust mite levels were more likely to have respiratory symptoms, which was consistent with other research. In effect, the number of homes with dust mite problems was not large enough to see a difference in health effects between the two groups, but the study suggests the creation of drier homes reduced asthma triggers and improved resident health.

The two studies[70,71] that considered other health effects also observed statistically significant improvements in health status: Upper respiratory conditions such as colds and sinus infections improved,[72] while reductions in blood pressure were observed in homes receiving enhanced energy efficiency measures in Great Britain.[73]

There is suggestive evidence of healthcare cost reductions for people with asthma who received an enhanced package. In the Washington State study that examined healthcare utilization,[74] Medicaid claims declined and associated annualized Medicaid costs declined by over $400 per year. Although this study had a relatively small sample of participants with usable Medicaid records (23) and did not assess changes in resident health status, the study offers positive findings that should be further explored in future studies. The British study[75] also considered the impact of its work on healthcare utilization, and while it did not show a statistically significant reduction, it did include case reports of fewer hospital admissions for cardiovascular problems and fewer doctor's visits for asthma.

Implications and Research Gaps

Enhanced energy efficiency, such as measures that could be conducted by home performance contractors, offer promise for improving the health of residents. The greatest opportunities to improve health over a one- to two-year period appear to be for those residents with an existing lower respiratory problem, such as asthma. The addition of better ventilation and filtration, moisture control, and pest control to the base energy efficiency package provides an opportunity to create drier, less polluted indoor environments with fewer allergens. The environments have fewer respiratory symptom triggers (moisture, mold, dust mites, pests, and other allergens). Although the field could benefit from additional studies with health outcomes**, the existing studies offer strong foundational evidence to support the benefits of this work on the indoor environment and on the expected health improvements from a healthier environment.**

A limitation of this analysis of enhanced energy efficiency measures is that some of the projects that were studied included elements that are outside of the traditional scope of home performance. For example, some of these projects included selective carpet replacement, pest exclusion, the use of healthier building materials, and client asthma education. Because these studies were designed as packages of services, it is not possible to identify how influential these non-energy elements were in the outcomes observed. Further study of traditional home performance services may be needed to further support the observation that these services improve health.

Three of the studies[76,77,78] in either the base or enhanced energy efficiency categories observed improvements in hypertension or high blood pressure. Hypertension is a precursor to heart disease, the leading cause of death in this country. The potential benefits of energy efficiency in reducing heart disease may be underreported. Because just one of the studies included clinical measurement of blood pressure, further **research documenting changes in hypertension or heart disease would be useful to provide added evidence of occupant health benefits.**

Resource constraints often limit the scope of measurements that can be collected as part of a study. With the exception of the National Evaluation of the Weatherization Assistance Program[79] and the CHARISMA[80] study[81] in Great Britain, none of the other studies in the base or enhanced energy efficiency categories measured air quality, health outcomes, and healthcare utilization in a single study. **Leaders in energy efficiency and health should consider whether a comprehensive study with all three of the elements is needed or if a series of studies examining individual elements is sufficient to assess the impact of home performance measures on health**. Ideally, all three elements would be included in future studies.

Health outcomes and healthcare utilization are also influenced by factors beyond the indoor environment, including access to preventive healthcare, access to treatment, health education, nutrition, gene/environment interactions, and behavior (e.g., exercise, tobacco use). Many of these factors are correlated with a household's socioeconomic status. Of the 10 studies in the base energy efficiency and enhanced energy efficiency categories that considered health effects, seven of the studies focused on low-income households. Additional studies of market rate households would be valuable. Seven of the studies focused on single-family homes, so additional studies of effects in multifamily homes should also be considered.

Table 3A: Enhanced Residential Energy Efficiency Studies: Summary of Work Performed

Study, Lead Author, Date of Publication, and Country Study Population	Energy Efficiency Activities					
	Insulation	Air Sealing	Heating Repair/ Replacement	Window/Door Replacement	Ventilation	Other
Highline Communities Healthy Homes Project (Breysse et al. 2014) US 102 homes	✓	✓*	✓	✓*	Exhaust*	Remove carpets, CO/smoke alarms, water leak repair
Heatfest Study (Lloyd et al. 2008) GB 36 adults	✓	✓	✓	✓	Whole-House (HRV)	Porches, solar panels
Evaluation of Canadian R-2000 Standard (Leech et al. 2004) CA 105 homes; 128 individuals	✓	✓	✓	✓	Whole-House (HRV)	Healthy material standards, CO alarms
Health Optimisation Project for Energy-Efficient (HOPE) Homes (Spertini et al. 2010) CH 78 homes; 181 individuals	✓	✓	✓	✓	Whole-House (HRV)	(Other: not reported) Homes built 20+ years ago
Mechanical Ventilation in Tight Homes v. Natural Ventilation in Standard Homes (Wallner et al. 2015) AT 123 homes	✓	✓	✓	✓	Whole-House (HRV)	Passive House (Other: not reported)
Impact of Weatherization and Healthy Homes Interventions on Asthma-Related Medicaid Claims (Rose et al. 2015) US 49 homes	✓*	✓*	✓*	✓*	Exhaust	Remove carpets, pest exclusion, dehumidifier, mattress cover, HEPA vacuum
Indoor Environmental Quality Benefits of Apartment Energy Retrofits (Noris et al. 2013) US 16 homes	✓*	✓*	✓*	✓*	Whole-House* (ERV) Exhaust*	Fan, CO alarms, stand-alone HEPA filter,* mold removed*

✓ Energy efficiency activity considered

*Installed in some dwellings.

AT: Austria; CA: Canada; CH: Switzerland; GB: Great Britain; US: United States

Table 3B: Health-Related Effects of Enhanced Residential Energy Efficiency by Study

Author and Date of Publication	Health-Related Outcomes						
	Healthcare Utilization	General Health/ Wellness	Lower Respiratory Health/Asthma	Upper Respiratory and Other Health	Comfort (Temperature/ Relative Humidity)	Indoor Air Pollutants	Other
Breysse (2014)			⊕				⊕ (mold, water damage)
Lloyd (2008)	~	⊕		⊕ (blood pressure, respiratory infections)			
Leech (2004)			⊕	⊕ (cold symptoms, fatigue, irritability)			
Wallner (2015)					⊕	⊕ (CO_2, TVOCs, formaldehyde, radon, airborne mold)	
Spertini (2010)			~		⊕	~ (airborne mold)	⊕ (dust mite allergens)
Rose (2015)	⊕				⊕		⊕ (mold)
Noris (2013)					⊕	⊕ (CO_2, VOCs, PM, acetaldehyde); +/- (formaldehyde)	

⊕ Positive (improved) effect; ⊖ Negative (worse) effect; ⊕/⊖ Positive and negative effects;
~ Effect tested but result not statistically significant at $p<0.05$
Fields in gray were not part of the study design; Fields in green highlight positive results

Green Renovations/Construction

The research that has been presented in the prior two sections focused on activities that most people will recognize as energy efficiency measures. This literature review also identified studies of the impact of other comprehensive residential construction activities on resident health. These studies were generally described as green building research. Green building is centered on three principles: energy efficiency, sustainable and integrated design, and healthy environments. Green building practices are becoming increasingly standardized with the adoption of programs/standards such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (USGBC LEED), Enterprise Green Communities, and the International Code Council's Green Construction Code. Although some builders and renovators may use the term "green" simply for marketing, green building is now more commonly associated with construction that objectively meets the three principles. The research that we explored only considered work that incorporated energy efficiency into the construction design.

Studies of green renovation or new green construction are not able to separate the impact of the energy efficiency measures on occupant health from the other activities that are undertaken, such as enhanced ventilation, water management, use of low-VOC products, and resilient flooring options. Even though health effects cannot be attributed to the individual components of the construction in these studies, theories of change[82] would suggest that the energy efficiency measures are an influential component. We include these green building studies to frame the discussion of how energy efficiency, when incorporated into a comprehensive package of building activities, can impact occupant health.

Green housing often goes beyond physical improvements and includes property management elements. A number of green housing developments include policies such as no-smoking policies or policies that require integrated pest management. The latter policy attempts to control pests through exclusion methods and with the least toxic pest control methods when pests are observed. Some housing for people with respiratory problems even exclude household pets. The objective of green building is to create the healthiest living environment with source control, mechanical ventilation, dehumidification, and filtration.[b]

Nine green renovation/construction studies were identified for this analysis (Table 4A). All of the studies were conducted in the United States and included:

- Four *renovation* studies of housing for low-income residents:
  - Two studies of renovations to properties for older adults[83,84,85]
  - Two studies of improvements to family housing[86,87,88]
- Four *new construction* studies of housing for low-income residents:
  - Two studies that targeted housing for families with a child with asthma[89,90]
  - Two studies that looked at the health effects in U.S. public housing[91,92]
- One study that considered the environmental effects of high-performance housing construction and renovation in California[93]

Green housing can improve environmental conditions. Three[94,95,96] of the five studies that included tests of indoor air quality observed lower levels of pollutants including VOCs/formaldehyde, particulate matter, and nitrogen dioxide, while a fourth[97] observed reductions in carbon dioxide, which is a marker for poorer ventilation. Jacobs et al. 2015[98] observed higher carbon dioxide and total volatile organic compound (TVOC) levels in new green properties than in leakier comparison properties, but the researchers did not report that the results were significantly different between the properties.

[b] US EPA recommends radon resistant new construction to prevent radon exposures (www.epa.gov/radon).

