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Improving Health Equity Through Residential Electrification And Energy Efficiency: State Of Practice In The Us

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Improving health equity through residential electrification and energy efficiency: State of practice in the US

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Abstract

Improving residential building efficiency and transitioning from fossil fuels for climate alignment has been a primary focus in climate change mitigation efforts. Energy efficiency is usually achieved through tightening buildings by sealing gaps that allow conditioned air to pass through. However, early research highlighted the potential for more efficient buildings to also limit the supply of outdoor air, leading to increased indoor concentrations of various air pollutants. Tightening buildings for efficiency must therefore be accompanied by supplemental ventilation to preserve indoor air quality. However, less is known about the effects of specific indoor pollutant sources. It is hypothesized that indoor air will still be negatively impacted if pollutant sources, such as combustion appliances, are not also removed. A scoping-style review identified 15 studies related to energy efficiency retrofits, building fuel types, and indoor air quality, and the related impact on health. Energy-efficiency interventions discussed in the reviewed publications included insulating, air sealing, upgrading appliances, upgrading or installing kitchen and bathroom exhaust, installing continuous mechanical ventilation, providing particle filtration, installing efficient windows and doors, and replacing gas stoves/ovens with newer or electric alternatives. Health was assessed in six of the studies; two studies considered asthma-related symptoms and four studies assessed other outcomes including $PM_{2.5}$-related mortality, sick building syndrome symptoms, general and mental health, and child behaviors. The quantification of costs associated with healthcare utilization and energy usage was not a primary focus in this literature. Health was generally improved through layered energy efficiency retrofit approaches that included exhaust, ventilation, filtration, and electric stove installation, which also reduced the payback periods of these interventions.

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1. Introduction

Most residential buildings in the United States are energy- and carbon-intensive to operate. In 2021, the building sector was responsible for 28% of the nation's energy consumption and 35% of CO_2 emissions. Residential buildings (hereon referred to as "buildings") accounted for over half of these estimates (U.S. EIA, 2021; U.S. EIA, 2022). Enhancing building efficiency and transitioning from fossil fuels for climate alignment has been a primary focus in climate change mitigation efforts. This effort has co-benefits, most notably through the improvement of indoor air quality and promotion of energy justice through reduced energy costs (Tonn et al., 2014).

Those working on the topic have raised questions about the health impacts associated with retrofits. For example, weatherizing without the addition of supplemental ventilation is well recognized to worsen indoor air quality. Early research on this topic highlighted the potential for more efficient buildings to limit the supply of outdoor air, leading to increased indoor concentrations of radon, carbon monoxide, nitrogen dioxide, and formaldehyde (Burkart & Chakraborty, 1984). Contemporary research supports this finding. A simulation study conducted by Gillingham et al. (2021) reported that improving the efficiency of the building envelope without implementing protective measures, such as ventilation and filtration to prevent pollutant buildup, can be detrimental to indoor air quality.

It is therefore hypothesized that the same negative impact on indoor air will occur without mitigating indoor sources of pollution, such as combustion appliances. The current research on the health impacts of energy efficiency improvements, indoor air quality, and heating/cooking fuels spans multiple disciplines, including engineering and public health. Informed decisions regarding the intersection of these topics requires an evidence base that is able to account for this multidisciplinary research. Understanding the landscape of existing research is needed to ensure policies that protect indoor air quality and resident health when increasing building efficiency.

A core goal of energy efficiency retrofits (EER) is the ability to keep heated or cooled air inside the building, thereby reducing the energy needed to maintain indoor conditions. EERs that improve the performance of existing buildings include sealing and insulating; installing efficient windows and doors; and upgrading to energy efficient water heaters, appliances, and heating, ventilation, and air conditioning (HVAC) systems (Office of Energy Efficiency & Renewable Energy, n.d.). Weatherization is similar to EER and adds a focus on safety by including combustion appliance testing, fire hazard assessments, and mechanical ventilation installations (Weatherization Assistance Program, n.d.). For the purposes of this study, EER will include weatherization and any interventions that improve overall building performance.

The efficacy of EERs, however, can be a double-edged sword for indoor air quality. A review by Wilson et al. (2016) found that residential energy efficiency upgrades can improve resident respiratory, cardiovascular, and overall health by removing pollutant sources and reducing indoor air emissions. Efficient, airtight building envelopes can further reduce the unwanted infiltration of outdoor air pollutants (Zhao et al., 2021). Despite this evidence, the effect of EERs on indoor air pollutants arising from behavioral factors, such as cooking, is less clear. More research is needed to understand how an airtight envelope impacts the concentration of air pollutants with indoor sources that are influenced by human actions.

Building electrification addresses this issue through shifting households' reliance on fossil fuels to electricity, thereby removing an indoor source of air pollutants. Although building electrification, like EER, is primarily related to energy, its associated health co-benefits cannot be understated. Typical natural gas appliances emit air pollutants that are well recognized to adversely affect health such as fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and volatile organic compounds (VOCs) (Vardoulakis et al., 2020; Brugge et al., 2003; Michanowicz et al., 2022; Hollowell & Miksch, 1981). These pollutants have a range of health impacts: $PM_{2.5}$ is linked to adverse pulmonary and cardiovascular outcomes and particularly exacerbates symptoms in children with asthma; NO_2 is associated with higher childhood asthma rates; VOCs, such as benzene, toluene, ethylbenzene, xylenes, acetaldehyde, and formaldehyde, are known or suspected human carcinogens (Vardoulakis et al., 2020; McCormack et al., 2009; Belanger et al., 2006; Michanowicz et al., 2022; World Health Organization, 2010). Replacing gas appliances with electric alternatives is important for health. Natural gas appliances, particularly those that do not vent outdoors such as gas stoves and ovens, are major sources of the aforementioned pollutants (Jones, 1999).

Despite the potential for EER and building electrification to improve a building's performance, environmental impact, and indoor air quality, these strategies are often not pursued in tandem. For example, the federally-funded Weatherization Assistance Program subsidizes EERs but rarely supports renewable energy upgrades or electrification projects (Whillans, 2022). This piecemeal approach creates challenges for holistic retrofits that incorporate energy-efficiency and electrification to allow for deep reductions in energy use. There is a need for researchers, policymakers, and those involved in building design and construction to better understand the impacts of joint EER and building electrification efforts, particularly how they interact to affect indoor air quality and health. While the extant research on health and indoor air quality impacts of pairing EERs with building electrification is still growing, there is evidence that combining EER and building electrification can both improve cost effectiveness of retrofits and indoor air quality (Amann et al., 2021).

Currently, research that connects the health and indoor air quality implications of EERs and certain building fuel types is lacking. Namely, very little has been written about the specific health impacts of EER and building electrification, especially those that are not pulmonary in nature. This thesis aims to provide a novel, scoping style synthesis of research on the studied health impacts of indoor air quality related to residential EER and appliance type. This project summarizes key findings, identifies best practices, and makes recommendations for further investigation. In addition, interviews were conducted with professionals in governmental, housing, health, and energy sectors discussing their perceived gaps in research and evidence that they would find to be most impactful. Given the dearth of research on the indoor air quality and health impacts of EER and building electrification, this work will support evidence-based decision-making regarding EER and electrification policies that have the potential to improve indoor air quality, and therefore public health.

2. Methods

A scoping-style review design was used to identify studies related to EER, building fuel type, and indoor air quality, and document their included health outcomes. The review consisted of three phases: article collection; article screening and content review; and extraction of key findings. The review was further informed by interviews with professionals in relevant industries to understand EERs being conducted and the supporting-research needs of the energy transition landscape.

2.1 Literature searches

Keywords were used to search for relevant studies in databases. Keywords included terms related to energy efficiency upgrades, building fuel type, indoor residential environments, and indoor air pollutants. Databases searched include PubMed, Lens, and EPA HERO. Full search strings and keywords used for each respective database are included in Appendix A. Results from these searches were imported into Zotero.

2.2 Screening of selected articles

Publications were included for review regardless of publication year but were excluded if they were not written in English or were conducted outside the United States. Inclusion criteria were as follows: based in the United States exploring residential EERs and the associated impact on indoor air quality, as well as the incorporation of residential appliance and fuel types. The inclusion of health-related outcomes was assessed in the following extraction stage. Publications considered for review were peer-reviewed reports, theses and dissertations, and white papers. Conference papers, systematic reviews, meta-analyses, and letters to the editor were included for source identification and citation chaining, but excluded from full-text review.

Publications that met the inclusion criteria underwent full text review and were evaluated based on specific EER interventions and the impact of appliance and/or fuel type on indoor air quality. Studies that met these criteria then moved on to the extraction phase.

Additional hand-searching was conducted to supplement the formal literature search. Industry organizations identified through discussions with professionals included Air Infiltration and Ventilation Centre (AIVC); American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); American Council for an Energy-Efficient Economy (ACEEE); Three3; and Green & Healthy Homes Initiative (GHHI). Reports published by these organizations were reviewed for their relevance. The ResearchRabbit (www.researchrabbitapp.com) tool was used to visualize bibliographic networks and identify related research. The articles included after the formal full text review were imported into ResearchRabbit and the resulting network of related papers were reviewed for their relevance.

2.3 Extraction of articles

The final stage of the scoping review was extraction of key findings from collected papers. All collected studies were reviewed to evaluate the study design, specific EER interventions used, housing type being studied, residential fuel type, effect on indoor air quality, associated impacts on health, and quantification of the cost- or energy-savings related to the EER.

