Home Rx: The Health Benefits of Home Performance

A Review of the Current Evidence

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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
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Preface

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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). 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. 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. 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>
<thead>
<tr>
<th>Energy Efficiency Measure</th>
<th>Primary Housing Effect</th>
<th>Secondary Housing Effect</th>
<th>Expected Health Outcomes</th>
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</table>
| 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  
  Cleaner burning heating systems  
  Combustion by-products properly vented to outdoors | • 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 |
| Improved Cooking Systems  | Cleaner-burning cooking systems  
  Combustion by-products properly vented to outdoors | • Reduced gases and particulates | • Reduced symptoms of respiratory disease  
  • Reduced risk of cancer |
| 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 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: 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.

**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 States9, 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 study15, the average temperature and humidity levels remained the same, but fuel costs declined. In addition to finding lower relative humidity and condensation, two studies16,17 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 studies18,19 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 four21,22,23,24 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 three25,26,27 of the six studies and were mixed in a fourth28 (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 study29 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 study30 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 studies31,32,33 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, 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 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. 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 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 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 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

<table>
<thead>
<tr>
<th>Study, Lead Author, Date of Publication, and Country</th>
<th>Study Population</th>
<th>Energy Efficiency Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Insulation</td>
</tr>
<tr>
<td><strong>Energy Efficiency and COPD</strong> (Osman et al. 2010)</td>
<td>GB 178 adults</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Watcombe Housing Study</strong> (Barton et al. 2007)</td>
<td>GB 119 homes; 45 individuals with asthma</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>Insulation and Health</strong> (Howden-Chapman et al. 2007)</td>
<td>NZ 1128 homes; 3,312 individuals</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Scottish Central Heating Programme</strong> (Walker et al. 2009)</td>
<td>GB 2,365 homes</td>
<td>✓</td>
</tr>
<tr>
<td><strong>US Weatherization Assistance Program</strong> (Pigg et al. 2014)</td>
<td>US 514 homes</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>(Tonn et al. 2014)</td>
<td>GB 828 occupants, 99 with pre-/post- asthma reports</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Watts-to-Wellbeing Study</strong> (Wilson et al. 2014)</td>
<td>US 248 homes</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓ 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

<table>
<thead>
<tr>
<th>Author and Date of Publication</th>
<th>Healthcare Utilization</th>
<th>General Health/Wellness</th>
<th>Lower Respiratory Health/Asthma</th>
<th>Upper Respiratory and Other Health</th>
<th>Comfort (Temperature/Relative Humidity)</th>
<th>Indoor Air Pollutants</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osman (2010)</td>
<td>~</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>Barton (2007)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~ (PM)</td>
<td></td>
</tr>
<tr>
<td>Richardson (2006)</td>
<td>~</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>(mold)</td>
<td></td>
</tr>
<tr>
<td>Howden-Chapman (2007)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>Walker (2009)</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>+ (cold/flu)</td>
<td>~</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>Pigg (2014a)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>+ (heart disease/hypertension)/- (nasal allergies)</td>
<td>~</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>Tonn (2014)</td>
<td>+</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>~ (mold, musty smells, pests)</td>
<td>~</td>
<td></td>
</tr>
<tr>
<td>Wilson (2014)</td>
<td>~</td>
<td>+</td>
<td>+/~</td>
<td>+ (sinus infection, hypertension)</td>
<td>~</td>
<td>~</td>
<td></td>
</tr>
</tbody>
</table>

+ 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 and (b) weatherization only and healthy homes repairs only. Other studies included a study in Canada comparing health outcomes of occupants of new highly energy-efficient homes to standard new homes, a Swiss study of energy-efficient homes built 20-26 years ago compared to standard homes built in the same era, an Austrian study of homes built to Passive House standards compared to conventional homes, and a British study of homes retrofitted with energy-efficient measures that included whole-house ventilation compared to untreated homes. A seventh study compared various energy efficiency measures including whole-house ventilation on indoor air quality in California multifamily dwellings.