Five[99,100,101,102,103] of the six studies that used observational assessments to consider changes in indoor environmental quality found statistically significant improvements. Common results included lower levels of dampness, musty odors, mold, rodents, and cockroaches than before renovations or compared to conventional (non-green) dwellings.

Green renovation work can improve overall physical and mental health, respiratory health, and reduce injuries. All four renovation studies that considered health outcomes used self-reports of general health and mental/emotional health outcomes. Two studies[104,105] identified improvements in adult general health and one[106] reported a marginal improvement, while two[107,108] reported improvements in adult mental health. Other health outcomes included improvements in respiratory symptoms.[109] Two studies[110,111] also reported reductions in falls or injuries by older adults. The studies of green renovation did not look at the effects of the work on healthcare utilization.

Green <u>new</u> construction can improve health outcomes for children with asthma and reduce healthcare utilization. Two[112,113] of the four studies of green new construction examined housing for children with asthma, while the other studies[114,115] included a population with a high proportion of people with respiratory conditions. Residents in all four studies reported reductions in asthma symptoms and significant declines in healthcare utilization. The fourth study[116] of green new construction found improvements in resident's self-reported general health symptom score.

Implications and Research Gaps

The purpose of including this category of research in this report is to frame the potential impact of home improvement work that goes beyond traditional home performance but includes energy efficiency effects. Further research that explores the impact of energy efficiency measures on the positive outcomes attributed to green renovation or construction would help better understand the benefits of energy efficiency on health.

Table 4A: Green Renovation/Construction: Summary of Work Performed by Study

Study, Lead Author, Date of Publication, and Country Study Population	Energy Efficiency Activities					
	Insulation	Air Sealing	Heating Replacement	Window/ Door Replacement	Ventilation	Other
Green Renovations						
Green Renovated Housing for Elderly Residents (Breysse et al., 2015) US 40 homes	✓	✓	✓	✓	Exhaust	Exhaust hoods, low-VOC products, no-smoking policy
Green Energy Efficiency for Older Adults (Ahrentzen, Erickson, and Fonseca, 2016) (Frey et al., 2015 US 57 homes	✓	✓	✓	✓	Exhaust	Exhaust hoods, low-VOC products
Green Renovation of Low-Income Housing (Jacobs et al., 2014) US 25 homes, 38 adults	✓	✓	✓	✓	Whole-house	Exhaust fans, low-VOC products, integrated pest management
Green Housing Renovation Study (Breysse et al., 2011) US 18 homes, 24 adults	✓	✓	✓	✓	Whole-house	Exhaust fans, low-VOC products, integrated pest management, no smoking in common area
Indoor Air Quality in California High Performance Homes (Less 2015) US 24 homes	✓	✓	✓	✓	Whole-house (HRV, ERV, or other)	Exhaust fans, low-VOC products, moisture/ humidity control

Table 4A, continued

Study, Lead Author Date of Publication, and Country Study Population	Energy Efficiency Activities					
	Insulation	Air Sealing	Heating Replacement	Window/ Door Replacement	Ventilation	Other
Green New Construction						
Moving into Green Healthy Housing (Jacobs et al., 2015) US 325 homes, 389 adults, 414 children	✓	✓	✓	✓	Exhaust	Exhaust fans, low-VOC products
Breathe Easy Study (Takaro et al., 2011) US 102 children	✓	✓	✓	✓	Whole-house (HRV)	Exhaust fans, low-VOC products, no-smoking policy, pet free, HEPA filters
Green New Public Housing (Colton et al., 2014) (Colton et al., 2015) US 31 adults	✓	✓	✓	✓	Whole-house (HRV or ERV)	Exhaust fans, low-VOC products, integrated pest management, no-smoking policy
Impact of LEED-Certified Affordable Housing on Asthma (Garland et al., 2013) US 18 residents	✓	✓	✓	✓	Whole-house (compart-mentalized)	Exhaust hoods, low-VOC products, integrated pest management, no-smoking policy, pet free, gas stove replaced

✓ Energy efficiency activity considered

US: United States

Table 4B: Health-Related Effects of Green Renovation/Construction by Study

Author and Date of Publication	Health-Related Outcomes						
	Healthcare Utilization	General Health/ Wellness	Lower Respiratory Health/Asthma	Upper Respiratory and Other Health	Comfort (Temperature/ Relative Humidity)	Indoor Air Pollutants	Other
Green Renovation							
Breysse (2015)		⊕ (general, mental health)		⊕ (falls)	⊕	⊕ (CO_2)	⊕ (musty smell, dampness)
Ahrentzen (2016) Frey (2015)		⊕ (general, emotional health)			⊕	⊕ (formaldehyde, PM in homes of smokers)	
Jacobs (2014)		⊕		~ (injuries)	⊕		⊕ (cockroach, mouse allergens, musty smell, dampness)
Breysse (2011)		~	⊕	⊕ (respiratory not defined)	⊕		⊕ (musty smell, rodents)
Less (2015)						⊕ (formaldehyde, PM in homes with active filtration, PM in homes with induction electric cooktops)	

Table 4B, continued

Author and Date of Publication	Outcome Measure Effects						
	Healthcare Utilization	General Health/ Wellness	Lower Respiratory Health/Asthma	Upper Respiratory and Other Health	Comfort (Temperature/ Relative Humidity)	Indoor Air Pollutants	Other
Green New Construction							
Jacobs (2015)	⊕	⊕	⊕	⊕ (headaches, sinusitis, hay fever, angina)		~	⊕ (pests, dampness)
Takaro (2011)	⊕		⊕				⊕ (pests, mold, water damage, smoking)
Colton (2014) Colton (2015)	⊕	⊕	⊕			⊕ ($PM_{2.5}$, NO_2, nicotine)	
Garland (2013)	⊕		⊕				~ (mold)

⊕ Positive (improved) effect; ⊖ Negative (worse) effect; ⊕/⊖ Positive and negative effects;
~ Effect tested but result not statistically significant at $p<0.05$
Fields in gray were not part of the study design; Fields in green highlight positive results

Ventilation

The ventilation category examines research that explored the effects of enhanced ventilation independent of other measures. In most of the studies considered, the baseline housing is energy efficient, and the ventilation is applied to a subset of the dwellings so that its effects can be compared. Enhanced ventilation involves whole-house ventilation that goes beyond minimum ASHRAE 62 standards. Examples of enhanced ventilation include the use of balanced systems such as energy recovery ventilators (ERV) or heat recovery ventilators (HRVs). These balanced systems mechanically supply fresh air from the outside, while exhausting indoor air. An ERV usually transfers heat and moisture, while an HRV transfers heat. Whole-house mechanical exhaust-only and supply-only ventilation are other examples of enhanced ventilation, although none of the studies that we reviewed considered the effects of supply-only ventilation on occupant health.

Eight ventilation studies were identified for this analysis (Table 5A):

- Five studies of balanced mechanical ventilation:
  - Three of these studies specifically investigated the effects of ERVs/HRVs on children:
    - Two of these studies intentionally enrolled households with a child with asthma (Canada[117] and Great Britain[118,119])
    - One study[120] was conducted in a Canadian community where children were at risk of respiratory problems
  - Two studies examined the effects of ventilation on dust mites in homes of people with asthma (Denmark[121] and Great Britain[122])
- Two studies[123,124] looked at exhaust-only whole-house ventilation in U.S. homes
- One study[125] evaluated ventilation type and environmental conditions in Sweden

Indoor environmental conditions generally improved with enhanced ventilation. Of the five studies that looked at indoor air outcomes, four[126,127,128,129] observed statistically significant improvements from enhanced ventilation. Pollutants that were reduced with ventilation included respiratory triggers such as formaldehyde and other VOCs, airborne mold and phthalates, as well as radon. One study[130] observed reductions in carbon dioxide. Two studies[131,132] observed that nitrogen dioxide increased with ventilation. One of the study researchers[133] suggested that, while formaldehyde and VOCs tend to have indoor sources, nitrogen dioxide can be found in higher concentrations in the outdoor air. Outdoor concentrations of nitrogen dioxide (largely from vehicular traffic and power plant emissions) tend to be higher than indoor levels in the absence of indoor sources such as unvented gas appliances or environmental tobacco smoke.[134] When ventilation increases air exchange rates between indoor and outdoor air, more nitrogen dioxide could be drawn into homes while VOCs are displaced to the outdoors.

The installation of HRVs/ERVs is associated with fewer asthma/respiratory symptoms. The three studies[135,136,137] that specifically looked at HRVs/ERVs on children with asthma or children at risk of respiratory illness found that their respiratory health was better than children living in homes without the ventilation installed. Improvements in skin allergies and general health were also observed. These studies did not observe a significant reduction in healthcare utilization. The ability to see an effect may have been limited by the length of the follow-up period and the study population sizes. Prior studies[138] have also observed that for people who have their asthma under control with medications, home interventions might not reduce healthcare utilization, but they may reduce the need for certain medications and improve the person's quality of life.

The installation of whole-house ventilation is associated with lower dust mite levels. Two studies[139,140] looked at the effect on whole-house balanced ventilation on dust mites. The studies found that when the ventilation systems are designed to reduce relative humidity levels in homes, the effect inhibits dust mite growth and reduces dust mite allergens. Both studies observed improvements in respiratory symptoms, although only one study had a sufficient study population size for the improvement to be statistically significant.