2.4 Interviewing industry professionals

Individuals engaged in policy and research at various institutions were interviewed for their expertise and understanding of key knowledge gaps in the field. A total of 16 individuals from 10 organizations spanning the governmental, housing quality and building science, health, or energy sectors were interviewed. Briefly, interview questions engaged with research practices, communication approaches, and perspectives of potential gaps in research. Interview guides specific to policy and research organizations, respectively, can be found in Appendix B.

3. Results

3.1 Reviewed studies and publications

All databases were searched on January 22, 2023. PubMed yielded 18 results, Lens yielded 1029 results, and EPA HERO yielded 31 results. The 1,078 references were downloaded and imported into Zotero. From these identified publications, 40 duplicates were removed, 1,038 underwent title and abstract screening, 68 were included in full-text screening, 10 full-text publications were used for data extraction, and an additional five studies identified through hand-searching were also included for data extraction (Figure 1).

Most of the included publications (12/15) were peer-reviewed journal articles. Study designs varied among all final publications and included 5 simulation studies and 10 experimental studies that involved indoor air sampling. All simulation studies were based on multifamily public housing in Boston, MA. Four experimental studies were conducted in multifamily public housing and six were conducted in single family homes and public housing. One experimental randomized control study was national in scope and included 35 states. Other experimental studies were conducted in Illinois, Indiana, California, New York, Ohio, and Arizona. Characteristics of included publications are listed in Appendix C: Overview of publications identified for evaluation.

Inclusion criteria ensured that all reviewed papers assessed some form of EER or building leakiness, discussed appliance fuel type(s), and considered indoor air pollutant(s). Interventions for EER varied and included insulating, air sealing, upgrading appliances, upgrading or installing kitchen and bathroom exhaust, installing continuous mechanical ventilation, providing particle filtration, installing efficient windows and doors, and replacing gas stoves/ovens with newer or electric alternatives. The primary indoor combustion source in the included studies were gas stoves (13/15). Of these studies, three considered gas oven usage and seven included homes with electric stoves as comparisons. Four studies included gas furnaces and two studies factored in the use of gas ovens for supplemental heating as a major contributor to indoor air pollutants.

Several studies assessed indoor levels of $PM_{2.5}$ (11/15) and NO_2 (10/15) related to residential gas combustion. Other related air pollutants studied include formaldehyde (7/15), CO_2 (4/15), total VOCs (4/15), CO (3/15), and acetaldehyde (2/15). The study that conducted the most comprehensive indoor air pollutant measurements included six pollutants: NO_2, $PM_{2.5}$, CO_2, formaldehyde, acetaldehyde, and total VOCs (Noris et al., 2013).

Discussion on health impacts of indoor air that was affected by EER and residential gas combustion was not an inclusion criterion and was instead evaluated during the data extraction stage of the review. Six studies incorporated some health assessment; of these, three quantified the economic implications of changes in studied health outcomes.

The potential energy savings of EER, quantified in either dollar amounts or usage reductions, were discussed in four of the included studies. Within all 15 studies, two simulation studies quantified both health benefits and energy savings related to building weatherization and/or swapping out gas appliances with electric alternatives. A full summary of findings and conclusions from each publication is outlined in Appendix D: Results of publications identified for evaluation.

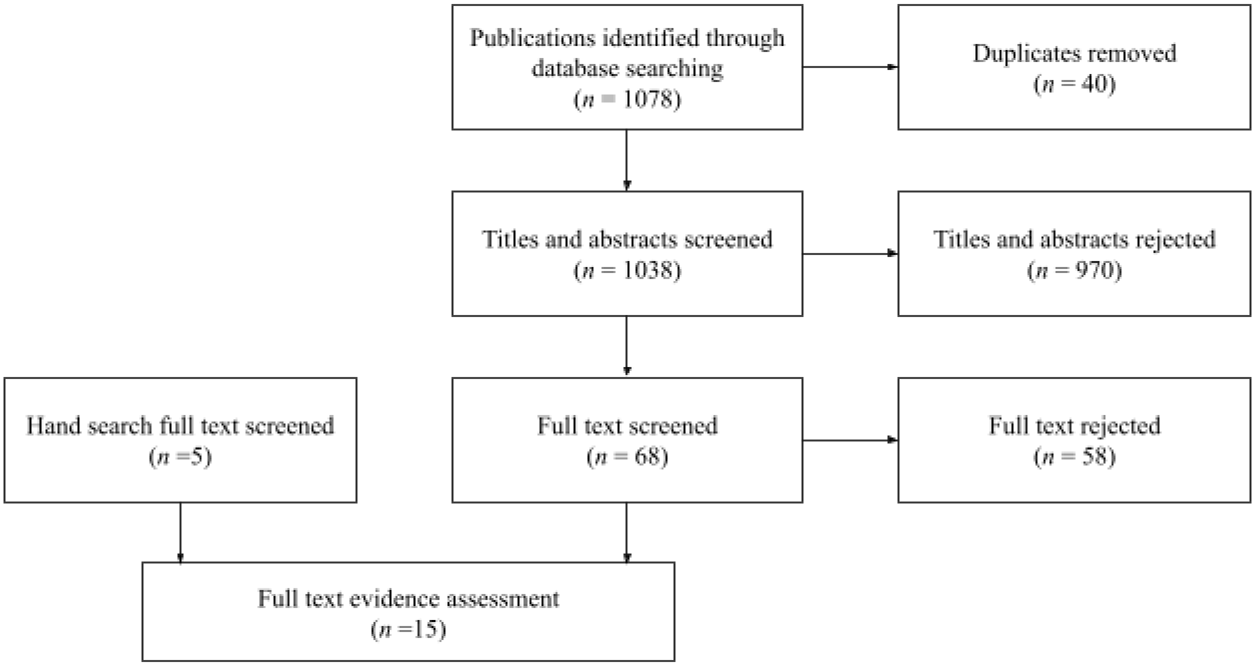

Figure 1. Number of papers at each review stage

3.2 Interview findings

Interviews with industry professionals from 10 organizations were conducted in January and February 2023. Individual expertise fell broadly into four categories: housing quality and building science, energy, health, and government. Interview guides covered the limited information available on specific effects from EER within the broader existing literature; the financial contextualization of health and equity impacts; and the need for a better understanding of health outcomes beyond childhood asthma.

3.2.1 Existing weatherization research strengths and limitations

Comments on the current state of research related to EER interventions, residential fuel type, and indoor air quality were made by individuals involved in housing quality and building science, energy, and health. According to the experts, there is a strong evidence base linking increased ventilation during cooking with improved indoor air quality. However, this literature is generally focused on indoor air quality changes and not on the particular health impacts related to energy efficiency or fuel-switching.

When health outcomes are considered, results can still be nuanced by housing characteristics under different study designs. Studies on indoor air quality related to energy efficiency and fuel type generally fall under two categories: those conducted in new construction or in retrofit housing. Findings from studies done in newly-constructed housing are limited in their ability to be extrapolated to retrofit scenarios. On the other hand, research findings from retrofit housing can be limited in generalizability due to their study populations; EER projects have tended towards older populations and participants with disabilities and/or preexisting health conditions.

3.2.2 Contextualization of health and equity impacts

Just as it is difficult to attribute health impacts to specific EER and fuel-switching interventions, there is a lack of information on how certain interventions can also save money. Experts in housing quality and building science, energy, and health discussed how local organizations and individuals – especially those in low-income households – could benefit from understanding just how costly poor indoor air quality can be, as well as the magnitude of potential savings that building improvements may confer.

3.2.3 Further exploration of associated health outcomes

Individuals from housing quality and building science, energy, and health organizations highlighted the need to explore health outcomes beyond asthma that are related to energy efficiency and indoor combustion. It was noted that the majority of existing research at this intersection focuses on asthma outcomes given its strong association with various indoor air pollutants. However, poor indoor air quality and environments are related to many issues of wellbeing, potentially impacting mental health, thermal comfort, and leading to missed work and school days.

4. Discussion

This scoping-style review assessed the extant literature on EER, residential fuel type, indoor air quality, and health. Peer-reviewed publications and reports were systematically searched for, collected, and reviewed to understand how health was being considered and quantified – if at all – within broader discussions on energy efficiency. Interviews with experts in the research area were conducted to inform the direction of the study.

Overall, 15 publications, including both reports and peer-reviewed studies, were included and 16 individuals were interviewed. The evidence suggests that different EER interventions have varying levels of efficacy for improving indoor air and reducing healthcare costs; these results are often highly context-specific. Swapping out gas appliances in efficient and ventilated homes can provide higher levels of healthcare and energy savings. These home retrofits also decrease emissions of gaseous pollutants, such as NO_2 and formaldehyde, which may be less effectively removed through conventional interventions.

4.1 Energy-efficiency retrofit package features

Among the various EER interventions, air sealing had the greatest adverse impact on indoor air quality. Air sealing (or sealing) is the practice of covering openings, such as those for plumbing and utilities, with materials to reduce air movement (Department of Energy, n.d.a). In comparison to interventions such as insulation, sealing is more effective at reducing energy and gas consumption (Underhill et al., 2020). In theory, sealing can reduce the movement of indoor air pollutants between spaces such as attics and garages (Less & Walker, 2014). In practice, sealing also reduces the dilution of indoor pollutants with infiltrated outdoor air and prevents the exfiltration of polluted indoor air if there is no proper ventilation system in place. Having a tighter building envelope is a hallmark of energy efficiency as it prevents conditioned air from escaping. However, effective sealing can also reduce the need for air conditioning, thereby reducing the use of filtration systems and ventilation fans that supply outdoor air (Underhill et al., 2020). The practice of air sealing is effective for reducing pollutant movement indoors but requires a holistic EER approach with the inclusion of ventilation to maintain indoor air quality.