Three of the studies 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 examined the effects on children with asthma, while one looked at the impact of the work on adults with high blood pressure. Another of the studies 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 in this category tested indoor air quality, one tested dust allergens, and two 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, although the levels increased in one of three multifamily buildings in the California study. The researchers conducting the latter study could not identify a reason for the increase.

The Swiss study 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 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 and the study 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 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
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, 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 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 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 and the CHARISMA study 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

<table>
<thead>
<tr>
<th>Study, Lead Author, Date of Publication, and Country Study Population</th>
<th>Energy Efficiency Activities</th>
<th>Ventilation</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Highline Communities Healthy Homes Project</strong> (Breysse et al. 2014) 102 homes</td>
<td>Insulation</td>
<td>Air Sealing</td>
<td>Heating Repair/Replacement</td>
</tr>
<tr>
<td>US</td>
<td>✓</td>
<td>✓*</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Heatfest Study</strong> (Lloyd et al. 2008) 36 adults</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GB</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Evaluation of Canadian R-2000 Standard</strong> (Leech et al. 2004) 105 homes; 128 individuals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Health Optimisation Project for Energy-Efficient (HOPE) Homes</strong> (Spertini et al. 2010) 78 homes; 181 individuals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Mechanical Ventilation in Tight Homes v. Natural Ventilation in Standard Homes</strong> (Wallner et al. 2015) 123 homes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Impact of Weatherization and Healthy Homes Interventions on Asthma-Related Medicaid Claims</strong> (Rose et al. 2015) 49 homes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>✓*</td>
<td>✓*</td>
<td>✓*</td>
</tr>
<tr>
<td><strong>Indoor Environmental Quality Benefits of Apartment Energy Retrofits</strong> (Noris et al. 2013) 16 homes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>✓*</td>
<td>✓*</td>
<td>✓*</td>
</tr>
</tbody>
</table>

* Installed in some dwellings.

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

✓ Energy efficiency activity considered
## Table 3B: Health-Related Effects of Enhanced Residential Energy Efficiency by Study

<table>
<thead>
<tr>
<th>Author and Date of Publication</th>
<th>Healthcare Utilization</th>
<th>General Health/Wellness</th>
<th>Lower Respiratory Health/Asthma</th>
<th>Upper Respiratory and Other Health</th>
<th>Comfort (Temperature/Relative Humidity)</th>
<th>Indoor Air Pollutants</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breysse (2014)</td>
<td>~</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>+ (mold, water damage)</td>
</tr>
<tr>
<td>Lloyd (2008)</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>(blood pressure, respiratory infections)</td>
</tr>
<tr>
<td>Leech (2004)</td>
<td>~</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>(cold symptoms, fatigue, irritability)</td>
</tr>
<tr>
<td>Wallner (2015)</td>
<td></td>
<td></td>
<td></td>
<td>~</td>
<td>~</td>
<td>+</td>
<td>(CO₂, TVOCs, formaldehyde, radon, airborne mold)</td>
</tr>
<tr>
<td>Spertini (2010)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>(airborne mold)</td>
</tr>
<tr>
<td>Rose (2015)</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>+ (dust mite allergens)</td>
</tr>
<tr>
<td>Noris (2013)</td>
<td></td>
<td></td>
<td></td>
<td>~</td>
<td>~</td>
<td>+</td>
<td>+ (mold)</td>
</tr>
</tbody>
</table>

+ 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 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.

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
  - Two studies of improvements to family housing
- Four new construction studies of housing for low-income residents:
  - Two studies that targeted housing for families with a child with asthma
  - Two studies that looked at the health effects in U.S. public housing
- One study that considered the environmental effects of high-performance housing construction and renovation in California

**Green housing can improve environmental conditions.** Three 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 observed reductions in carbon dioxide, which is a marker for poorer ventilation. Jacobs et al. 2015 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.