Reductions in radon exposures may be possible with enhanced ventilation. Data from a supplemental analysis[141] to the Evaluation of the Weatherization Assistance Program found that installation of whole-house exhaust-only ventilation was associated with lower levels of radon. A second study[142] of weatherized homes observed a similar effect, although the result did not reach statistical significance.

Implications and Research Gaps

The studies of the effects of ventilation on the health of people with respiratory issues were well designed and provide strong evidence in support of mechanical ventilation systems. Researchers used randomized control trials to compare effects and in one study blinded the households using a "placebo" HRV. Even so, the study population sizes and/or the length of the follow-up period were not great enough to see impacts on healthcare utilization. The data from these studies could be used to estimate population sizes needed in future research to demonstrate healthcare utilization declines. Even without this additional research, the evidence shows that improvements of ventilation reduce indoor pollutants and are statistically associated with health improvements for children with respiratory problems.

Pollutants such as radon and formaldehyde are carcinogens with long-term health effects that cannot be observed in a one- to two-year follow-up period. Additional studies of *indoor air quality* following ventilation are needed. The two small studies of weatherized homes suggest that exhaust ventilation offers the potential to reduce radon levels in living areas of homes. However, the evidence is inconclusive and follow-up studies with comparison groups are needed to validate the results.

Table 5A: Ventilation: Summary of Work Performed by Study

Study, Lead Author, Date of Publication, and Country Study Population		Study Population	Intervention Activities
Ventilation			
CHARISMA Study (Woodfine et al. 2011) (Edwards et al. 2011) 192 homes	GB	Homes with children with asthma	Heat recovery ventilators (HRV) installed in all homes and heating system repairs in 22% of homes
Healthy Air Study (Kovesi et al. 2009) 52 homes	CA	Homes with Inuit children less than 6	Heat recovery ventilators (HRV) installed compared to placebo ventilators
IVAIRE Project (Lajoie et al. 2015) 83 homes	CA	Homes with children with asthma and air exchange rates less than 0.3	Energy recovery ventilator (ERV) (19 homes) or HRV (21 homes) installed or HRV (3 homes) repaired/modified
Mechanical Ventilation to Control Mites (Warner et al. 2000) 40 homes	GB	Homes with people with asthma who are sensitive to dust mites	Whole-house mechanical ventilation (HRV) installed; separate arm received high efficiency vacuum cleaner
Mechanically Ventilated Healthy Homes (Harving et al. 1994) 25 homes	DK	Homes with people with asthma who are sensitive to dust mites	Whole-house mechanical ventilation installed
Indoor Air Quality in Swedish Housing (Langer and Beko 2013) 157 single family/148 multifamily	SE	Homes in Sweden that were part of a national survey	Compared indoor air quality measures by housing type and ventilation type
HEALTH-V Study (Francisco et al. 2016) 81 homes; 187 individuals	US	Weatherized homes	Exhaust ventilation compliant with ASHRAE-62.2 (2010) compared to natural ventilation – met ASHRAE-62 (1989)
US Weatherization Assistance Program (Pigg 2014) 18 homes	US	Weatherized homes	Exhaust ventilation compliant with ASHRAE-62 (2010) – focus effects on radon and relative humidity

CA: Canada; DK: Denmark; GB: Great Britain; SE: Sweden; US: United States

Table 5B: Health-Related Effects of Ventilation Measures by Study

Author and Date of Publication	Health-Related Outcomes						
	Healthcare Utilization	General Health/ Wellness	Lower Respiratory Health/Asthma	Upper Respiratory and Other Health	Comfort (Temperature/ Relative Humidity)	Indoor Air Pollutants	Other
Woodfine (2011) Edwards (2011)	~	⊕ (4 months) ~ (1 year)	⊕				
Kovesi (2009)	~		⊕	⊕ (skin allergies)	⊕	⊕ (CO_2)	
Lajoie (2015)	~		⊕		⊕	⊕ (VOCs, airborne mold)/ - (NO_2)	~(phthalates in dust)
Warner (2000)			~				⊕ (dust mite allergen)
Harving (1994)			⊕				⊕ (dust mite allergen)
Langer (2013)						⊕ (formaldehyde, TVOC)/ - (NO_2)	
Francisco (2016)		~	~	⊕ (headaches)	~	~	
Pigg (2014b)					⊕	⊕ (radon)	

⊕ Positive (improved) effect; ⊖ Negative (worse) effect; ⊕/⊖ Positive and negative effects;
~ Effect tested but result not statistically significant at $p<0.05$
Fields in gray were not part of the study design; Fields in green highlight positive results

Potential Supplemental Services

We considered research in two areas where home performance contractors might consider providing supplemental services[143] to clients. These two areas include:

- Installation of in-room air cleaners/filters and
- Replacement of stoves: gas to electric or wood stove to cleaner-burning wood stove.

In-Room Cleaners

In-room air cleaners using high-efficiency particulate air (HEPA) filters have been proposed as methods to remove local particulate loads from specific home locations (e.g., a bedroom) to improve the indoor air quality and improve respiratory health. All the air cleaners evaluated relied on filtration. None of the cleaners used ionization to remove particles because concerns have been raised about the ozone that these devices can generate and the potential adverse health effects of the ozone, which is a known respiratory irritant.

Air Cleaners

Five indoor in-room air cleaner studies were considered (Table 6A). Three of the studies[144,145,146] targeted the homes of children with asthma who also had a caregiver who was a current smoker. One study[147] from Canada considered the effects of air filters installed in a community with a high smoking prevalence, while the final study[148] by Paulin et al. included three intervention options in homes with unvented gas stoves. Except for the study conducted in Canada, the studies were all conducted in the United States.

Air cleaners can improve indoor air quality. All of the studies examined environmental outcomes, primarily particulate matter levels. PM levels declined between 16-50%. The studies did not find declines in nicotine levels. The study[149] in the community with a high smoking prevalence saw a 20% decline in nitrogen dioxide.

The installation of air cleaners resulted in a reduction in asthma symptoms and healthcare utilization. Three of the studies considered health outcomes, and two[150,151] observed reductions in asthma symptoms or improved lung function. Two of the studies considered healthcare utilization as an endpoint, and one[152] observed a reduction in unscheduled visits for asthma. Most studies noted that occupant use of the devices was an issue and was an important factor in their effectiveness.

Stove Replacement

Public health professionals have proposed the replacement of gas stoves with electric stoves as a method to reduce pollutants such as nitrogen dioxide from the indoor environment. The use of EPA-certified wood stoves instead of older models is expected to reduce indoor particulate levels.

Gas Stove Replacement

Two studies of the potential effects of gas stove replacement were considered (Table 6A). The research included the study[153] by Paulin et al. (previously discussed under room air cleaners) of three intervention options for homes with gas stoves and a study[154] that used United States health survey data to document the association between unvented gas stoves *used for heat* and the health of young children. The health survey analysis[155] found **a strong association between unvented gas stoves *used for heat* and childhood pneumonia and coughing** after adjusting for other factors. The intervention study[156] reported that nitrogen dioxide declined 50-80% after gas stove replacement.

Wood Stove Replacement

Three studies considered the effects of wood stove replacement with cleaner-burning models. Two[157,158] were conducted in the United States where EPA-certified stoves were installed, while one[159] was conducted in Canada. All three studies only considered the impact of the changes on the indoor environment, specifically particulate matter.

The use of cleaner burning wood stoves can improve indoor air quality. Two[160,161] of the studies observed substantial reductions in $PM_{2.5}$ (36-53%), and their authors concluded that replacement should be encouraged. However, all studies noted that roughly a third of the homes did not see air quality improvements, and this was an area that needed further investigation.

Implications and Research Gaps

The findings offer positive results for all three areas of potential supplemental services. However, each of these groups of research findings do have some potential limitations. The study of in-room air cleaners has largely been focused on homes of smokers with children with asthma. Whether these outcomes would be observed in homes without these conditions would require study of other populations of homes.

Gas stove replacement appears promising, but the research to date has largely looked at homes of lower-income households where the gas stoves are often being used for primary or supplemental heat. The evidence supporting gas stove replacement with electric stoves is not as clear where stoves are only being used for cooking.

When the benefits to the outdoor air are considered as well as the potential benefits to the indoor air, the justification for upgrading wood stoves to EPA-certified models is strong. But the fact that a significant portion of homes did not experience improvements deserves further analysis, and research on health effects would be useful.