Source exhaust and filtration were effective interventions used in addressing indoor air pollutant buildup from EERs and were the interventions most commonly included in EER packages. Adding and/or fixing source exhaust in the kitchen or bathroom was a frequently-implemented intervention in the examined studies. Locating exhaust in areas with sources of indoor pollutants, such as kitchens and bathrooms, can limit the ability for pollutants to mix with the indoor air. Inclusion of these ventilation interventions were found to be effective for reducing indoor air pollutants in both simulation and experimental studies, multifamily and single family housing settings, and low-income and market-rate housing.

Filtration in mechanical ventilation systems was also effective at reducing concentrations of air pollutants indoors. Specifically, it was noted that filtration of recirculated air was better able to reduce indoor air pollutants than filtration of ventilation supply air (Less et al., 2015). Residential environments are typically not fitted with an active outdoor air intake to make filtration of supply air effective for improving indoor air. Homes that are especially tight may opt to install an energy recovery or heat recovery ventilator to control and improve air exchange rates. Both ventilation systems use a heat exchanger to capture or remove heat from vented indoor air and preheat or cool supplied outdoor air; energy recovery systems can also address indoor humidity levels (Whole-House Ventilation, n.d.). These systems are usually fitted with filtration for outdoor air intake.

Four experimental studies considered single family homes with an energy recovery system and observed marginal impacts on indoor air quality when compared to controls. Less et al. (2015) found higher concentrations of NO_2 to be associated with general kitchen exhaust from energy recovery ventilation systems that operated at low levels. Norris et al. (2013) noted similar levels of indoor $PM_{2.5}$ in homes with energy recovery ventilators that used low-efficiency (MERV 6) filters. Wells et al. (2015) did not find any significant changes in CO_2 or total VOCs between homes with energy recovery ventilators and control homes. These findings suggest that, while increased ventilation and filtration can be beneficial for addressing certain indoor air pollutants, preserving indoor air quality requires interventions beyond whole-home ventilation.

Coupling source exhaust, such as range hoods, and whole-home ventilation and filtration can provide greater improvements in indoor air through addressing different sources of pollutants. Source ventilation in a kitchen, for example, can remove pollutants derived from cooking and gas appliances while ventilation and filtration can address whole-home particulate reduction (Underhill et al., 2018). This distinction is important because filtration tends to only be effective at removing particulates; gaseous pollutants such as NO_2 and formaldehyde, which will be discussed further, are likely to be less affected by filtration (Sublett, 2011). Overall, the efficacy of source exhaust, ventilation, and filtration depends on airflow and filtration efficiency as well as the nature of the pollutant and the exhaust's proximity to the pollutant source.

Properly-commissioned and functioning HVAC is known to improve indoor air quality, especially in energy efficient homes (Wilson et al., 2016; Colton et al., 2014). Without ventilation, EERs alone can have deleterious effects beyond indoor air quality, such as increasing indoor dampness. EERs alone can be more expensive than bundled interventions after accounting for increased indoor-air-related health costs (Fabian et al., 2014; Tieskens et al., 2021; Underhill et al., 2020).

Ventilation was most impactful when it met or exceeded industry standards of ASHRAE 62.2 (Francisco et al., 2017; Less et al., 2015; National Center for Healthy Housing, 2022; Tieskens et al., 2021). Federally-funded EER projects are required to meet the most current ASHRAE 62.2 guidelines (Department of Energy, n.d.b). While this standard applies to all long-term residential settings, regardless of building height, it is not required for retrofits or new construction that is not Weatherization Assistance Program-funded (Department of Energy, 2021).

Interventions that included ASHRAE 62.2 standards for ventilation as part of their EER packages were found to achieve the greatest health benefit through reductions in asthma, improved self-reported health, and better indoor air quality than control homes (Less et al., 2015; Francisco et al., 2017).

Tieskens et al. (2021) found that EER coupled with ventilation interventions that met ASHRAE 62.2 standards, when compared to minimum ventilation standards and interventions, showed the greatest reduction in asthma-related hospitalizations, emergency room and clinic visits, and health costs among children living in Boston low-income housing. This reduction was resilient to a range of occupant behaviors such as smoking and cooking with gas stoves.

4.2 Gas stoves, ovens, and health equity

Removal of indoor combustion sources is an effective way of improving indoor air quality regardless of EER conditions. Replacing gas stoves with electric stoves decreased indoor concentrations of $PM_{2.5}$, NO_2, and CO (Colton et al., 2014; Offermann et al., 1982; Pigg et al., 2014). These improvements were associated with reduced healthcare costs. A simulation study observed further benefits by layering interventions that removed gas stoves and installed exhaust fans in energy-efficient buildings as they had the greatest health savings among all studied interventions (Fabian et al., 2014). Correct usage of the exhaust fans was modeled, which may not have reflected and instead overestimated actual operating practices.

The effects of gas stoves are not borne equally by all. Low-income households are more likely to reside in housing with poorer ventilation and filtration, denser occupancy, and smaller volume than single family homes (Zota et al., 2005). As a result, indoor air pollutants from gas stove/oven use may be less-efficiently removed and lead to high resident exposures. For example, respiratory health impacts from NO_2 exposure – which, as will be discussed in the next section, is primarily emitted from gas stoves – are experienced acutely by children living in multifamily, public housing (Belanger et al., 2006).

The harm associated with gas kitchen appliances extends beyond cooking; gas ovens are often used by energy-insecure households for supplemental heating. These appliances release high emissions of air pollutants (Hernández, 2016; Brugge et al., 2003). Two simulation studies considered the impacts of supplemental gas oven heating, finding a drastically increased exposure to indoor NO_2 associated with this practice (Fabian et al., 2012; Fabian et al., 2014). Electrifying the kitchen can reduce these exposures but does not attend to the issue of high energy bills. Coupling EER and electrification can both lower associated energy costs through more efficient heating and cooling, reducing the need for supplemental heating and avoiding pollutant buildup indoors. The impact of supplemental oven heating and ability for layered interventions to address health equity is one that was not discussed in the evaluated publications. Supplemental oven heating also was not evaluated in experimental studies. This gap may be due to the dearth of available study projects and populations that have received bundled EER and electrification services, especially among low-income and energy-insecure homes.

4.3 Indoor air quality

The most commonly studied air pollutants associated with gas appliances were $PM_{2.5}$, NO_2, and formaldehyde. Fine particulate matter is a widely-studied air pollutant that has been linked directly to mortality by the U.S. Environmental Protection Agency (Gallagher and Holloway, 2020). Indoor $PM_{2.5}$ has many sources, including cooking and gas appliance use. Levels of $PM_{2.5}$ are also dependent on the type and duration of cooking (National Center for Healthy Housing, 2022). Homes that cooked less with gas stoves had lower indoor $PM_{2.5}$ concentrations compared to levels in homes that cooked more (Fabian et al., 2012). Tight (mean 0.15 ach), single family homes were prone to $PM_{2.5}$ accumulation but utilizing ventilation filtration with a range of MERV 7, 8, 12 and 14 filters (mean 0.36 ach) was shown to be effective at lowering these levels (Less & Walker, 2014; Less et al., 2015).

Residential gas appliances are the primary source of indoor NO_2. Unlike $PM_{2.5}$, holistic EER interventions are not effective at decreasing indoor NO_2 concentrations. NO_2 levels were generally higher in energy-efficient homes with gas ranges and appliances compared to homes with electric appliances (Less et al., 2015; Offermann et al., 1982). Gas stoves, especially older models with standing pilot lights, contributed to higher indoor NO_2 levels (Less et al., 2014; Noris et al., 2013; Brugge et al., 2003; Less et al., 2015). Occupant behaviors, such as a lack of vented range hood use, can also lead to higher levels of NO_2 in residences with gas stoves (Less et al., 2015). Offermann et al. (1982) observed nearly two times the reduction in NO_2 levels in a relatively-tight home (mean 0.38 ± 0.15 ach) with kitchen ventilation as compared to similar homes without this source exhaust. The air exchange rate of this particular home doubled when the kitchen ventilation source was used (mean 0.78 ± 0.16 ach).

While ventilation rate was able to address indoor NO_2 levels in certain contexts, some studied residences showed that whole-home EER interventions with ventilation did not affect NO_2 levels (National Center for Healthy Housing, 2022). Factors such as season, ambient NO_2 levels, and indoor chemistries can affect NO_2 beyond gas appliances alone. The air exchange rates of the studied apartments (mean 0.64 ach) and single family homes (mean 0.53 ach) were lower than that of the homes in the 1982 Offermann et al. study. Higher levels of ventilation may be needed in modern homes to effectively reduce NO_2 levels, but increasing air exchange rates through more advanced ventilation systems may not always be realistic as it can require costly upgrades. For example, an energy recovery ventilator may average between $1,000 to over $2,000 to purchase and install (Shine, 2022; Cost of Energy Recovery Ventilators, n.d.). These limitations in the efficacy of addressing NO_2 indoors by simply increasing ventilation do not negate the importance of air exchange. It instead points to the need for measures beyond the current framework of “build tight, ventilate right” and underscores the importance of removing gas appliances as pollutant sources altogether.