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b US EPA recommends radon resistant new construction to prevent radon exposures (www.epa.gov/radon).
Five⁹⁹,¹⁰⁰,¹⁰¹,¹⁰²,¹⁰³ 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 studies¹⁰⁴,¹⁰⁵ identified improvements in adult general health and one¹⁰⁶ reported a marginal improvement, while two¹⁰⁷,¹⁰⁸ reported improvements in adult mental health. Other health outcomes included improvements in respiratory symptoms.¹⁰⁹ Two studies¹¹⁰,¹¹¹ 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 new construction can improve health outcomes for children with asthma and reduce healthcare utilization.** Two¹¹²,¹¹³ of the four studies of green new construction examined housing for children with asthma, while the other studies¹¹⁴,¹¹⁵ 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 study¹¹⁶ 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

<table>
<thead>
<tr>
<th>Study, Lead Author, Date of Publication, and Country</th>
<th>Study Population</th>
<th>Energy Efficiency Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Insulation</td>
</tr>
<tr>
<td><strong>Green Renovations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Renovated Housing for Elderly Residents</td>
<td>40 homes</td>
<td>✓</td>
</tr>
<tr>
<td>(Breysse et al., 2015)</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td>Green Energy Efficiency for Older Adults</td>
<td>57 homes</td>
<td>✓</td>
</tr>
<tr>
<td>(Ahrentzen, Erickson, and Fonseca, 2016) (Frey et al., 2015)</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td>Green Renovation of Low-Income Housing</td>
<td>25 homes, 38 adults</td>
<td>✓</td>
</tr>
<tr>
<td>(Jacobs et al., 2014)</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td>Green Housing Renovation Study</td>
<td>18 homes, 24 adults</td>
<td>✓</td>
</tr>
<tr>
<td>(Breysse et al., 2011)</td>
<td>US</td>
<td></td>
</tr>
<tr>
<td>Indoor Air Quality in California High Performance Homes</td>
<td>24 homes</td>
<td>✓</td>
</tr>
<tr>
<td>(Less 2015)</td>
<td>US</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4A, continued

<table>
<thead>
<tr>
<th>Study, Lead Author Date of Publication, and Country Study Population</th>
<th>Energy Efficiency Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Insulation</strong></td>
<td><strong>Air Sealing</strong></td>
</tr>
<tr>
<td><strong>Green New Construction</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Moving into Green Healthy Housing</strong> (Jacobs et al., 2015) US 325 homes, 389 adults, 414 children</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Breathe Easy Study</strong> (Takaro et al., 2011) US 102 children</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Green New Public Housing</strong> (Colton et al., 2014) (Colton et al., 2015) US 31 adults</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Impact of LEED-Certified Affordable Housing on Asthma</strong> (Garland et al., 2013) US 18 residents</td>
<td>✓</td>
</tr>
</tbody>
</table>

✓ Energy efficiency activity considered

US: United States
### Table 4B: Health-Related Effects of Green Renovation/Construction by Study

<table>
<thead>
<tr>
<th>Author and Date of Publication</th>
<th>Healthcare Utilization</th>
<th>General Health/Wellness</th>
<th>Lower Respiratory Health/Asthma</th>
<th>Upper Respiratory and Other Health</th>
<th>Comfort (Temperature/Relative Humidity)</th>
<th>Indoor Air Pollutants</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Green Renovation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breysse (2015)</td>
<td></td>
<td>+ (general, mental health)</td>
<td></td>
<td>+ (falls)</td>
<td>+ (CO₂)</td>
<td>+ (musty smell, dampness)</td>
<td></td>
</tr>
<tr>
<td>Jacobs (2014)</td>
<td></td>
<td>+</td>
<td>+ (injuries)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breysse (2011)</td>
<td>+</td>
<td></td>
<td>+ (respiratory not defined)</td>
<td></td>
<td></td>
<td>+ (musty smell, rodents)</td>
<td></td>
</tr>
<tr>
<td>Less (2015)</td>
<td>~</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 4B, continued