Table 6A: Services to Supplement Home Performance Work: Summary of Work Performed by Study

Study, Lead Author, Date of Publication, and Country Study Population	Study Population	Intervention Activities
In-room Air Cleaner Installation		
Cincinnati Asthma Prevention (Lanphear et al. 2010) US 215 individuals	Children with asthma residing with smoker	In-room HEPA air cleaners installed in living room and child's bedroom
Particulate Reduction Education in City Homes (PREACH) Study (Butz et al. 2011) US 115 children	Children with asthma residing with smoker	In-room HEPA air cleaners installed in living room and child's bedroom
First Nations Food, Nutrition, and Environment Study (Weichenthal et al. 2013) CA 20 homes/37 individuals	First Nations people (predominately young adults) living in homes with high prevalence of smokers	In-room Ultra Clean air purifier installed in a room in home
Community Action Against Asthma (Batterman et al. 2012) US 126 children	Children with asthma	In-room HEPA air cleaners installed in child's bedroom
Home Interventions to Control Nitrogen Dioxide (Paulin et al. 2014) US 73 individuals	Homes with unvented gas stove	In-room HEPA air cleaner kitchen and child's bedroom; one of three interventions in study
Replacement of Gas Stove with Electric		
Home Interventions to Control Nitrogen Dioxide (Paulin et al. 2014) US 73 individuals	Homes with unvented gas stove	Replacement of gas stove with electric stove; one of three interventions in study
Analysis of Effects of Gas Stoves on Respiratory Health (Coker et al. 2015) US ~3,200 children	Analysis of data from National Health and Nutrition Examination Survey (US) – children less than 5	Homes with gas stoves compared to homes without them; data included information whether stove was vented and/or if used for heating

Table 6A, continued

Study, Lead Author, Date of Publication, and Country Study Population	Study Population	Intervention Activities
Replacement of Wood Stove with Clean-Burning Model		
Nez Perce Tribe's Environmental Restoration and Waste Management Air Quality Program (Ward et al. 2011) US 15 homes	Homes on Nez Perce reservation with wood as the primary heating source (nonsmoking households with child with asthma present)	Wood stoves replaced with new, cleaner-burning EPA-certified wood stoves
Woodstove Replacement Study (Allen et al. 2009) CA 15 homes	Homes with wood as the primary or secondary heating source (nonsmoking households)	Wood stoves replaced with new, cleaner-burning EPA-certified wood stoves
Libby Changeout Program (Noonan et al. 2012) US 21 homes	Homes with wood as the primary heating source (nonsmoking households)	Wood stoves replaced with new, cleaner-burning EPA-certified wood stoves

CA: Canada; US: United States

Table 6B: Health-Related Effects of Supplemental Home Performance Services by Study

Author and Date of Publication	Health-Related Outcomes						
	Healthcare Utilization	General Health/ Wellness	Lower Respiratory Health/Asthma	Upper Respiratory and Other Health	Comfort (Temperature/ Relative Humidity)	Indoor Air Pollutants	Other
Lanphear (2010)	⊕		~			⊕ (PM)	
Butz (2011)	~		⊕			⊕ ($PM_{2.5}$)	
Weichenthal (2013)			⊕	~ (blood pressure)	~	⊕ ($PM_{2.5}$ /VOCs)	
Batterman (2012)						⊕ (PM)	
Paulin (2014)						⊕ (NO_2)	
Coker (2015)			⊕				
Ward (2011)						⊕ (PM2.5)	
Allen (2009)					~	~ (PM)	
Noonan (2012)						⊕ ($PM_{2.5}$)	

⊕ Positive (improved) effect; ⊖ Negative (worse) effect; ⊕/⊖ Positive and negative effects;
~ Effect tested but result not statistically significant at $p<0.05$
Fields in gray were not part of the study design; Fields in green highlight positive results

Implications of This Literature Search

This literature review examined current common practices and, in some cases, best practices in energy efficiency and broader green renovation or construction activities to assess their impact on occupant health. We excluded a body of research that has examined unsafe practices used in the past. Although such studies meet the definition of research that examines the effects of energy efficiency on occupant health, the studies of outdated, and in some cases banned, practices were not the focal point of this literature review.

This review is on one hand broad as it considered a spectrum of activities from base energy efficiency to green new construction; on the other hand, it is narrow because certain energy and health-related literature were not included in the detailed review. Some of the research that was not reviewed in depth includes a body of research that demonstrates that people who live in homes with adequate heat are healthier (Thomson et al. 2013).[162] We did not include these studies because most homes in the United States already have heating equipment installed to provide adequate heat. There is also evidence (Frank et al. 2006)[163] that shows that when occupants have lower fuel bills, more of their income is available to spend on other needs such as food or medicine. Energy efficiency programs improve the health of occupants not only by improving their physical environment but by assisting households economically.

As the home performance industry begins to promote health as a fundamental value of its work, some contractors may look to activities associated with green renovation as a growth area for business. Radon remediation, mold remediation, pest exclusion, and other activities to reduce asthma triggers may be services that some firms may want to offer to clients. In addition to the green construction studies presented here, there have been reviews of multiple studies that have looked at the benefits of housing interventions to control mold/moisture (Sauni et al. 2013)[164] and asthma triggers (Crocker et al. 2011).[165] The section on potential supplemental services was limited to the activities more closely associated with the core HVAC business of most home performance contractors. The potential supplemental services examined included stove replacement (gas to electric, wood to modern wood stove) and in-room filtration.

Common findings emerge from the analyses by category. The following sections summarize the findings by outcome measure and comment on gaps in this research base.

Healthcare Utilization and Cost

Out of 40 studies, 16 considered the effects on healthcare utilization and/or costs. Seven studies found that residents utilized the healthcare system less after energy efficiency activities, while the remaining studies had inconclusive results. None of the studies showed an increase in healthcare utilization. A few common factors are present with the studies that documented significant reductions in healthcare usage. Most of the studies specifically targeted the research to children with asthma; those children often had poorly controlled asthma, so they were at higher risk of using the healthcare system. For the studies that did not specifically target people with asthma, they had large study populations (over 400 children in one study and over 3000 individuals in the other) and healthcare utilization for respiratory symptoms declined significantly. Half of these studies with positive findings examined green new construction as the intervention so the activities included some actions like no-smoking policies that go beyond the normal scope of home performance work. However, the study[166] from New Zealand demonstrates that with a very large study population, even a base energy efficiency package of insulation and air sealing can result in a decline in healthcare utilization.

Additional research is needed to provide strong evidence to healthcare providers/insurers that energy efficiency work in U.S. homes or such work bundled with added health focused interventions can result in reductions of healthcare utilization The study[167] of energy-plus-health on Medicaid expenses offers some early indications that these activities can reduce healthcare costs for children with asthma, but that study did not have a sufficient population size to consider which of three intervention protocols that were used were effective. The Evaluation of the Weatherization Assistance Program also provides indications of reduced health care use for people with asthma.[168] Further research on healthcare utilization might also be considered for other at-risk populations such as adults with asthma or COPD, or adults with hypertension, where prior studies have shown improvements in health outcomes but healthcare impact has not yet been demonstrated.

Health Outcomes

Twenty-nine of the 40 studies examined health outcomes of the residents such as general health and lower respiratory system health. Just over a third of the studies were designed to intentionally consider the effects of home improvement on residents with a pre-existing respiratory problem. Seven studies looked at the effects on children with asthma, two looked at adults or all individuals with asthma, and a tenth study considered the effects on adults with COPD. **In all but two of these studies, there was a significant improvement in at least one self-reported measure of respiratory health following the completion of work. These outcomes were true across the spectrum of categories: from base energy efficiency packages to new green construction and supplemental services.**

The remaining studies considered the effects of housing improvements on residents who were not specifically targeted with a pre-existing health condition. The studies varied with who in the home was being assessed: all individuals, adults only, children only, or older adults only. The most common outcomes were that respondents reported that they felt their general health improved after work was complete. For another three studies, the respondents reported that their mental health improved. Of the studies that did not specifically target a population with respiratory issues, seven reported improvements in lower respiratory symptoms, while another four studies reported improvements in blood pressure/hypertension or other cardiovascular issues. Other studies reported reductions in outcomes such as upper respiratory symptoms and headaches. Because the questionnaires used in these studies varied, it is possible that some of these effects would have been observed in more studies had the same questions been asked.

Indoor Environmental Outcomes

Thirty-five of the 40 studies reported on indoor environmental outcomes. Twenty-six of the studies measured indoor environmental quality with empirical air samples and/or allergen tests, while the remaining studies assessed the indoor environment based on self-report or study assessor observations. Because of the diversity of measures and the cost of testing, the environmental measures that were observed varied by the intent of the research.

Energy efficiency measures conducted in cooler climates can improve resident comfort by giving the occupant the opportunity to live in a warmer (in the winter) and less humid environment. These actions would be expected to improve human health by reducing thermal stress and reducing dampness that has been associated with respiratory problems. However, the tightening of a home can trap indoor contaminants as seen by the two studies where formaldehyde and carbon dioxide or radon levels increased. A similar conclusion was reached by Offerman 2009[169], who examined both natural (76%) and mechanical (24%) ventilation in new homes in California and found that average air changes per hour were below state code requirements in two-thirds of the homes, and formaldehyde levels in all homes studied exceeded guidelines for cancer and chronic irritation. This provides added support for the importance of proper ventilation. Studies of ventilation found that indoor air quality improved after installation of improved ventilation. Reducing indoor contaminants and irritants results in improved respiratory health in the short term and reduces the risk of cancer from formaldehyde and radon in the long term. For certain health effects, indoor air quality testing may be the only way to analyze the potential health benefits of home performance measures. Including air sampling in future research on energy efficiency measures would fill gaps in the current research base. It could help build the case that ventilation must be a fundamental part of any energy efficiency activity.

Base energy efficiency and enhanced energy efficiency studies were most focused on changes in temperature, humidity, and dampness. A few of the studies also included air sampling, and some of the enhanced energy efficiency studies looked at common asthma triggers. Green intervention studies often considered asthma triggers, air quality including particulate matter, and mold and moisture. Ventilation studies tended to include indoor air quality measures as well as humidity. Most of the studies in the supplemental services category measured particulate matter or nitrogen dioxide levels.

The most commonly observed measure across all categories of studies was humidity or dampness (18 studies); with a few exceptions, humidity/dampness improved after energy efficiency work. Indoor temperatures were more comfortable. Across the 24 studies that tested air quality, measures of air quality tended to improve, although there were some studies where CO_2, NO_2, formaldehyde, and radon did increase after work. The findings underscore the importance of proper ventilation practices in conjunction with air sealing and insulation.