The range of indoor formaldehyde sources makes it difficult to study in relation to residential gas combustion. Cooking with gas stoves tends to increase indoor formaldehyde levels (Hollowell & Miksch, 1981). However, indoor levels of formaldehyde were not constant across bundled EER and green-building interventions that included ventilation, use of low-emitting materials, and replacement of gas stoves. Noris et al. (2015) observed increased formaldehyde concentrations in EER single-family homes with electric stoves and highlighted the role that higher temperatures and humidity can have in promoting formaldehyde emissions from indoor sources. Less et al. (2015) were not able to reliably predict indoor formaldehyde levels in green new construction or EER single-family homes on the basis of air exchange rates, mechanical ventilation, new materials, or fuel type. Colton et al. (2014) found similar formaldehyde levels even after gas stoves were replaced with electric alternatives.

Discrepancies in the ability for ventilation and fuel-switching interventions to reduce formaldehyde may also be due to the range of potential indoor sources. Furnishing and carpets are known to off-gas formaldehyde and other VOCs, making the removal of these physical sources the most effective way of reducing indoor formaldehyde (Noris et al., 2013; Francisco et al., 2017; Hollowell & Miksch, 1981). Overall, EER homes with mechanical ventilation tended to achieve lower levels of formaldehyde than conventional homes, pointing again to the importance of increasing ventilation through whole-home ventilation and filtration that meets ASHRAE 62.2 standards and removing indoor combustion sources (Less and Walker, 2014; National Center for Healthy Housing, 2022; Hollowell & Miksch, 1981; Frey et al., 2015).

4.4 Health in holistic EER projects

Health outcomes were evaluated in children and adults; adults over the age of 65 were only included in healthcare cost estimates. Despite the well-established link between combustion-derived air pollutants to human health, it is not a primary focus within existing research on weatherization and residential fuel types. Three of the six evaluated studies that included a health component were simulation studies. These studies assessed changes in premature mortality related to indoor $PM_{2.5}$ exposure and asthma-related healthcare utilization – such as clinic, emergency-department, and hospital visits over several years and for thousands of children (Fabian et al., 2014; Underhill et al., 2020; Tieskens et al., 2021). Pertinent simulation studies utilized validated models such as CONTAM and EnergyPlus but were unable to accurately model kitchen source ventilation, account for variability in outdoor ambient pollutant levels, and include all relevant factors that influence health outcomes (Fabian et al., 2012; Fabian et al., 2014; Tieskens et al., 2021). Another three health-related studies were experimental and focused on self-reported health outcomes related to sick building syndrome symptoms, general health, mental health, and child behaviors (Colton et al., 2014; Frey et al., 2015; Francisco et al., 2017).

This lack of consideration for health outcomes, in experimental studies especially, is perhaps due to the longer timeline required for the onset of asthma, for changes in symptoms to occur, and for outcomes related to chronic air pollution exposures to unfold. Experimental studies may be constrained by resources and time. Included publications that were experimental generally sampled fewer than 100 homes; a government-funded Oak Ridge National Laboratory study and National Center for Healthy Housing report were two particularly-large studies that sampled from 514 and 152 homes, respectively. Previously-discussed self-reported health outcomes, including sick building syndrome symptoms, general health, mental health, and child behaviors, in existing experimental studies sets a foundation for future studies to evaluate a broader range of health outcomes associated with indoor air quality. For example, interviews with subject matter experts highlighted thermal comfort and missed work and school days as salient health-related outcomes. Establishing a broader understanding of the range of ways in which health may be impacted can allow for these effects to be quantified and for these quantified impacts to guide funding allocations and inform policy interventions.

4.5 Costs

Energy efficiency retrofits alone can be costly, even after considering savings associated with reduced energy usage. Some of the most aggressive renovations for efficiency – known as deep energy efficiency retrofits – can lower energy consumption in homes by at least 70% (Well et al., 2015). In addition to energy, EERs also reduced water and gas usage (Less & Walker, 2014; Frey et al., 2015). However, these savings are mostly short-term as EERs can prove to be costly in the long run without proper joint interventions such as ventilation, filtration, and source control (Underhill et al., 2020). Evidence from the included publications showed that increased health costs from lack of ventilation and/or filtration in EERs, or even only meeting minimum standards for ventilation, outweighed any savings from reduced energy usage (Underhill et al., 2020; Fabian et al., 2014; Tieskens et al., 2021).

The high cost associated with EERs on their own was driven by the increases in healthcare utilization from exposures to indoor air pollutants that became trapped in the tight building envelope. Bundling ventilation, filtration, and source control with EER was a way of promoting the cost-effectiveness of efficiency interventions through decreasing indoor air pollutant concentrations while maintaining savings in energy usage (Underhill et al., 2018; Fabian et al., 2014). Several examples from studies that quantified the health and energy impacts associated with various bundles of EER interventions underscored this caveat to efficiency projects.

Modeled insulation and sealing without ventilation or filtration in Boston multifamily units led to increases in healthcare costs, with more efficient retrofits associated with higher costs ranging between \$24,000 to \$170,000 annually for adults in these households (Underhill et al., 2020). For comparison, the average healthcare spending in New England in 2020 was estimated to be \$12,728 (U.S. Centers for Medicare & Medicaid Services, 2023). Energy savings from insulation and sealing interventions only provided savings of \$42-190 each year (Underhill et al., 2020). Pairing insulation and sealing with both source exhaust (30% cooking pollutant removal) and filtration (MERV8 or MERV12 filters) reduced indoor air quality-related health costs the most, conferring energy savings and improved outdoor air as well (Underhill et al., 2020).

Bundling approaches were further found to reduce the payback period of EER packages. Solely tightening modeled multifamily public housing units in Boston had a payback period with associated health costs (23 years) that more than doubled the period of when energy savings were considered alone (11 years) (Fabian et al., 2014). It was shown that even simply including a \$400 range hood for outdoor source exhaust in tightening interventions was estimated to reduce the payback period that included health costs to 13 years — a marginal difference compared to the 11.6-year estimated payback period that only considered energy savings (Fabian et al., 2014). EER coupled with pollutant-reduction interventions, such as adding source exhaust and replacing gas stoves with electric stoves, both avoided long-term expenses from increased health costs and reduced the time to a positive return on investment.

It is likely that even the current estimated healthcare savings are conservative. Included healthcare cost quantification studies considered $PM_{2.5}$-related health impacts and childhood asthma outcomes, and did not account for the range of other adverse health effects associated with exposure to indoor air pollutant mixtures. Equally important, health quantifications in the model studies were based on estimated costs of various health services and were not validated. The process of generalizing estimated model costs may also underestimate the actual cost of these services.

4.6 Feasibility

It is generally agreed that a major hurdle in more holistic EERs which bundle efficiency and pollutant-reduction measures is the lack of effective funding streams that can support the high cost of implementation. This issue is acutely felt by residents in low-income households who bear the greatest burden of health outcomes related to poor indoor air quality and lack the financial resources to undergo EERs. Despite these concerns, potential avenues exist for improving access. First, retrofit packages can be tailored to different residential settings and occupant behaviors to provide bundles that are able to promote health in efficient homes while attending to high costs as a common barrier to access. For example, no-smoking policies can reduce the need for retrofits to include whole-home filtration as the main pollutant sources can be addressed in the kitchen and bathroom with local exhaust (Underhill et al., 2018).

Building electrification is another health-promoting measure that has historically rarely been paired with EERs. An estimated third of affordable housing units in the United States have gas stoves that may eventually need to be replaced with ongoing electrification efforts (York et al., 2020). Any upfront holistic EER and electrification package will be costly, but processes such as Resource Efficient Electrification can offer a piecemeal approach as a solution. Resource Efficient Electrification essentially incrementally retrofits and decarbonizes buildings, leveraging different funding sources as they are needed to produce more holistic retrofits (WE ACT for Environmental Justice, 2023). In practice, this may involve remediating hazards, weatherizing and tightening the building, and increasing the capacity of a building’s electrical grid to ensure that eventual electrification is seamless.

4.7 Limitations and strengths

There are several limitations to this scoping style review. The literature was searched for and assessed by one researcher, meaning there is the potential for bias to affect the ultimate collection of included publications. This review was conducted to prepare a roadmap for further research and did not aim to be comprehensive.

Drawing from simulation and experimental study designs as well as different interventions and outcomes limited the ability for findings to be compared. Different study designs had their own limitations that affected the outcomes and interventions that they included.

Simulation studies were able to model exposures and outcomes at a scale that was not achieved by experimental studies. However, simulation studies were bound by the limitations of the models and could not assess actual occupant behaviors, such as range hood use, window-opening, cooking practices, and choice of furnishings.

Experimental studies were able to test several different EER and fuel-switching scenarios that, although ideal in some cases, were purposeful and not reflective of actual interventions that a household would realistically achieve. Again, access to funds, the high cost of implementation, and limitations to feasibility based on building type makes it so that EER interventions in included studies may not be appropriate for all settings.