<table>
<thead>
<tr>
<th>Author and Date of Publication</th>
<th>Healthcare Utilization</th>
<th>General Health/Wellness</th>
<th>Lower Respiratory Health/Asthma</th>
<th>Upper Respiratory and Other Health</th>
<th>Comfort (Temperature/Relative Humidity)</th>
<th>Indoor Air Pollutants</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Green New Construction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jacobs (2015)</td>
<td>+</td>
<td>+</td>
<td>(headaches, sinusitis, hay fever, angina)</td>
<td></td>
<td></td>
<td></td>
<td>+ (pests, dampness)</td>
</tr>
<tr>
<td>Takaro (2011)</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+ (pests, mold, water damage, smoking)</td>
</tr>
<tr>
<td>Garland (2013)</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~ (mold)</td>
</tr>
</tbody>
</table>

- **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\textsuperscript{117} and Great Britain\textsuperscript{118,119})
    - One study\textsuperscript{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\textsuperscript{121} and Great Britain\textsuperscript{122})
- Two studies\textsuperscript{123,124} looked at exhaust-only whole-house ventilation in U.S. homes
- One study\textsuperscript{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\textsuperscript{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\textsuperscript{130} observed reductions in carbon dioxide. Two studies\textsuperscript{131,132} observed that nitrogen dioxide increased with ventilation. One of the study researchers\textsuperscript{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.\textsuperscript{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\textsuperscript{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\textsuperscript{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\textsuperscript{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>
<thead>
<tr>
<th>Study, Lead Author, Date of Publication, and Country</th>
<th>Study Population</th>
<th>Intervention Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ventilation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CHARISMA Study</strong> (Woodfine et al. 2011) (Edwards et al. 2011) 192 homes GB</td>
<td>Homes with children with asthma</td>
<td>Heat recovery ventilators (HRV) installed in all homes and heating system repairs in 22% of homes</td>
</tr>
<tr>
<td><strong>Healthy Air Study</strong> (Kovesi et al. 2009) 52 homes CA</td>
<td>Homes with Inuit children less than 6</td>
<td>Heat recovery ventilators (HRV) installed compared to placebo ventilators</td>
</tr>
<tr>
<td><strong>IVAIRE Project</strong> (Lajoie et al. 2015) 83 homes CA</td>
<td>Homes with children with asthma and air exchange rates less than 0.3</td>
<td>Energy recovery ventilator (ERV) (19 homes) or HRV (21 homes) installed or HRV (3 homes) repaired/modified</td>
</tr>
<tr>
<td><strong>Mechanical Ventilation to Control Mites</strong> (Warner et al. 2000) 40 homes GB</td>
<td>Homes with people with asthma who are sensitive to dust mites</td>
<td>Whole-house mechanical ventilation (HRV) installed; separate arm received high efficiency vacuum cleaner</td>
</tr>
<tr>
<td><strong>Mechanically Ventilated Healthy Homes</strong> (Harving et al. 1994) 25 homes DK</td>
<td>Homes with people with asthma who are sensitive to dust mites</td>
<td>Whole-house mechanical ventilation installed</td>
</tr>
<tr>
<td><strong>Indoor Air Quality in Swedish Housing</strong> (Langer and Beko 2013) 157 single family/148 multifamily SE</td>
<td>Homes in Sweden that were part of a national survey</td>
<td>Compared indoor air quality measures by housing type and ventilation type</td>
</tr>
<tr>
<td><strong>US Weatherization Assistance Program</strong> (Pigg 2014) 18 homes US</td>
<td>Weatherized homes</td>
<td>Exhaust ventilation compliant with ASHRAE-62 (2010) – focus effects on radon and relative humidity</td>
</tr>
</tbody>
</table>

CA: Canada; DK: Denmark; GB: Great Britain; SE: Sweden; US: United States
### Table 5B: Health-Related Effects of Ventilation Measures by Study