Conclusions and Future Research Needs

The research base offers strong suggestive results that home performance work can improve occupant health. **The evidence is strongest for occupants with existing respiratory problems. The evidence is also strong for actions that improve whole-house ventilation and programs and policies that go beyond home performance to include property management actions such as no-smoking policies**.

There is a need to advance the research base and strengthen the case that homeowners and the healthcare sector should invest in home performance measures for their health benefits. Areas where further research is needed include:

- *Studies need to maximize the chances of observing an effect by focusing on clients with pre-existing health conditions.* Studies of people with poorly controlled asthma, sensitivities to dust mites, or hypertension would appear to be the most fruitful.
- *Studies such as the Washington State evaluation of the impact on energy efficiency on Medicaid costs and other costs need to be replicated with larger populations and longer follow-up periods.* The study[170] offers promising results that energy efficiency measures will improve the health of children with asthma and reduce the Medicaid costs associated with those households. With a larger study population and follow-up period that is more than a year, the effects of base energy efficiency as compared to enhanced energy efficiency can be observed. Such a study would benefit by assessing health outcomes and indoor environmental outcomes as well as healthcare utilization measures.
- *The research base would benefit by having more research on market rate homes.* The majority of the studies in this analysis were conducted in the homes of low-income residents. Socio-economic factors have been shown to have an impact on health status and access to care, and these factors could affect the impact of energy efficiency measures on a person's health.
- *Additional evidence of impacts in multifamily units may be needed.* With the exception of the green construction studies, the majority of the studies were conducted in single-family homes. This may be appropriate for the home performance marketplace, but where actions are being taken to attract health partners to multifamily housing, the lack of multifamily research is a limitation.
- *Additional studies of housing in this country would strengthen the evidence to support the impact of U.S. practices.* Studies of green construction and supplemental services have largely been conducted in North America, but only half of the studies of base or enhanced energy efficiency measures have been conducted on this continent. A strong case can be made that the results of studies from Europe and New Zealand can be transferred to our housing stock, but this may not be sufficient for some decision-makers.
- *Studies of the effects of air conditioning on occupant health are needed.* Almost all of the research examined here focused on the effects of heating to improve comfort and health. There is evidence that avoiding extreme heat can also have significant health benefits, but this factor has not been well explored in home performance research. More research on the effects of energy efficiency measures on health in warmer, more humid climates is needed.
- *Studies of the effects of the heating and cooling systems including the distribution process (i.e., ductwork) would be of value.* The focus of most of the research has been on ventilation and thermal

boundaries. No studies examining the effects on health of replacing or modifying HVAC systems and ductwork were identified in this review.

- *Research into the potential health effects of energy efficiency should consider long-term health outcomes from potential exposures to radon and formaldehyde.* There remains a need for further research on the impact on energy efficiency measures on these indoor environmental outcomes, as some studies documented increases after energy efficiency. These environmental measures have been associated with further cases of cancer and other diseases.
- *Studies must include an element that considers resident compliance.* Studies of the use of range hoods, bath fans, or wood stoves have all found that, while the technologies are validated, households who do not use the technologies as recommended will not reap the benefits. The study[171] of high performance homes reported that failure to follow best practices in high-performance homes led to indoor air quality failures in some cases.
- *Studies should include details about standards the energy or home performance/rehabilitation contractors followed.* With the emergence of compliance standards, such as ASHRAE 62 for ventilation and building performance work standards, researchers can now better define the scope of work assessed. This can help compare effects between studies. Furthermore, researchers should state what compliance testing was conducted to verify that the standards were achieved. It was presumed that future home performance services delivered for the purpose of verified health improvement would be compliant with industry-accepted standards and potentially third-party quality oversight such as what is offered in HPwES.
- *Studies must recognize the influence of the outdoor environment on the indoor environment.* Ventilation measures that prove to be successful in drawing in dry, fresh outdoor air in one community may not be successful in communities with extremes in outdoor temperatures and humidity, high pollen levels, and/or polluted outdoor air. Many of the studies in the analysis took into account outdoor air quality but not all of them did.
- *Research into new monitoring devices that can communicate risks to occupants and/or proactively control ventilation or other home assets should be considered as another set of home performance measures, much as insulation and air sealing currently are.*

There is a strong foundation to "connect the dots," making the case that energy efficiency measures can improve occupant health. Yet, for any combination of treatments and health outcomes (e.g., enhanced energy efficiency and hypertension), there may only be one or two studies demonstrating benefits. Such studies should be replicated to gain support from the healthcare community. For healthcare providers/insurers, they may also question whether self-reported improvements in health will result in changes in healthcare utilization. Although there will always be some early adopters, the healthcare field will likely need some of the research gaps filled before becoming invested in the benefit of home energy improvements or comprehensive services that include energy efficiency. For home performance contractors, the evidence that residents feel better, have fewer respiratory symptoms, and experience fewer headaches should be sufficient to help clients understand the potential added benefits of their work. The information in this report can help the *Health and Home Performance Initiative* prepare communication tools about energy efficiency and health. Although no one should use this research to guarantee health effects for any particular client, the evidence is clear that population health benefits are real. Consumers should be educated that a properly conducted energy efficiency job will improve the indoor environment and likely improve occupant health.[c]

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[c] Properly conducted energy efficiency projects positively impact indoor environmental quality with well-designed air sealing, insulation, and heating/cooling upgrades compliant with industry-accepted standards and quality assurance oversight.

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Appendix A: Keyword Search Findings

Keywords	Total articles identified before terms combined and filters applied	Peer-reviewed articles identified after terms combined and filters applied	After review for irrelevant articles	Filters
"Home performance"	36	36	0	
Weatherization	13	13	10	
"Energy conservation" AND housing	134	134	43	
Insulation AND housing AND health	3,390,192	68	40	
Ventilation AND housing AND health AND humans	270,956	81	29	Humans added; limited to last 5 years
Dehumidification AND housing	3	3	0	
"Climate change" AND housing	140	140	30	
Allergies AND housing AND humans	1,253	208	68	Humans added; limited to last 5 years
Asthma AND housing AND humans	1,061	249	105	Humans added; limited to last 5 years
Mold AND housing AND humans	352,318	112	28	Humans added; limited to last 5 years
"Carbon monoxide" AND housing	198	198	44	
"General health" AND housing	154	154	15	
"Healthy housing"	77	77	25	
"Indoor air quality" AND housing	2,076	190	48	
TOTALS after duplicates removed	3,667,665	505	308	

Appendix B: Matrix

Category	Lead Author, Publication Date	Study Design						Outcomes (a)			Demographics			Literature Citation
		Study Type	Study Population Size	Follow-Up Period	Comparison 1	Comparison 2	Comparison 3	Healthcare Use	Health	Indoor Environment	Building Type (b)	Income Level (c)	Location	
ENERGY EFFICIENCY	Osman 2010	Randomized control trial (RCT) of adults with COPD	178 adults	5 months	Package	No Work	NA	No effect on hospital admissions	Respiratory symptom scores improved by 9 points (4 is clinically significant) in treated homes. (treated v. untreated homes) General health changes not significant	No difference in RH. No change in temperature, but fuel costs declined and energy efficiency rating improved	SF	MR	Great Britain	Osman LM, Ayres JG, Garden C, Reglitz K, Lyon J, Douglas JG. (2010). A randomised trial of home energy efficiency improvement in the homes of elderly COPD patients. The European Respiratory Journal, 35(2), 303-309. doi:10.1183/09031936.00187708
ENERGY EFFICIENCY	Barton 2007 Richardson 2006	RCT of residents in housing complex scheduled for renovation	119 homes; 45 individuals with asthma	12 months	Package	Control (package provided year later)	NA	No significant differences in health care costs nine months or less after work.	Asthma symptom score better for adults after work Bronchitis improved 1% after work and worsened by 4% in control homes. No other significant differences in health/lung function based on questionnaire/spirometry	Bedrooms 1°C warmer Short-term improvement in wall dampness	SF	LI	Great Britain	Barton A, Basham M, Foy C, Buckingham K, Somerville M, Torbay Healthy Housing Group. (2007). The Watcombe housing study: The short term effect of improving housing conditions on the health of residents. Journal of Epidemiology and Community Health, 61(9), 771-777. doi:10.1136/jech.2006.048462
ENERGY EFFICIENCY	Howden-Chapman 2007	RCT of insulation and air sealing	1128 homes; 3312 individuals	12 months (up to)	Package	Control	NA	0.57 Odds Ratio of report hospital admission for respiratory condition (trx v. ctl)	Individuals: 0.50-0.57 Odds Ratio of report being in fair/poor health; having a cold/flu; having wheeze in last 3 months (trx v. ctl). Children: O.57 Odds Ratio of report of problems sleeping because of wheezing (trx v. ctl)	1.7 hour/day decline in temperature less than 50°F (trx v ctl) 2.1 hour/day incease in RH less than 75% (trx v ctl) 0.16 Odds Ratio report of condensation; 0.24 Odds Ratio report of mold (trx v. ctl)	SF	LI	New Zealand	Howden-Chapman P, Matheson A, Crane J, Viggers H, Cunningham M, Blakely T, Cunningham C, Woodward A, Saville-Smith K, O'Dea D, Kennedy M, Baker M, Waipara N, Chapman R, Davie G. (2007). Effect of insulating existing houses on health inequality: Cluster randomised study in the community. BMJ (Clinical Research Ed.), 334(7591), 460. doi:10.1136/bmj.39070.573032.80
ENERGY EFFICIENCY	Walker 2009	RCT of new heating systems plus insulation and air sealing	2365 homes	24 months	Package	Control	NA	No significant effect on health care usage	Improved general health (2.57 OR) Fewer new diagnoses of heart disease (OR 0.69), hypertension (OR 0.77), but more new diagnoses of nasal allergies (OR 1.53) (trx v ctl) No significant change in cardiac or respiratory symptoms	Resident reported home comfortable in winter (OR 3.5) (trx v ctl) Treated homes less likely to have more than half of rooms unheated (OR 0.22)	SF	MIXED	Great Britain	Walker J, Mitchell R, Petticrew M, Platt S. (2009). The effects on health of a publicly funded domestic heating programme: A prospective controlled study. Journal of Epidemiology and Community Health, 63(1), 12-17. doi:10.1136/jech.2008.074096