Both simulation and experimental studies assessed multiple air pollutants but did not study the effects of exposures to pollutants as mixtures. Multipollutant approaches can better-reflect actual resident exposures and are important to identifying high-pollution sources and understanding the complex range of health impacts (Dominici et al., 2010). Health outcomes were also divided by study type. Asthma outcomes, asthma-related hospital visits, and premature mortality related to $PM_{2.5}$ exposure was assessed in simulation studies. Self-reported health through quality of life, mental health, and sick building syndrome symptoms were assessed in experimental studies. This clear distinction in studied health outcomes between study designs did not allow for effective comparisons of health impacts from interventions and air pollutant changes.

Analysis of costs was limited by the fact that all studies quantifying healthcare costs and energy savings were simulation studies. These values are often highly context-specific as populations will have varying baseline levels of health, buildings will have different airflow patterns depending on construction, and healthcare costs and energy prices will vary by location. As such, findings from included simulation studies, which were all based on multifamily public housing units in Boston, may not be generalizable to other populations in different geographic areas, climates, and building types. Additionally, these simulation studies only modeled homes with gas stoves and could not provide a deeper understanding of how fuel-switching might affect health and energy costs.

This issue of generalizability extends to experimental studies as well. Interviewed subject matter experts underscored the importance of understanding local housing conditions and energy markets to assess the best interventions specific to a given location. While the included studies were conducted in multiple U.S. cities, it is unlikely that estimated health outcomes and cost savings can be broadly applicable.

Despite these limitations, this study also has several strengths. First, the scoping style of review produced a novel exploratory assessment of what health research currently exists at the nascent intersection of EERs, residential gas combustion, and indoor air quality. Second, the inclusion of reports and studies beyond those that are strictly peer-reviewed allowed for a more holistic assessment of existing research from across academic disciplines and organizations. This is important given the range of disciplines involved in this research, allowing for studies from industry organizations to also be included in the review. Finally, the incorporation of qualitative interviews augmented the literature search with knowledge and experience from subject-matter experts working on related topics.

4.8 Implications for future research

The multidisciplinary approach of this review highlighted areas for improvement and further investigation in research, funding, and messaging. Additional research at the intersection of EERs, fuel type, and indoor air quality can explore intervention efficacy and less-studied health outcomes.

Subject-matter experts discussed the need for a better understanding of the specific health impacts of certain EER interventions. This can allow for interventions to be targeted to specific health benefits. Similarly, while indoor air quality-related asthma outcomes may be common in studies related to building tightness or gas appliance usage, it seems that combining the two factors attenuates that association. Studies related to asthma outcomes should be conducted in households with tight envelopes and gas appliances to assess the asthma burden associated with this particular environment. A more thorough investigation of the role of fuel switching in energy-efficient residences can also improve the understanding of the potential benefits to holistic EER and building electrification practices. Overall, experimental studies assessing indoor air quality and health in efficient and controlled homes should consider tracking and quantifying asthma-related healthcare utilization in addition to other related outcomes such as thermal comfort and missed work and school days .

Funding is a major barrier to more holistic and health-conducive EER packages, especially among low-income households. Federally-funded Weatherization Assistance Program monies are often relegated to EER interventions and do not cover building electrification costs. Other general building energy efficiency programs tailored to low-income housing are also lacking because the process itself is costly. A potential way of addressing this gap in EER and building electrification funding may be through leveraging complementary funding streams. One subject-matter expert highlighted the importance for states to understand how money from the Inflation Reduction Act of 2022, which supports building electrification, can be used in conjunction with Weatherization Assistance Program funding to provide low-income households with both EER services and building electrification.

Messaging and communication is important for leveraging findings to inform interventions. One way of making results relevant to others is through economic contextualization. Changes in health resulting from improved indoor environments need to be translated to economic metrics, especially as they relate to low-income households. This focus on health equity and the greater health and financial burden borne by low-income households is one that should be highlighted and centered in the discussion on EER, building electrification, and indoor air quality. Another mode of sharing information to promote behavior change is through providing educational interventions with directed and quantitative feedback to residents. This can include informational packets that share best practices for maintaining indoor air, digestible report-backs on indoor air quality, and comparative graphics that show a household's indoor air quality in relation to similar homes. Subject-matter experts also commented on the need for synthesizing findings from existing references, analyses, and methods to provide stakeholders with a general understanding of the current research.

5. Conclusion

The main air pollutants studied in the 15 evaluated publications were $PM_{2.5}$, NO_2, and formaldehyde. The majority (13/15) of publications included gas stoves as a primary residential combustion source. Of these, three considered the impact of gas ovens on indoor air quality and seven compared indoor environments between homes with gas and electric stoves.

Health was assessed in six of the 15 studies; asthma-related symptoms were only considered in two simulation studies while another four studies assessed other outcomes including $PM_{2.5}$-related mortality, sick building syndrome symptoms, general and mental health, and child behaviors.

Costs associated with changes in healthcare utilization and energy usage were included in select studies. Of the studies that considered health impacts of different EER interventions, three quantified the related healthcare costs. Four of the 15 studies quantified energy savings from EERs and two quantified both healthcare and energy savings.

Overall, findings from the review were reflected in the responses from subject-matter expert interviews. The health impacts and costs associated with certain EERs and fuel-switching practices were not extensively covered in the existing literature. Nevertheless, EERs and replacing gas appliances, such as gas stoves with electric alternatives, were likely to save money for some in the long run and should be communicated to homeowners and residents, especially low-income households. More asthma outcomes were expected in reviewed publications given the comments from experts on the prevalence of asthma as the frequently-studied health outcome associated with poor indoor air quality.

This review highlighted that health is not a primary focus in the existing literature on EERs, residential fuel types, and indoor air quality. When health was included, it was often a primary factor in determining the cost-effectiveness of EERs. A greater focus on the health impacts of certain EER interventions can help identify potentially harmful practices, as well as opportunities to strategically layer interventions.

Specifically, air sealing had some of the greatest adverse effects on indoor air quality; it reduced energy usage but also prevented the movement and dilution of indoor air pollutants. Source exhaust and filtration were seen to be effective across different study designs and housing types in preserving indoor air quality and should be paired with sealing for energy efficiency.

However, these interventions were often not effective in homes with gas stoves, as they were unable to reduce indoor NO_2 and formaldehyde levels. For this reason, replacing gas stoves with electric alternatives was the most immediate solution for removing a primary source of NO_2 and formaldehyde, among other indoor air pollutants. Health was generally improved through layered EER approaches that included exhaust, ventilation, filtration, and electric stoves, which also reduced the payback periods of these interventions. Taken together, findings from this project aim to provide an understanding of the landscape and scope of existing health-related research within the EER, building electrification, and indoor air quality literature.

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7. Appendices

Appendix A: Keyword searches

Database	Search terms	Results	Date
PubMed	("PM" [All Fields] OR "PM2.5" [All Fields] OR "PM10" [All Fields] OR "PM1" [All Fields] OR "Particulate matter" [All Fields] OR "Fine particulate matter" [All Fields] OR "FPM" [All Fields] "VOC" [All Fields] OR "VOCs" [All Fields] OR "Volatile organic compound" [All Fields] OR "Volatile organic compounds" [All Fields] OR "Methane" [All Fields] OR "CH4" [All Fields] OR "Nitrogen oxide" [All Fields] OR "Nitrogen oxides" [All Fields] OR "NOx" [All Fields] OR "Nitrogen dioxide" [All Fields] OR "NO2" [All Fields] OR "Formaldehyde" [All Fields] OR "CH2O" [All Fields] OR "Carbon monoxide" [All Fields] OR "CO" [All Fields] OR "Carbon dioxide" [All Fields] OR "CO2" [All Fields] OR "Ultrafine particle" [All Fields] OR "Ultrafine particles" [All Fields] OR "Ultra-fine particle" [All Fields] OR "Ultra-fine particles" [All Fields] OR "UFP" [All Fields] OR "UFPs" [All Fields] OR "Air pollutant" [All Fields] OR "Air pollution" [All Fields] OR "Air pollutants" [All Fields] OR "BTEX" [All Fields] OR "Benzene" [All Fields] OR "Toluene" [All Fields] OR "Ethylbenzene" [All Fields] OR "Xylene" [All Fields]) AND ("Housing Quality"[Mesh] OR "Housing"[Mesh] OR "Home Environment"[Mesh] OR "Residential" [All Fields] OR "Resident" [All Fields] OR "Residential" [All Fields] OR "Residence" [All Fields] OR "Residences" [All Fields] OR "Home" [All Fields] OR "Homes" [All Fields] OR "Kitchen" [All Fields] OR "Kitchens" [All Fields] OR "Indoor" [All Fields] OR "House" [All Fields] OR "Houses" [All Fields] OR "Housing" [All Fields] OR "Household" [All Fields] OR "Households" [All Fields] "Apartment" [All Fields] OR "Apartments" [All Fields] OR "Multifamily" [All Fields] OR "Multifamilies" [All Fields] OR "Multi-family" [All Fields] OR "Multi-families" [All Fields] OR "Single family" [All Fields] OR "Single families" [All Fields] OR "Single-family" [All Fields] OR "Single-families" [All Fields]) AND (cooking[MeSH Terms] OR "Electrify" [All Fields] OR "Electrification" [All Fields] OR "Electrified" [All Fields] OR "Electric" [All Fields] OR "Electricity" [All Fields] OR "Gas" [All Fields] OR "Stove" [All Fields] OR "Stoves" [All Fields] OR "Cooktop" [All Fields] OR "Cooktops" [All Fields] OR "Cook top" [All Fields] OR "Cook tops" [All Fields] OR "Cook-top" [All Fields] OR "Cook-tops" [All Fields] OR "Cookstove" [All Fields] OR "Cookstoves" [All Fields] OR "Cook stove" [All Fields] OR "Cook stoves" [All Fields] OR "Cook-stove" [All Fields] OR "Cook-stoves" [All Fields] OR "Cook" [All Fields] OR "Cooks" [All Fields] OR "Cooking" [All Fields] OR "Burner" [All Fields] OR "Burners" [All Fields] OR "Electric stove" [All Fields] OR "Electric stoves" [All Fields] OR "Induction" [All Fields] OR "Induction stove" [All Fields] OR "Induction stoves" [All Fields] OR "Wood stove" [All Fields] OR "Wood stoves" [All Fields] OR "Heat pump" [All Fields] OR "Heat pumps" [All Fields] OR "Electric appliance" [All Fields] OR "Electric appliances" [All Fields] OR "Electrical appliance" [All Fields] OR "Electrical appliances" [All Fields] OR "Water heater" [All Fields] OR "Water heaters" [All Fields] OR "Boiler" [All Fields] OR "Boilers" [All Fields] OR "Oven" [All Fields] OR "Ovens" [All Fields]) AND ("Weatherization" [All Fields] OR "Weatherize" [All Fields] OR "Weatherized" [All Fields] OR "Weatherisation" [All Fields] OR "Weatherise" [All Fields] OR "Weatherised" [All Fields] OR "Energy efficient" [All	18	01/22/2023