<table>
<thead>
<tr>
<th>Author and Date of Publication</th>
<th>Healthcare Utilization</th>
<th>General Health/Wellness</th>
<th>Lower Respiratory Health/Asthma</th>
<th>Upper Respiratory and Other Health</th>
<th>Comfort (Temperature/Relative Humidity)</th>
<th>Indoor Air Pollutants</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kovesi (2009)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Lajoie (2015)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~ (VOCs, airborne mold/ - (NO2))</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Warner (2000)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~ (dust mite allergen)</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Harving (1994)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~ (dust mite allergen)</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Langer (2013)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~ (formaldehyde, TVOC)/ - (NO2)</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Francisco (2016)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>Pigg (2014b)</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
</tr>
</tbody>
</table>

positive 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\textsuperscript{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\textsuperscript{144,145,146} targeted the homes of children with asthma who also had a caregiver who was a current smoker. One study\textsuperscript{147} from Canada considered the effects of air filters installed in a community with a high smoking prevalence, while the final study\textsuperscript{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\textsuperscript{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\textsuperscript{150,151} observed reductions in asthma symptoms or improved lung function. Two of the studies considered healthcare utilization as an endpoint, and one\textsuperscript{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\textsuperscript{153} by Paulin et al. (previously discussed under room air cleaners) of three intervention options for homes with gas stoves and a study\textsuperscript{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\textsuperscript{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\textsuperscript{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\textsuperscript{157,158} were conducted in the United States where EPA-certified stoves were installed, while one\textsuperscript{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\textsuperscript{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>
<thead>
<tr>
<th>Study, Lead Author, Date of Publication, and Country</th>
<th>Study Population</th>
<th>Intervention Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In-room Air Cleaner Installation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Cincinnati Asthma Prevention</em> (Lanphear et al. 2010) 215 individuals</td>
<td>Children with asthma residing with smoker</td>
<td>In-room HEPA air cleaners installed in living room and child’s bedroom</td>
</tr>
<tr>
<td><em>Particulate Reduction Education in City Homes (PREACH) Study</em> (Butz et al. 2011) 115 children</td>
<td>Children with asthma residing with smoker</td>
<td>In-room HEPA air cleaners installed in living room and child’s bedroom</td>
</tr>
<tr>
<td><em>First Nations Food, Nutrition, and Environment Study</em> (Weichenthal et al. 2013) 20 homes/37 individuals</td>
<td>First Nations people (predominately young adults) living in homes with high prevalence of smokers</td>
<td>In-room Ultra Clean air purifier installed in a room in home</td>
</tr>
<tr>
<td><em>Community Action Against Asthma</em> (Batterman et al. 2012) 126 children</td>
<td>Children with asthma</td>
<td>In-room HEPA air cleaners installed in child’s bedroom</td>
</tr>
<tr>
<td><em>Home Interventions to Control Nitrogen Dioxide</em> (Paulin et al. 2014) 73 individuals</td>
<td>Homes with unvented gas stove</td>
<td>In-room HEPA air cleaner kitchen and child’s bedroom; one of three interventions in study</td>
</tr>
<tr>
<td><strong>Replacement of Gas Stove with Electric</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Home Interventions to Control Nitrogen Dioxide</em> (Paulin et al. 2014) 73 individuals</td>
<td>Homes with unvented gas stove</td>
<td>Replacement of gas stove with electric stove; one of three interventions in study</td>
</tr>
<tr>
<td><em>Analysis of Effects of Gas Stoves on Respiratory Health</em> (Coker et al. 2015) ~3,200 children</td>
<td>Analysis of data from National Health and Nutrition Examination Survey (US) – children less than 5</td>
<td>Homes with gas stoves compared to homes without them; data included information whether stove was vented and/or if used for heating</td>
</tr>
</tbody>
</table>
Table 6A, continued

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

CA: Canada; US: United States
### Table 6B: Health-Related Effects of Supplemental Home Performance Services by Study