Category	Lead Author, Publication Date	Study Design						Outcomes (a)			Demographics			Literature Citation
		Study Type	Study Population Size	Follow-Up Period	Comparison 1	Comparison 2	Comparison 3	Healthcare Use	Health	Indoor Environment	Building Type (b)	Income Level (c)	Location	
ENERGY EFFICIENCY	Pigg 2014a	Observational evaluation of National Weatherization program	514 homes	month immediately before/after work	PRE	POST	NA	Not Studied	Not Studied	RH increased 1% in winter Radon increased 7% in study group and declined 15% in the comparison group Formaldehyde increased 23% in study group while it increased 11% in the comparison group	SF	LI	U.S.	Pigg S, Cautley D, Francisco P, Hawkins B, Brennan T. (2014a) WEATHERIZATION AND INDOOR AIR QUALITY: MEASURED IMPACTS IN SINGLE-FAMILY HOMES UNDER THE WEATHERIZATION ASSISTANCE PROGRAM. Oak Ridge National Laboratory. Env Sciences Division. ORNL/TM-2014/170.
ENERGY EFFICIENCY	Tonn 2014	Observational evaluation of National Weatherization program	828 occupants, 99 with pre-/post- asthma reports	month immediately after work	PRE Health data has comparison group	POST	NA	6 fold decline in ED visits for asthma after controling for other factors; ED visits for asthma reduced 6% in study group v 2% in comparison group (not significant) Hospitalizations for asthma reduced 6% in study group v. no change in comparison group (not significant)	Cold symptoms in last 14 days reduced 9% in study group v 5% in comparison group (significant) Changes in asthma symptoms not significant (small sample size)	Observed mold, moisture and pests declined	MIXED	LI	U.S.	Tonn B, Rose W, Hawkins B, Conlon B. (2014). Health and household-related benefits attributable to the weatherization assistance program. Oak Ridge National Laboratory. Env Sciences Division. ORNL/TM-2014/345.
ENERGY EFFICIENCY	Wilson 2014	Observational study of weatherization in three cities	248 homes	3-12 months (mean 9 months)	PRE	POST	NA	Not Studied	Reported improvements in comfort, general health, sinusitis (5% less), hypertension (14% less), and use of asthma medications. Reported increases in asthma symptom days and asthma sleep disruption	Reductions in observed moisture and smoke in dwelling. No significant changes in air quality 16-19% improvement in comfort in winter and summer	MIXED	LI	U.S.	Wilson J, Dixon S, Jacobs D, Breysse J, Akoto J, Tohn E, Isaacson M, Evens A, Hernandez Y. (2014). Watts-to-Wellbeing: does residential energy conservation improve health? Energy Effic. 1–10. doi:10.1007/s12053-013-9216-8
ENHANCED ENERGY EFFICIENCY	Breysse 2014	Comparison of children with asthma following Weatherization plus asthma interventions v. asthma education only	102 homes	12 months	Weatherization plus (PRE/POST)	Asthma home ed. (PRE/POST)	NA	Not Studied	Percent with uncontrolled asthma 23% lower in study homes than education homes Caregiver Quality of Life score 31% higher one year after work in study vs. 17% reduction in education homes	Home asthma trigger score 55% lower one-year after work in study homes vs. 41% reduction in education homes (marginal effect); less mold	SF	LI	U.S.	Breysse J, Dixon S, Gregory J, Philby M, Jacobs DE, Krieger J. (2014). Effect of weatherization combined with community health worker in-home education on asthma control. American Journal of Public Health, 104(1), 57. doi:10.2105/AJPH.2013.301402

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ENHANCED ENERGY EFFICIENCY	Lloyd 2008	Comparison study of energy-efficient upgrades v. no changes	36 adults	12-30 months	Package	Control	NA	Case report of fewer admissions to hospital for cardiovascular issues (non-significant)	Significant reductions in blood pressure (trx v. ctl) Improved general health	Not Studied	MF	MIXED	Great Britain	Lloyd EL, McCormack C, McKeever M, Syme M. (2008). The effect of improving the thermal quality of cold housing on blood pressure and general health: A research note. Journal of Epidemiology and Community Health,62(9), 793-797. doi:10.1136/jech.2007.067835
ENHANCED ENERGY EFFICIENCY	Leech 2004	Case-control study of new energy-efficient residential buildings vs standard buildings	105 homes/128 individuals	12 months	Package	Standard New Construction	NA	Not Studied	Overall asthma symptom score better in R-2000 homes Less throat irritation, cough, fatigue, and irritability in R-2000 homes	Not Studied	SF	MR	Canada	Leech JA, Raizenne M, Gusdorf J. (2004). Health in occupants of energy efficient new homes. Indoor Air 14, 169–173. doi:10.1111/j.1600-0668.2004.00212.x
ENHANCED ENERGY EFFICIENCY	Wallner 2015	Comparison study of passive houses v. conventional	123 homes	12 months	HRVs present	Natural Ventilation	NA	Not Studied	Not Studied	Better IAQ formaldehyde, radon, CO2 20% lower RH in EE homes	MIXED	MR	Austria	Wallner P, Munoz U, Tappler P, Wanka A, Kundi M, Shelton JF, Hutter HP. (2015) Indoor Environmental Quality in Mechanically Ventilated, Energy-Efficient Buildings vs. Conventional Buildings. Int J Environ Res Public Health. 6;12(11):14132-47. doi: 10.3390/ijerph121114132.
ENHANCED ENERGY EFFICIENCY	Spertini 2010	Comparison study of energy-efficient residential buildings vs standard buildings	78 homes/181 individuals	20-26 years after construction	Package (Installed at construction; average age 20 yrs)	Natural Ventilation (Average age 26 yrs)	NA	Not Studied	Percent of people with signs/symptoms of allergies not significantly different	89-93% less dust mite allergen in carpet/mattresses in EE homes 11% lower RH in EE homes 5% higher temperature No significant difference in cat or cockroach allergens	MF	MR	Switzerland	Spertini F, Berney M, Foradini F, Roulet CA. (2010). Major mite allergen der f 1 concentration is reduced in buildings with improved energy performance. Allergy, 65(5), 623-629. doi:10.1111/j.1398-9995.2009.02230.x
ENHANCED ENERGY EFFICIENCY	Rose 2015	Healthcare impacts study of children with asthma in homes receiving Weatherization and healthy homes services	49 homes	3-52 months (mean 26 months	Weatherize Only	Weatherize + Healthy Homes	Healthy Homes Only	Annualized Medicaid costs declined $421 across all study groups Claims per month declined in Wx PLUS HH and Wx Only groups	Health survey only conducted post-work so no comparison	Reports of unformtable temperature declined 82% across all groups and excessive humidity declined 62% across all groups; mold declined	SF	LI	U.S.	Rose E, Hawkins B, Tonn, B, Paton D, Shah L. (2015) 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. ORNL/TM-2015-213.