	Fields] OR "Energy efficiency" [All Fields] OR "Retrofit" [All Fields] OR "Retrofits" [All Fields] OR "Retrofitting" [All Fields] OR "Retrofitted" [All Fields] OR "Retro-fit" [All Fields] OR "Retro-fits" [All Fields] OR "Retro-fitting" [All Fields] OR "Retro-fitted" [All Fields] OR "Passive house" [All Fields] OR "Passive haus" [All Fields] OR "Passivhaus" [All Fields] OR "Energy saving" [All Fields] OR "Energy savings" [All Fields] OR "Energy upgrade" [All Fields] OR "Energy upgrades" [All Fields] OR "Home performance" [All Fields] OR "Energy conserving" [All Fields] OR "Energy conservation" [All Fields] OR "Insulation" [All Fields] OR "Insulate" [All Fields] OR "Insulated" [All Fields] OR "Green building" [All Fields] OR "Green buildings" [All Fields])		
Lens	(title:(Weatheriz* OR Weatheris* OR "Energy efficien*" OR Retrofit* OR "Retro-fit*" OR "Passive house" OR "Passive haus" OR Passivhaus OR "Energy-sav*" OR "Energy upgrade*" OR "Home performance" OR "Energy conserv*" OR Insulat* OR "Green building*") OR abstract:(Weatheriz* OR Weatheris* OR "Energy efficien*" OR Retrofit* OR "Retro-fit*" OR "Passive house" OR "Passive haus" OR Passivhaus OR "Energy-sav*" OR "Energy upgrade*" OR "Home performance" OR "Energy conserv*" OR Insulat* OR "Green building*") OR keyword:(Weatheriz* OR Weatheris* OR "Energy efficien*" OR Retrofit* OR "Retro-fit*" OR "Passive house" OR "Passive haus" OR Passivhaus OR "Energy-sav*" OR "Energy upgrade*" OR "Home performance" OR "Energy conserv*" OR Insulat* OR "Green building*")) AND (title:(PM OR PM2.5 OR PM10 OR PM1 OR "Particulate matter" OR "Fine particulate matter" OR FPM OR VOC* OR "Volatile organic compound*" OR Methane OR CH4 OR "Nitrogen oxide*" OR NOx OR "Nitrogen dioxide" OR NO2 OR Formaldehyde OR CH2O OR "Carbon monoxide" OR CO OR "Carbon dioxide" OR CO2 OR "Ultrafine particle*" OR "Ultra-fine particle*" OR UFP* OR "Air pollut*" OR BTEX OR Benzene OR Toluene OR Ethylbenzene OR Xylene) OR abstract:(PM OR PM2.5 OR PM10 OR PM1 OR "Particulate matter" OR "Fine particulate matter" OR FPM OR VOC* OR "Volatile organic compound*" OR Methane OR CH4 OR "Nitrogen oxide*" OR NOx OR "Nitrogen dioxide" OR NO2 OR Formaldehyde OR CH2O OR "Carbon monoxide" OR CO OR "Carbon dioxide" OR CO2 OR "Ultrafine particle*" OR "Ultra-fine particle*" OR UFP* OR "Air pollut*" OR BTEX OR Benzene OR Toluene OR Ethylbenzene OR Xylene) OR keyword:(PM OR PM2.5 OR PM10 OR PM1 OR "Particulate matter" OR "Fine particulate matter" OR FPM OR VOC* OR "Volatile organic compound*" OR Methane OR CH4 OR "Nitrogen oxide*" OR NOx OR "Nitrogen dioxide" OR NO2 OR Formaldehyde OR CH2O OR "Carbon monoxide" OR CO OR "Carbon dioxide" OR CO2 OR "Ultrafine particle*" OR "Ultra-fine particle*" OR UFP* OR "Air pollut*" OR BTEX OR Benzene OR Toluene OR Ethylbenzene OR Xylene)) AND (title:(Resident* OR Home* OR Kitchen OR Indoor OR Hous* OR Apartment* OR Multifamil* OR "Multi-famil*" OR "Single famil*" OR "Single-famil*") OR abstract:(Resident* OR Home* OR Kitchen OR Indoor OR Hous* OR Apartment* OR Multifamil* OR "Multi-famil*" OR "Single famil*" OR "Single-famil*") OR keyword:(Resident* OR Home* OR Kitchen OR Indoor OR Hous* OR Apartment* OR Multifamil* OR "Multi-famil*" OR "Single famil*" OR "Single-famil*")) AND (title:(Electrif* OR Electric* OR Gas OR Stove* OR Cooktop* OR Cookstove* OR Cook* OR Burner* OR "Electric stove*" OR "Induction stove*" OR "Wood stove*" OR "Heat pump*" OR "Electric appliance*" OR "Electrical appliance*" OR "Water heater*" OR Boiler* OR Oven*) OR abstract:(Electrif* OR Electric* OR Gas OR Stove* OR Cooktop* OR	1029	1/22/2023

	Cookstove* OR Cook* OR Burner* OR "Electric stove*" OR "Induction stove*" OR "Wood stove*" OR "Heat pump*" OR "Electric appliance*" OR "Electrical appliance*" OR "Water heater*" OR Boiler* OR Oven*) OR keyword:(Electrif* OR Electric* OR Gas OR Stove* OR Cooktop* OR Cookstove* OR Cook* OR Burner* OR "Electric stove*" OR "Induction stove*" OR "Wood stove*" OR "Heat pump*" OR "Electric appliance*" OR "Electrical appliance*" OR "Water heater*" OR Boiler* OR Oven*))		
EPA HERO	weatheriz* indoor air	31	1/22/2023

Appendix B: Interview guides

Introductions: (5min)

Objectives of research (5 min)
- Attempt to understand the breadth of existing research on the indoor air quality impacts of building weatherization and EER, especially how the fuel type of a residence impacts this association
- There is evidence that without consideration for the indoor pollutant sources, building weatherization can trap pollutants and worsen indoor air quality. Points to the need for holistic EER that addresses indoor pollutant sources such as combustion appliances
- Any questions?

Organization specific questions (10min)
- For research-adjacent organizations:
    - How are policy implications considered in your work?
    - What are potential barriers that keep you from working more directly with advocacy?
    - In your opinion, what are gaps at the intersection of weatherization, indoor air quality, and health that could benefit from further research?
- For policy-adjacent organizations:
    - What resources have you found to be the most helpful in informing your work?
    - When considering policies around weatherization and/or electrification, what kind of evidence do you turn to?
    - From your experience, what are areas or topics you would like to have more evidence and research for?

Project focused questions (10min)
- *Provide a recap of the study*
- For research-adjacent organizations:
    - Are there additional topics or areas of research I should look into for my project?
    - What have you found to be the most effective methods of communicating your research to policymakers?
- For policy-adjacent organizations:
    - Can you envision this work being utilized by your organization? What could make it more useful?
    - What methods of communication have you found to be the most informative?
    - What are your questions on EERs, indoor air quality, and health that you would like to know more about?
- Is there anything else you think should be added?

Appendix C: Overview of publications identified for evaluation

Table 1A: Overview of reviewed papers describing simulation studies.

Authors, year, publication type	**Study design**	**Housing type**	**Location**
Fabian et al., 2012 Journal article	Modeled indoor air contaminants and occupant behaviors for 1,000 houses	Multifamily housing: public housing built 1940-1969	Boston, MA
Fabian et al., 2014 Journal article	Discrete event simulation model of indoor air contaminants and pediatric asthma outcomes for one million children	Multifamily housing: public housing	Boston, MA
Underhill et al., 2018 Journal article	Modeled indoor air contaminants associated with EER in one low-income apartment building	Multifamily housing: low-rise, stacked townhouse apartment building	South End neighborhood of Boston, MA
Underhill et al., 2020 Journal article	Modeled indoor air contaminants and building energy models in one low-income apartment building after EER	Multifamily housing: 8-unit public housing building	Boston, MA
Tieskens et al., 2021 Journal article	Discrete event simulation model of pediatric asthma outcomes for 10,000 children related to indoor air contaminants and 2012 EER	Multifamily housing: public housing	South End neighborhood of Boston, MA

Table 1B: Overview of reviewed papers describing experimental studies.