<table>
<thead>
<tr>
<th>Author and Date of Publication</th>
<th>Healthcare Utilization</th>
<th>General Health/Wellness</th>
<th>Lower Respiratory Health/Asthma</th>
<th>Upper Respiratory and Other Health</th>
<th>Comfort (Temperature/Relative Humidity)</th>
<th>Indoor Air Pollutants</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanphear (2010)</td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>+ (PM)</td>
<td></td>
</tr>
<tr>
<td>Butz (2011)</td>
<td>~</td>
<td>+</td>
<td></td>
<td>~</td>
<td>~</td>
<td>+ (PM2.5)</td>
<td></td>
</tr>
<tr>
<td>Weichenthal (2013)</td>
<td></td>
<td></td>
<td>+</td>
<td>~</td>
<td>~</td>
<td>+ (PM2.5 /VOCs)</td>
<td></td>
</tr>
<tr>
<td>Batterman (2012)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~</td>
<td>+ (PM)</td>
<td></td>
</tr>
<tr>
<td>Paulin (2014)</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>~</td>
<td>+ (NO₂)</td>
<td></td>
</tr>
<tr>
<td>Coker (2015)</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>~</td>
<td>~ (blood pressure)</td>
<td></td>
</tr>
<tr>
<td>Ward (2011)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~</td>
<td>+ (PM2.5)</td>
<td></td>
</tr>
<tr>
<td>Allen (2009)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~</td>
<td>~ (PM2.5)</td>
<td></td>
</tr>
<tr>
<td>Noonan (2012)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~</td>
<td>+ (PM1.3)</td>
<td></td>
</tr>
</tbody>
</table>

+ 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 study166 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 study167 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\textsuperscript{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 CO₂, NO₂, 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 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[^71] 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].

[^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.
Bibliography


## Appendix A: Keyword Search Findings

<table>
<thead>
<tr>
<th>Keywords</th>
<th>Total articles identified before terms combined and filters applied</th>
<th>Peer-reviewed articles identified after terms combined and filters applied</th>
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### Appendix B: Matrix