Category	Lead Author, Publication Date	Study Design						Outcomes (a)			Demographics			Literature Citation
		Study Type	Study Population Size	Follow-Up Period	Comparison 1	Comparison 2	Comparison 3	Healthcare Use	Health	Indoor Environment	Building Type (b)	Income Level (c)	Location	
ENHANCED ENERGY EFFICIENCY	Noris 2013	Observational study of energy retrofits in multifamily units	16 homes	2 weeks	PRE	POST	NA	Not Studied	Not Studied	Improved CO_2, acetaldehyde, VOCs, and particle counts Improved temperature and RH Units with ERVs had increased air exchange rates and greater IAQ improvements Formaldehyde and NO_2 fell in one bldg., level in second, and increased in third	MF	MR	U.S.	Noris F, Adamkiewicz G, Delp WW, Hotchi T, Russell M, Singer BC, Spears M, Vermeer K, Fisk WJ. (2013). Indoor environmental quality benefits of apartment energy retrofits. Build. Environ. 68, 170–178. doi:10.1016/j.buildenv.2013.07.003
VENTILATION	Woodfine 2011 Edwards 2011	RCT of ventilation improvements on children (5-14) with asthma	192 homes	12 months	HRV installed	Standard system	NA	No significant change in health care costs	(Children) Fewer symptoms, Better Quality of Life score	Not Studied	SF	MIXED	Great Britain	Woodfine L, Neal RD, Bruce N, Edwards RT, Linck P, Mullock L, Nelhans N, Pasterfield D, Russell D, Russell I. (2011) Enhancing ventilation in homes of children with asthma: Pragmatic randomised controlled trial. Br J Gen Pract. 61(592):e724-32. doi: 10.3399/bjgp11X606636.
VENTILATION	Kovesi 2009	RCT of ventilation improvements on Inuit Children < 6 years old Northern Canada, general risk of respiratory problems	52 homes	6 months	HRV installed	Placebo HRV installed	NA	No significant change in health care usage	(Children) Less wheezing, less rhinitis	Less CO_2, Lower RH	SF	Mixed	Canada	Kovesi T, Zaloum C, Stocco C, Fugler D, Dales RE, Ni A, Barrowman N, Gilbert NL, Miller JD. (2009). Heat recovery ventilators prevent respiratory disorders in Inuit children. Indoor Air 19, 489–499. doi:10.1111/j.1600-0668.2009.00615.x
VENTILATION	Lajoie 2015	RCT of ventilation improvements on children with asthma; ACH < 30	83 homes	24 months	HRV/ERV installed	Standard system	NA	No significant change in health care usage	(Children) Less wheezing, Less wheezing episodes (>4/wk) No significant change in other asthma symptoms	Higher air changes per hour, 33% decrease in formaldehyde Lower airborne mold levels 31% increase in NO_2 Increased phthalates in dust Lower RH	SF	MR	Canada	Lajoie P, Aubin D, Gingras V, Daigneault P, Ducharme F, Gauvin D, Fugler D, Leclerc JM, Won D, Courteau M, Gingras S, Héroux MÈ, Yang W, Schleibinger H. (2015). 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, 25(6), 582-597. doi:10.1111/ina.12181

Category	Lead Author, Publication Date	Study Design						Outcomes (a)			Demographics			Literature Citation
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VENTILATION	Warner 2000	RCT of ventilation improvements on children and adults with asthma/sensitive to dust mites	40 homes	12 months	Whole house ventilation	Special Vacuum	Control	Not Studied	Reduced histimine (not significant)	Dust mite allergen concentrations significantly lower with ventilation than in control group	SF	MR	Great Britain	Warner JA, Frederick JM, Bryant TN, Weich C, Raw GJ, Hunter C, Stephen FR, McIntyre DA, Warner JO.. (2000) Mechanical ventilation and high-efficiency vacuum cleaning: a combined strategy of mite and mite allergen reduction in the control of mite-sensitive asthma. J Allergy Clin Immunol. 105(1):75–82.
VENTILATION	Harving 1996	Case-control study of ventilation improvements on children and adults with asthma/sensitive to dust mites	25 homes	15 months	Whole house ventilation	Control	NA	Not Studied	Improved function, symptom scores, and blood (dust mite) allergen levels. Use of medicines declined.	Dust mite allergen concentrations significantly lower with ventilation than in control group	SF	MR	Denmark	Harving H, Korsgaard J, Dahl R. (1994) Clinical efficacy of reduction in house-dust mite exposure in specially designed, mechanically ventilated "healthy" homes. Allergy. 49(10):866–70.
VENTILATION	Langer 2013	Comparision study of ventilation methods using survey of Swedish housing	157 single family homes/148 multifamily units	single sample	with Whole house ventilation	w/o Whole house ventilation	NA	Not Studied	Not Studied	Lower TVOC and formaldehyde/higher NO2 in homes with whole house ventilation	Mixed	Mixed	Sweden	Langer S, Beko G. (2013) Indoor air quality in the Swedish housing stock and its dependence on building characteristics. Build Environ. 69:44-54.
VENTILATION	Francisco 2016	RCT of ASHRAE 62-1989 v. 62.2-2010 in Weatherized homes	81 homes; 178 individuals	4-15 months (mean 8 months)	Weatherization w/ASHRAE 1989 (PRE-POST)	Weatherization w/ASHRAE 1989 (PRE-POST)	NA	Not Studied	Children's headaches declined in both groups. Decline was significantly greater in 2010 group than 1989 group.	CO2, Formaldehyde, and TVOCs lower after work in 2010 group. No significant difference between groups.	SF	LI	U.S.	Francisco PW, Jacobs DE, Targo L, Dixon SL, Breysse J, Rose W, Cali S. Ventilation and Housing Weatherization. Indoor Air (Submitted)
VENTILATION	Pigg 2014b	Exhaust-only ventilation tested for radon/humidity control	18 homes	6 months	PRE	POST	NA	Not Studied	Not Studied	Radon declined 12% Relative Humidity (RH) declined 1.7%	SF	LI	U.S.	Pigg S. (2014b) NATIONAL WEATHERIZATION ASSISTANCE PROGRAM IMPACT EVALUATION: IMPACT OF EXHAUST-ONLY VENTILATION ON INDOOR RADON AND HUMIDITY – A FIELD INVESTIGATION. Oak Ridge National Laboratory. Env Sciences Division. ORNL/TM-2014/367.
GREEN RENOVATIONS	Breysse 2015	Comparison study of impact of building interventions on older residents compared to a general comparison group	40 homes/adults	12 months	Intervention PRE-	Comparison group POST- (for environmental data)	NA	Not Studied	Mental health improved more than in comparison group Half as many falls as in comparison group (marginal)	Carbon dioxide declined by 32% in summer RH increased 18% in the summer	MF	LI	U.S.	Breysse J, Dixon SL, Jacobs DE, Lopez J, Weber W. (2015). Self-reported health outcomes associated with green-renovated public housing among primarily elderly residents. Journal of Public Health Management and Practice, 21(4), 355-367. doi:10.1097/PHH.0000000000000199

Category	Lead Author, Publication Date	Study Design						Outcomes (a)			Demographics			Literature Citation
		Study Type	Study Population Size	Follow-Up Period	Comparison 1	Comparison 2	Comparison 3	Healthcare Use	Health	Indoor Environment	Building Type (b)	Income Level (c)	Location	
GREEN RENOVATIONS	Ahrentzen 2016 Frey 2015	Observational study of impact of building interventions on older residents	57 homes	12 months	PRE	POST	NA	Not Studied	Residents reported better health, less emotional distress, and more hours sleeping in housing with fewer quarter hours exceeding 81°F Lower formaldehyde associated with less emotional distress	Formaldehyde levels declined Particulate matter levels declined in dwellings with residents who had smoked or who had lived in the unit longer than average	MF	LI	U.S.	Ahrentzen S, Erickson J, Fonseca E. (2016). Thermal and health outcomes of energy efficiency retrofits of homes of older adults. Indoor Air, 26(4): 582-93 doi:10.1111/ina.12239
GREEN RENOVATIONS	Jacobs 2014	Observational study of impact of building interventions on residents	25 homes; 38 adults	12 months	PRE	POST	NA	Not Studied	Adult general health improved from baseline to 1 year (59% to 67% good or better)	Mildew/musty odor, dampness, cockroaches, rodents, and pesticide use all declined from baseline to 1 year Cockroach and mouse allergens declined from baseline to 1 year.	MF	LI	U.S.	Jacobs DE, Breysse J, Dixon SL, Aceti S, Kawecki C, James M, Wilson J. (2014). Health and housing outcomes from green renovation of low-income housing in washington, DC. Journal of Environmental Health, 76(7), 16; quiz 60.
GREEN RENOVATIONS	Breysse 2011	Observational study of impact of building interventions on residents	18 homes; 24 adults	12 months	PRE	POST	NA	Not Studied	Adult non-asthma respiratory issues improved from baseline to 1 year. Adult general health improved from move-in to 1 year (marginal)	Mildew/musty odor declined from baseline to 1 year. Pesticide use and observation of rodents declined from baseline to 1 year.	MF	LI	U.S.	Breysse J, Jacobs DE, Weber W, Dixon S, Kawecki C, Aceti S, Lopez J. (2011). Health outcomes and green renovation of affordable housing. Public Health Reports, 126 Suppl 1, 64-75.
GREEN RENOVATIONS	Less 2015	Observational Study of new or deeply energy retrofitted homes designed to be green high performance homes	24 homes	4.3 years (mean) after construction	Opportunistic Comparisons (e.g., w/ vs. w/o mechnical ventilaton)	NA	NA	Not Studied	Not Studied	Mechanical vented homes 6 time more airtight than non-mechanically ventilated homes, but air exchange rates similar Pollutant levels similar between ventilation types Particle counts 50% lower with filtration system	SF	MR	U.S.	Less B, (2012). Indoor Air Quality in 24 California Residences Designed as High Performance Green Homes. University of California, Berkeley, Berkeley, CA.
GREEN NEW CONSTRUCTION	Jacobs 2015	Comparison study: residents moved into green or conventional dwellings	325 homes; 389 adults-414 children	12 months	Green	Conventional	NA	Children with asthma 21% less likely to visit doctor for urgent asthma symptoms	Improved general health (children); mental health (adults). Reduced hay fever (c/a), headaches (c), respiratory allergies (c) sinusitis (a), and angina (a).	Lower levels of musty odors, dampness, rodents, cockroaches, and pesticide use in green development. CO2, TVOCs higher in green development than conventional	MF	LI	U.S.	Jacobs DE, Ahonen E, Dixon SL, Dorevitch S, Breysse J, Smith J, Evens A, Dobrez D, Isaacson M, Murphy C, Conroy L, Levavi P. (2015). Moving into green healthy housing. Journal of Public Health Management and Practice: JPHMP, 21(4), 345-354. doi:10.1097/PHH.0000000000000047