Authors, year, publication type	**Study design**	**Housing type**	**Location**
Offermann et al., 1982 Journal article	Comparison of indoor air measured over one week in 9 tight homes and 1 control home without then with mechanical ventilation; 1980-1981	Single family homes	Rochester, NY
Noris et al., 2013 Journal article	Comparison of indoor environment after weatherization (2011, 2012) in 8 apartments with and 8 apartments without mechanical ventilation	Low-income housing built in 1967, 1973, and 1975	Sacramento, Richmond , and Fresno , CA

Pigg et al., 2014 Report by ORNL for DOE	Randomized control trial: indoor air quality impacts in 514 homes randomly assigned to weatherization or control; 2010-2011	Single family housing including detached, attached, and manufactured or mobile homes	National: 35 states
Colton et al., 2014 Journal article	Environmental sampling and health questionnaires with residents in 18 newly-constructed green homes and 6 control units; 2012	Multifamily housing: green affordable housing units built in 2012 and traditional 1940s units	Old Colony, South Boston, MA
Less and Walker, 2014 Report by LBNL for CEC	Measurements of indoor environment of 17 deep energy retrofit homes; January - April, 2012	Single-family homes	Northern California, within 100 miles of Berkeley, CA
Frey et al., 2015 Journal article	Indoor air sampling in homes before (n=72), immediately after (n=55), and a year (n=53) after green EER in 2011; summer 2010, 2011, 2012	Multifamily low-income senior housing built in early 1970s	Phoenix, AZ
Less et al., 2015 Journal article	Measurements of indoor air quality in 12 heavily-renovated and 12 newly constructed homes; January - April, 2012	Single family homes	Northern California, within 100 miles of Berkeley, CA
Wells et al., 2015 Journal article	Longitudinal study of indoor air quality over 1 year in 6 meeting deep energy retrofit homes and 6 Energy Star standard homes; 2011-2013	Single family public housing, approximately 100 years old	Cleveland, OH
Francisco et al., 2017 Journal article	Randomized control trial: 39 and 42 houses weatherized to meet ASHRAE 62-1989 or 62.2-2010 ventilation standards, respectively	Single family public housing	Cook County, IL and various locations in Indiana
National Center for Healthy Housing, 2022 Report by NCHH	Indoor air sampling in 152 control and renovated Enterprise Green Communities Criteria homes before and after renovation; 2018-2020	Multifamily low-income housing	New York City, NY and Chicago, IL

LBNL: Lawrence Berkeley National Laboratory; CEC: California Energy Commission; ORNL: Oak Ridge National Laboratory; DOE: US Department of Energy

Appendix D: Results of publications identified for evaluation

Table 2A: Overview of findings from reviewed simulation studies.

Authors, year	EER / intervention	Fuel type	Indoor air pollutants*	Health	Health quantification	EE savings quantification	Major findings
Fabian et al., 2012	Mean building AER for: LEED housing (0.33/hr), and average(0.85/hr) and leaky (1.2/hr) Boston public housing	89% residences with gas stoves, 38% used oven for supplemental heat	NO_2, $PM_{2.5}$	—	—	—	Lowest quartile NO_2 exposure: 3% from gas oven heating; 29% from gas stove cooking; 68% from outdoors 44% homes had gas stove, 49% did not use range hood; building AER not predictive Highest quartile NO_2 exposure: 12% from gas oven heating; 68% from gas stove cooking; 20% from outdoors nearly all homes had gas stove, used gas oven for supplemental heat, did not use range hood; building AER not predictive Lowest quantile $PM_{2.5}$ exposure: 62% from gas stove cooking; 98% nonsmoking households, 74% used gas stove twice daily Highest quantile $PM_{2.5}$ exposure: 46% from gas stove cooking; 44% from smoking; 10% from outdoors 91% smoking, 64% used gas stove thrice daily; lower AER than low-exposure households NO_2 not influenced by building air exchange; heavily influenced by gas stoves $PM_{2.5}$ lower in homes with less gas stove cooking
Fabian et al., 2014	Wx: insulating floors, walls, roof; weather stripping; installing double-pane windows. Exhaust fan fixes. Gas stoves replacement, No use	89% residences with gas stoves, 38% used oven for supplemental heat	NO_2, $PM_{2.5}$	Childhood asthma outcomes: asthma-related clinic visits, emergency department visits,	Installing a \$300-550 range hood can reduce healthcare use by \$175 annually per asthmatic patient, leading to a 1.6-3 year payback period	Estimates savings and payback periods in 700 ft^2, 4-person/apartment building constructed in 1955 for Wx alone, and Wx plus fixing exhaust fans	IPM, fixing exhaust fans, and replacing gas with electric stoves had the greatest health savings Wx alone was the most costly intervention Bundling Wx and kitchen exhaust fans had a shorter payback period (13 years) than Wx

	of ovens for heat. No smoking indoors. HEPA air filters. Integrated pest management (IPM)			hospitalizations		Weatherization without ventilation ($6500) increases health costs ($322/year) but reduces energy usage ($605/year) Weatherization ($6500) with kitchen exhaust ($400) reduces energy usage and health costs	alone (23 years) when considering energy and healthcare costs
Underhill et al., 2018	Comparison of pre-Wx, Wx (air sealing, replacement of windows and doors, appliance upgrades), Wx plus bathroom and kitchen exhaust fans, and Wx plus high efficiency HVAC particle filtration in heating season	Gas stoves	$PM_{2.5}$, NO_2	—	—	—	Comprehensive EER Wx with adequate ventilation was most resilient to occupant activities EER Wx without ventilation can increase indoor $PM_{2.5}$ and NO_2 Wx only: $PM_{2.5}$ increased for most and was worsened by cooking, smoking, and not opening windows; NO_2 increased for some and was worsened by cooking and not opening windows Wx + exhaust fans: reduced cooking $PM_{2.5}$ and NO_2, especially when windows were closed Wx + particle filtration: lowered $PM_{2.5}$ from all sources beyond cooking but did not change NO_2 levels Wx + exhaust fans + particle filtration: greatest $PM_{2.5}$ reductions Delivering smaller Wx packages with no-smoking policies can reduce need for costly HVAC particle filtration
Underhill et al., 2020	Insulation, air sealing; insulation and sealing together;	Gas heating and gas stove cooking	$PM_{2.5}$	Changes in premature mortality related	Insulation and sealing only: $24,000 annual health cost increase	Insulation and sealing only: $42 (standard) or $190 (high	$PM_{2.5}$ associated with gas stove cooking increased when no ventilation or filtration was used

	insulation, sealing, MERV 4, 8, or 12 HVAC particle filters, and kitchen exhaust fan Compares no intervention, above interventions to standard levels, and above interventions to high-performing levels			to indoor PM2.5 exposure	among age 25+ with standard performance intervention; $170,000 annual health cost increase among age 25+ with high performance intervention Source exhaust ventilation and filtration: $49,000 (standard) or $26,000 (high-performance) annual health cost reduction among age 25+; $170,000 (standard) or $93,000 (high performance) annual health cost reduction among age 65+	performance) annual apartment-level energy savings Insulation: 2.4% annual electricity reduction; 15% annual gas reduction with standard intervention; 21% annual gas reduction with high-performance; intervention Sealing: 2.8% annual electricity reduction; 18% annual gas reduction with standard intervention; 54% annual gas reduction with high-performance intervention	Health costs far exceed energy savings from insulation and/or sealing when not paired with ventilation or filtration Joint Wx, ventilation, and filtration had the best results for energy savings, improved indoor air quality, and reduced outdoor air pollutants related to energy production
Tieskens et al., 2021	Air sealing, efficient heat and hot water boilers, HVAC air filtration, kitchen and bathroom exhaust fans, efficient lights and appliances Compares no intervention, minimum MA state ventilation standards, and ASHRAE 62.2	Gas stove cooking frequency	$PM_{2.5}$, NO_2	Asthma outcome counts among children living in apartments	Healthcare costs: prescribed medication, emergency department visits, hospitalizations, clinic visits Wx with no intervention: $1164 (±701) annual healthcare cost per asthmatic child Wx with minimum MA state ventilation: $1253 (±731) annual	—	ASHRAE 62.2 Wx reduced serious annual asthma events while minimum Wx increased them 62.2 Wx reduced healthcare costs while minimum Wx increased them 62.2 Wx more resilient to different cooking and smoking behaviors Opening windows improved health in baseline and minimum Wx, but was harmful in 62.2 Wx Simply meeting minimum Wx did not protect health and worsened pediatric asthma

					healthcare cost per asthmatic child Wx with ASHRAE 62.2 ventilation: $1115 (±675) annual healthcare cost per asthmatic child		

Table 2B: Overview of findings from reviewed experimental studies.