<table>
<thead>
<tr>
<th>Category</th>
<th>Lead Author, Publication Date</th>
<th>Study Design</th>
<th>Outcomes (a)</th>
<th>Demographics</th>
<th>Literature Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ENERGY EFFICIENCY</strong></td>
<td>Walker 2009</td>
<td>RCT of new heating systems plus insulation and air sealing</td>
<td>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 health care usage</td>
<td>SF MIXED</td>
<td>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</td>
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<td>Study Population Size</td>
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<td>ENERGY EFFICIENCY</td>
<td>Pigg 2014a</td>
<td>Observational evaluation of National Weatherization program</td>
<td>514 homes</td>
<td>month immediately before/after work</td>
<td>PRE POST NA</td>
</tr>
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<td>ENERGY EFFICIENCY</td>
<td>Tonn 2014</td>
<td>Observational evaluation of National Weatherization program</td>
<td>828 occupants, 99 with pre-post asthma reports</td>
<td>month immediately after work</td>
<td>PRE Health data has comparison group</td>
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<tr>
<td>ENHANCED ENERGY EFFICIENCY</td>
<td>Breysse 2014</td>
<td>Comparison of children with asthma following Weatherization plus asthma interventions v. asthma education only</td>
<td>102 homes</td>
<td>12 months</td>
<td>Weatherization plus (PRE/POST) Asthma home ed. (PRE/POST)</td>
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<td>Follow-Up Period</td>
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<td>ENHANCED ENERGY EFFICIENCY</td>
<td>Spertini 2010</td>
<td>Comparison study of energy-efficient residential buildings vs standard buildings</td>
<td>78 homes/181 individuals</td>
<td>20-26 years after construction</td>
<td>Package (Installed at construction; average age 20 yrs)</td>
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<tr>
<td>ENHANCED ENERGY EFFICIENCY</td>
<td>Rose 2015</td>
<td>Healthcare impacts study of children with asthma in homes receiving Weatherization and healthy homes services</td>
<td>49 homes</td>
<td>3-52 months (mean 26 months)</td>
<td>Weatherize Only</td>
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<tr>
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<td>Outcomes (a)</td>
<td>Demographics</td>
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<td>VENTILATION</td>
<td>Warner 2000</td>
<td>RCT of ventilation improvements on children and adults with asthma/sensitive to dust mites</td>
<td>40 homes</td>
<td>12 months</td>
<td>Whole house ventilation</td>
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<td>VENTILATION</td>
<td>Harving 1996</td>
<td>Case-control study of ventilation improvements on children and adults with asthma/sensitive to dust mites</td>
<td>25 homes</td>
<td>15 months</td>
<td>Whole house ventilation</td>
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<td>VENTILATION</td>
<td>Langer 2013</td>
<td>Comparison study of ventilation methods using survey of Swedish housing</td>
<td>157 single family homes/148 multifamily units</td>
<td>single sample</td>
<td>with Whole house ventilation</td>
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<td>VENTILATION</td>
<td>Francisco 2016</td>
<td>RCT of ASHRAE 62-1989 v. 62.2-2010 in Weatherized homes</td>
<td>61 homes; 178 individuals</td>
<td>4-15 months (mean 8 months)</td>
<td>Weatherization w/ASHRAE 1989 (PRE-POST)</td>
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<td>VENTILATION</td>
<td>Pigg 2014b</td>
<td>Exhaust-only ventilation tested for radon/humidity control</td>
<td>18 homes</td>
<td>6 months</td>
<td>PRE</td>
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<tr>
<td>GREEN RENOVATIONS</td>
<td>Breysse 2015</td>
<td>Comparison study of impact of building interventions on older residents compared to a general comparison group</td>
<td>40 homes/adults</td>
<td>12 months</td>
<td>Intervention PRE-</td>
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**Note:** The table provides a summary of studies examining the health benefits of home performance, including ventilation and green renovations. It lists the study type, lead author, publication date, study design, outcomes, and demographics, along with references for further reading.
<table>
<thead>
<tr>
<th>Category</th>
<th>Lead Author, Publication Date</th>
<th>Study Design</th>
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<tr>
<td>GREEN RENOVATIONS</td>
<td>Ahrentzen 2016 Frey 2015</td>
<td>Observational study of impact of building interventions on older residents</td>
<td>Residents reported better health, less emotional distress, and more hours sleeping in housing with fewer quarter hours exceeding 81°F. Lower formaldehyde levels declined. Particulate matter levels declined in dwellings with residents who had smoked or who had lived in the unit longer than average.</td>
<td>MF LI U.S.</td>
<td>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</td>
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<tr>
<td>GREEN RENOVATIONS</td>
<td>Jacobs 2014</td>
<td>Observational study of impact of building interventions on residents</td>
<td>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. Pesticide use and observation of rodents declined from baseline to 1 year.</td>
<td>MF LI U.S.</td>
<td>Jacobs DE, Breyesse 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.</td>
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<td>GREEN RENOVATIONS</td>
<td>Less 2015</td>
<td>Observational Study of new or deeply energy retrofitted homes designed to be green high performance homes</td>
<td>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.</td>
<td>SF MR U.S.</td>
<td>Less B, (2012). Indoor Air Quality in 24 California Residences Designed as High Performance Green Homes. University of California, Berkeley, Berkeley, CA.</td>
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<td>GREEN NEW CONSTRUCTION</td>
<td>Jacobs 2015</td>
<td>Comparison study: residents moved into green or conventional dwellings</td>
<td>Children with asthma 21% less likely to visit doctor for urgent asthma symptoms. Improved general health (children); mental health (adults). Reduced hay fever (c), 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.</td>
<td>MF LI U.S.</td>
<td>Jacobs DE, Ahonen E, Dixon SL, Dorevitch S, Breyesse 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</td>
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<td>GREEN NEW CONSTRUCTION</td>
<td>Colton 2014 Colton 2015</td>
<td>Comparison study: adult residents moved into green or conventional dwellings</td>
<td>24 adults; 44 children</td>
<td>12 months</td>
<td>Green</td>
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<td>GREEN NEW CONSTRUCTION</td>
<td>Garland 2013</td>
<td>Observational study residents with asthma moved into green dwellings</td>
<td>18 individuals</td>
<td>18 months</td>
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<td>SUPPLEMENTAL SERVICES- AIR CLEANERS</td>
<td>Lanphear 2010</td>
<td>RCT of use of HEPA room air cleaner in homes with a child with asthma and caregiver that smokes</td>
<td>215 individuals</td>
<td>12 months</td>
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(a) Green=Positive Results; Blue=Inconclusive Results
(b) SF=Single–Family; MF=Multifamily; MIXED=Either
(c) LI=Low-Income; MR=Market Rate; MIXED=Either
Endnotes


2 As of January 1, 2012, WAP required all projects to meet ventilation measures consistent with ASHRAE 62.2. (ASHRAE: American Society of Heating Refrigeration and Air-Conditioning Engineers) (WPN 11-6)


5 These contaminants are characterized as non-airborne because their detection is not based on air measurements; however, residents are exposed to them through the inhalation of particles or compounds in the air.