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GREEN NEW CONSTRUCTION	Takaro 2011	Comparison study: children with asthma moved into green compared to children from prior study	102 children	12 months	Green	Conventional	NA	41% reduction in urgent clinical care	Asthma-symptom–free days increased 44%	Lower levels of mold, moisture and rodents	SF	LI	U.S.	Takaro TK, Krieger J, Song L, Sharify D, Beaudet N. (2011) The Breathe-Easy Home: the impact of asthma-friendly home construction on clinical outcomes and trigger exposure. Am J Public Health. 101(1):55-62. doi: 10.2105/AJPH.2010.300008.
GREEN NEW CONSTRUCTION	Colton 2014 Colton 2015	Comparison study: adult residents moved into green or conventional dwellings	24 adults; 44 children	12 months	Green	Conventional	NA	.24 OR asthma related hosptial visits (child)	47% fewer sick building symptoms in green dwellings (adult) .34 OR asthma symptoms (child) .31 OR asthma attacks (child)	Lower levels of PM2.5 (57%); NO2 (65%); and nicotine (93%) in green dwellings	MF	LI	U.S.	Colton MD, MacNaughton P, Vallarino J, Kane J., Bennett-Fripp M, Spengler JD, Adamkiewicz, G. (2014). Indoor air quality in green vs conventional multifamily low-income housing. Environmental Science & Technology, 48(14), 7833-7841. doi:10.1021/es501489u
GREEN NEW CONSTRUCTION	Garland 2013	Observational study residents with asthma moved into green dwellings	18 individuals	18 months	PRE	POST	NA	Urgent visits to a healthcare professional for asthma in the past 3 months declined	Fewer continuous daily respiratory symptoms and asthma symptoms disrupting sleep in the past month, fewer days with asthma symptoms and asthma episodes	Not Studied	MF	LI	U.S.	Garland E, Steenburgh ET, Sanchez SH, Geevarughese A, Bluestone L, Rothenberg L, Rialdi A, Foley M. (2013). Impact of LEED-certified affordable housing on asthma in the South Bronx. Progress in Community Health Partnerships: Research, Education, and Action, 7(1), 29-37. doi:10.1353/cpr.2013.0010
SUPPLEMANTAL SERVICES- AIR CLEANERS	Lanphear 2010	RCT of use of HEPA room air cleaner in homes with a child with asthma and caregiver that smokes	215 individuals	12 months	HEPA AIR CLEANER	Placebo Filter	NA	19% fewer unscheduled asthma visits (trx v ctl)	No significant difference in asthma symptoms or exhaled nitric oxide levels	25% reduction in PM <0.3 compared to 5% reduction in control No significant difference in air nicotine levels	MIXED	MIXED	U.S.	Lanphear BP, Hornung RW, Khoury J, Yolton K, Lierl M, Kalkbrenner A. (2011) Effects of HEPA air cleaners on unscheduled asthma visits and asthma symptoms for children exposed to secondhand tobacco smoke. Pediatrics. 127(1):93-101. doi: 10.1542/peds.2009-2312. Epub 2010 Dec 13.
SUPPLEMANTAL SERVICES- AIR CLEANERS	Butz 2011	RCT of use of HEPA room air cleaner in homes with a child with asthma and caregiver that smokes	115 children	6 months	HEPA AIR CLEANER w/health coach	HEPA AIR CLEANER	Control	No significant difference in health care events	Seven times more asthma symptom free days in combined air cleaner groups than in control (marginally significant)	PM2.5 declined between 16-20% in air cleaner groups and rose 4% in control No significant difference in air nicotine levels	SF	LI	U.S.	Butz AM, Matsui EC, Breysse P, Curtin-Brosnan J, Eggleston P, Diette G, Williams D, Yuan J, Bernert JT, Rand C. (2011). A randomized trial of air cleaners and a health coach to improve indoor air quality for inner-city children with asthma and secondhand smoke exposure. Archives of Pediatrics & Adolescent Medicine. 165(8):741–748. [PubMed: 21810636]

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SUPPLEMANTAL SERVICES- AIR CLEANERS	Weichenthal 2013	RCT of use of electrostatic air cleaner	20 homes/37 individuals	1 week	Air cleaner	Placebo Filter	NA	Not Studied	Significantly better lung function with active air cleaner No significant difference in blood pressure	PM2.5 and VOCs significantly lower with active air cleaner	SF	MIXED	Canada	Weichenthal S, Mallach G, Kulka R, Black A, Wheeler A, You H, St-Jean M, Kwiatkowski R, Sharp D. (2013) A randomized double-blind crossover study of indoor air filtration and acute changes in cardiorespiratory health in a First Nations community. Indoor Air. 23(3):175-84. doi: 10.1111/ina.12019. Epub 2013 Jan 19.
SUPPLEMANTAL SERVICES- AIR CLEANERS	Batterman 2012	RCT of use of HEPA room air cleaner in homes with a child with asthma and caregiver that smokes	126 children	12 months	HEPA AIR CLEANER w/AC	HEPA AIR CLEANER	Control	Not Studied	Not Studied	PM declined 50% in HEPA Cleaner group. Not significantly better in group with AC. No significant improvement in CO2.	SF	LI	U.S.	Batterman S, Du L, Mentz G, Mukherjee B, Parker E, Godwin C, Chin JY, O'Toole A, Robins T, Rowe Z, Lewis T. (2012) Particulate matter concentrations in residences: an intervention study evaluating stand-alone filters and air conditioners. Indoor Air. 22(3):235–252. [PubMed: 22145709]
SUPPLEMANTAL SERVICES- AIR CLEANERS/GAS STOVE REPLACEMENT	Paulin 2014	RCT of three interventions in homes with unvented gas stoves	73 individuals	3 months	STOVE REPLACED - GAStoELECT.	VENT HOOD INSTALLED	HEPA AIR CLEANER	Not Studied	Not Studied	NO2 declined 51% with stove replace.; NO2 declined 20% with HEPA Cleaner No significant change with vent hood	SF	LI	U.S.	Paulin LM, Diette GB, Scott M, McCormack MC, Matsui EC, Curtin-Brosnan J, Williams DL, Kidd-Taylor A, Shea M, Breysse PN, Hansel NN. (2014) Home interventions are effective at decreasing indoor nitrogen dioxide concentrations. Indoor Air. 24(4):416-24. doi: 10.1111/ina.12085. Epub 2014 Jan 11.
SUPPLEMANTAL SERVICES- GAS STOVE REPLACEMENT	Coker 2015	Comparison study of effects of gas stove used for heating on childhood (age<5) pneumonia	~3,200 children	NA	GAS STOVE used for heat	GAS STOVE used only for cooking	NA	Not Studied	2.08-1.66 adj Odds Ratio of report of pneumonia and cough when gas stove used for heat instead of just cooking; 1.76 adj Odds Ratio of report of pneumonia (not cough) when gas stove used without ventilation	Not Studied	ALL	MIXED	U.S.	Coker ES, Smit E, Harding AK, Molitor J, Kile ML. (2015) A cross sectional analysis of behaviors related to operating gas stoves and pneumonia in U.S. children under the age of 5. BMC Public Health. 15:77. doi: 10.1186/s12889-015-1425-y.
SUPPLEMANTAL SERVICES- WOOD STOVE REPLACEMENT	Ward 2011	Observational pre-/post- study of wood stove replacement with EPA certified stoves in homes of children with asthma	15 homes	12 months	PRE-	POST-	NA	Not Studied	Not Studied	36% reduction in mean PM2.5 33% of homes had higher PM2.5 one-year after replacement	SF	MIXED	U.S.	Ward T, Boulafentis J, Simpson J, Hester C, Moliga T, Warden K, Noonan C. (2011) Lessons learned from a woodstove changeout on the Nez Perce Reservation. Sci Total Environ. 409(4):664-70. doi: 10.1016/j.scitotenv.2010.11.006. Epub 2010 Dec 7.

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SUPPLEMANTAL SERVICES- WOOD STOVE REPLACEMENT	Allen 2009	Observational pre-/post- study of wood stove replacement with less polluting stoves	15 homes	immediately after insulation	PRE-	POST-	NA	Not Studied	Not Studied	5% reduction in mean PM2.5 (not significant) 40% of homes had higher PM2.5 after replacement	SF	MIXED	Canada	Allen R, Leckie S, Millar G, Brauer M. (2009) The impact of wood stove technology upgrades on indoor residential air quality. Atmospheric Environment. 43:5908–5915.
SUPPLEMANTAL SERVICES- WOOD STOVE REPLACEMENT	Noonan 2012	Observational pre-/post- study of wood stove replacement with EPA certified stoves	21 homes	24 months	PRE-	POST-	NA	Not Studied	Not Studied	53% reduction in PM2.5 33% of homes had at least 1 (of 3) post-replacement PM2.5 sample that exceeded pre-samples	SF	MIXED	U.S.	Noonan CW, Navidi W, Sheppard L, Palmer CP, Bergauff M, Hooper K, Ward TJ. (2012). Residential indoor PM2.5 in wood stove homes: Follow-up of the Libby changeout program. Indoor Air, 22(6), 492-500. doi:10.1111/j.1600-0668.2012.00789.x

(a) Green=Positive Results; Blue=Inconclusive Results

(b) SF=Single–Family; MF=Multifamily; MIXED=Either

(c) LI=Low-Income; MR=Market Rate; MIXED=Either

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DOE/EE-1505 • December 2016