Authors, year	EER / intervention	Fuel type	Indoor air pollutants*	Health	Health quantification	EE savings quantification	Major findings
Offermann et al., 1982	Updated polyethylene exterior wall barriers, joint and plumbing spaces sealing, mechanical ventilation Relative airtightness.	Gas stoves, water heaters, furnaces, and dryers in select homes	Formaldehyde, NO_2	—	—	—	Formaldehyde: remained below 100 ppb NO_2: Homes with gas stoves had higher levels than homes with electric stoves; A home with unvented gas clothes dryer and gas stove had highest levels; Tight buildings had low NO2 levels, likely due to use of vented range hoods Mechanical ventilation in tight homes increased AER by 80%, decreased formaldehyde by 21%, and increased NO_2 slightly due to higher outdoor levels Acceptable IAQ can be achieved with low-AER efficient homes by reducing sources of indoor contaminants
Noris et al., 2013	Sacramento: continuous mechanical ventilation (5 ERV), upgraded range hood and HVAC particle filtration,	Sacramento: replaced standing pilot to electronic ignition gas stoves	$PM_{2.5}$, CO_2, NO_2, formaldehyde, acetaldehyde, TVOCs	—	—	—	EER associated with improvements in comfort, humidity, CO_2, acetaldehyde, TVOCs, and PM Formaldehyde and NO_2 were more variable: both decreased in Sacramento and did not change in Richmond; NO2 was extremely

	energy efficient appliances Richmond: air sealing, continuous bathroom exhaust, upgraded range hood and HVAC filter, energy efficient appliances, attic insulation, HEPA filter Fresno: air sealing, continuous mechanical ventilation (3 ERV) and bathroom exhaust, upgraded range hood and HVAC filter, energy efficient appliances, attic insulation, HEPA filter	Richmond: gas stoves without pilot lights Fresno: electric stoves					low and formaldehyde increased in Fresno CO was consistently low and was not included Overall: EER improved indoor air more than it degraded it and increasing ventilation decreased indoor pollutants
Pigg et al., 2014	Insulation, heating system and water heater replacement, exhaust fan, whole-house ventilation	Natural gas or propane range/oven; natural gas, propane, or fuel oil heating system Treatment: 44% gas, 56% electric range/oven; 81% fuel-fired, 17% electric heating system Control: 41% gas, 59% electric	CO	—	—	—	Different aspects of Wx package are effective in their own way but were generally able to address issues of elevated CO from attached garages and furnaces Higher indoor CO levels most likely due to gas ranges and furnaces

		range/oven; 82% fuel-fired, 14% electric heating system					
Colton et al., 2014	Green new construction: green building materials, efficient gas-fired heat and hot water furnaces, continuous bathroom exhaust, swap from gas to electric stoves	Gas stoves: 93% of control homes Electric stoves: 100% new green homes	$PM_{2.5}$, NO_2, formaldehyde	Self-reported sick building syndrome symptoms: 48% reduction in neurological, 58% reduction in mucosal, 55% reduction in lower respiratory, and 48% reduction in fatigue symptoms in green versus control homes	—	—	$PM_{2.5}$: 57% reduction in green versus control home NO_2: 65% reduction in green versus control home Formaldehyde: no significant reduction between green and control home Lack of mechanical ventilation in 86% control homes as compared to 11% green homes Swapping to electric stoves believed to reduce $PM_{2.5}$ and NO_2
Less and Walker, 2014	Deep energy retrofits: airtightness, continuous mechanical ventilation (3 ERV, 3 HRV, 2 CFIS, 1 exhaust fan), kitchen and bathroom ventilation	Gas stoves in certain homes	Formaldehyde, NO_2, $PM_{2.5}$	—	—	Accounting for weather, 58% net-site energy savings; 43% net-source energy reductions; 54% net-source carbon emissions reductions	Homes with high NO_2 levels had older gas stoves with pilot lights, recirculating range hoods with low rates of continuous ventilation, and high outdoor ambient NO_2 levels Most important IAQ factors: exhaust fan usage, particle filtration, source control of formaldehyde, removing gas stoves with standing pilot lights, especially in tight DER homes Formaldehyde: lower in EER than non-retrofitted CA homes NO_2: kitchen concentrations higher in gas stove homes than electric stove homes. Levels lower in DER homes than regular homes $PM_{2.5}$: DER homes with air filtration had lower levels than those without

Frey et al., 2015	Air conditioner units, bathroom exhaust, range hood, energy-efficient windows and doors, low-VOC flooring and carpets, new cabinets, zero-VOC paint, ES kitchen appliances, electric range, bedroom ceiling fan	Gas stoves pre-retrofit replaced with electric stoves after	$PM_{2.5}$, TVOCs	Self-reported health Changes in formaldehyde levels associated with improvement in self-reported quality of life and emotional distress over short term	—	12.6% reduction in water usage; 19.4% reduction in electricity consumption during study period (July 2009-September 2012)	Formaldehyde decreased for all homes; $PM_{2.5}$ decreased for those with higher initial levels Did not attribute changes to stove swapping $PM_{2.5}$: indoor levels always higher than outdoors; no significant change before and after ER both over short and long term; top 25th percentile of indoor $PM_{2.5}$ and PM_{10} households saw decrease over long term TVOCs: samples before and after EER exceeded CA EPA's 8-hour reference level standard of 7 ppb; formaldehyde decreased over long term; acetone and acetaldehyde increased in short term
Less et al., 2015	Deep retrofits and new construction: deep energy retrofits, green certification, Passive House, or net-zero Continuous mechanical ventilation in 13/24 homes (3 ERV, 6 HRV, 3 CFIS, 1 exhaust fan); kitchen exhaust in 17/23 homes; bathroom exhaust in 23/24 homes	Gas stoves in 63% homes	NO_2, formaldehyde, acetaldehyde, PM	—	—	—	High-performing, energy efficient homes are at risk of poor indoor air quality given airtightness. Meeting at least ASHRAE 62.2-2013, addressing pollutant sources, using kitchen exhaust, and filtering particles can help NO_2: higher likely due to older gas stoves with pilot lights, recirculating range hood and low kitchen exhaust, and high outdoor levels Formaldehyde: 96% homes exceeded 9 ug/m^3 CA EPA Chronic reference but all below reported 36 ug/m^3 in standard CA new construction; no difference in new construction or EER Acetaldehyde: higher levels in new construction than retrofits PM: 48% lower $PM_{0.5}$ and 57% lower $PM_{2.5}$ in homes with MERV 7-14 filtration as compared to homes with no filtration; $PM_{2.5}$ lower in kitchens with electric induction stoves than those with gas or electric resistance stoves
Wells et al.,	Insulation, thermal	Gas furnace	CO_2, TVOCs	—	—	—	No differences in indoor CO_2 or TVOCs were

2015	barriers, energy-efficient appliances ES retrofits swapped to standard gas furnaces and exhaust ventilation DER swapped to air-source heat pump and ERV						measured before and after ES retrofit or DER CO_2: attenuated borderline significant increase adjusting for other variables TVOCs: no change between baseline and any retrofit
Francisco et al., 2017	Building tightening (bypass sealing between conditioned and unconditioned spaces) to meet ASHRAE 62-1989 or 62.2-2010	Natural gas fueled forced air home heating	Formaldehyde, TVOCs, CO_2, CO	Self-reported adult mental health and child behavior and emotions	—	–-	Children: significant reduction in headaches in ASHRAE 62.2 + Wx; non-significant reductions in respiratory allergies, eczema, and skin allergies in both ASHRAE 62 and 62.2 + Wx; general health improvement in ASHRAE 62 + Wx Adults: significant improvement in psychological distress score in both ASHRAE 62 and 62.2 + Wx ASHRAE 62.2 + Wx had greater IAQ and self-reported health improvements Formaldehyde: reductions in both ASHRAE 62 and 62.2 + Wx TVOCs: significant reductions in 62.2 Wx CO_2: reductions in ASHRAE 62.2 + Wx CO: reduction after Wx
National Center for Healthy Housing, 2022	EER to meet Enterprise Green Communities Criteria, which mandates compliance with ASHRAE 62.2	Gas stoves	NO_2, $PM_{2.5}$, CO_2, CO, formaldehyde	—	—	—	Elevated NO_2 and CO_2 associated with gas stove usage; potential greatest source of formaldehyde in renovated kitchens Continuous exhaust ventilation in kitchen and bathroom important for reducing $PM_{2.5}$, CO_2, formaldehyde, and CO, regardless of stove

							type Pollutants from indoor combustion can be eliminated with building electrification NO_2: remained high in EER and control homes, potentially due to outdoor levels, seasons, and/or chemical reactions; 13% increase per additional meal cooked with gas stove each day during study period $PM_{2.5}$: 21% reduction in EER homes with continuous exhaust ventilation when compared to control homes without; influenced by type and duration of cooking CO_2: 13% reduction in EER homes with continuous exhaust ventilation when compared to control units without; 11-12% increase per additional meal cooked with gas stove each day during study period CO: 41-49% reduction in ER homes with continuous kitchen exhaust when compared to control units without; 20-22% increase per additional meal cooked with gas stove each day during study period Formaldehyde: 9-10% reduction in EER homes with continuous ventilation when compared to control units without; 23-29% reduction in EER homes with kitchen exhaust ventilation when compared to control units without

* indoor pollutants studied in relation to residential combustion
Wx: weatherization
TVOCs: total volatile compounds
AER: air exchange rates
ERV: energy recovery ventilator
HRV: heat recovery ventilator
CFIS: central fan integrated supply