7 Bruce Tonn et al., Health and Household-Related Benefits Attributable to the Weatherization Assistance Program. Oak Ridge National Laboratory. Env Sciences Division. 2014. ORNL/TM-2014/345.

8 Scott Pigg et al., Weatherization and Indoor Air Quality: Measured Impacts in Single-Family Homes under the Weatherization Assistance Program. Oak Ridge National Laboratory. Env Sciences Division. 2014. ORNL/TM-2014/170.


15 Osman et al., “A Randomised Trial of Home Energy Efficiency Improvement in the Homes of Elderly COPD Patients.”

16 Howden-Chapman et al., “Effect of Insulating Existing Houses on Health Inequality: Cluster Randomised Study in the Community,” 4.

17 Tonn et al., Health and Household-Related Benefits Attributable to the Weatherization Assistance Program, 22.

18 Richardson et al., “The Watcombe Housing Study: The Short-Term Effect of Improving Housing Conditions on the Indoor Environment”

20 Pigg et al., Weatherization and Indoor Air Quality: Measured Impacts in Single-Family Homes under the Weatherization Assistance Program.

21 Howden-Chapman et al., “Effect of Insulating Existing Houses on Health Inequality: Cluster Randomised Study in the Community”

22 Walker et al., “The Effects on Health of a Publicly Funded Domestic Heating Programme: A Prospective Controlled Study.”

23 Tonn et al., Health and Household-Related Benefits Attributable to the Weatherization Assistance Program.


26 Barton et al., “The Watcombe Housing Study: The Short Term Effect of Improving Housing Conditions on the Health of Residents.”

27 Howden-Chapman et al., “Effect of Insulating Existing Houses on Health Inequality: Cluster Randomised Study in the Community.”


29 Howden-Chapman et al., “Effect of Insulating Existing Houses on Health Inequality: Cluster Randomised Study in the Community.”

30 Tonn et al., Health and Household-Related Benefits Attributable to the Weatherization Assistance Program.

31 Osman et al., “A Randomised Trial of Home Energy Efficiency Improvement in the Homes of Elderly COPD Patients.”

32 Barton et al., “The Watcombe Housing Study: The Short Term Effect of Improving Housing Conditions on the Health of Residents.”

33 Walker et al., “The Effects on Health of a Publicly Funded Domestic Heating Programme: A Prospective Controlled Study.”

34 Barton et al., “The Watcombe Housing Study: The Short Term Effect of Improving Housing Conditions on the Health of Residents.”

35 Walker et al., “The Effects on Health of a Publicly Funded Domestic Heating Programme: A Prospective Controlled Study.”

36 Tonn et al., Health and Household-Related Benefits Attributable to the Weatherization Assistance Program.


38 Pigg et al., Weatherization and Indoor Air Quality: Measured Impacts in Single-Family Homes under the Weatherization Assistance Program.

39 Howden-Chapman et al., “Effect of Insulating Existing Houses on Health Inequality: Cluster Randomised Study in the Community.”

40 Tonn et al., Health and Household-Related Benefits Attributable to the Weatherization Assistance Program, 52.


48 Breyssse et al., “Effect of Weatherization Combined with Community Health Worker In-Home Education on Asthma Control.”

49 Rose et al., Exploring Potential Impacts of Weatherization and Healthy Homes Interventions on Asthma-Related Medicaid Claims and Costs in a Small Cohort in Washington State.

50 Lloyd et al., “The Effect of Improving the Thermal Quality of Cold Housing on Blood Pressure and General Health: A Research Note.”

51 Breyssse et al., “Effect of Weatherization Combined with Community Health Worker In-Home Education on Asthma Control.”

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