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Saving lives by saving energy? Examining the health benefits of energy efficiency in multifamily buildings in the United States

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ABSTRACT

This study reported herein assesses the health benefits attributable to weatherizing affordable multifamily buildings in the United States. Weatherization is a term used to describe programs that install comprehensive sets of energy efficiency measures into low-income homes and affordable multifamily buildings, such as air sealing, insulation, and heating system repair and replacement. Using a convenience sampling approach, 382 multifamily buildings located in the Northeast and Midwest regions were recruited for this study that fell into three samples: an already weatherized group: a treatment group; and a control group. Households in these buildings were surveyed to collect data about the quality of their dwellings (i.e., apartments), health, and demographic characteristics. The survey was 1) administered twice to the treatment group, once pre-weatherization and once one-year post-weatherization, 2) twice to the control group, also one year apart, and 3) once to the comparison group during the first phase of the survey administration. The survey results suggest that many dwelling conditions improved after weatherization, including improvements in thermal performance and reductions in noise, dust and drafts. Respondents reported improvements in mental health and sleep quality and less need of medical interventions for arthritis and being too cold in their homes. Frequency of headaches decreased. There were no impacts upon respiratory conditions such as asthma and COPD.

1. Introduction

This paper reports the results of research that assessed the health benefits attributable to weatherizing affordable multifamily (MF) buildings[1] in the United States (U.S.). The term weatherization is used to describe comprehensive energy retrofits to the homes of income eligible households and affordable MF buildings that include insulation, air sealing, and heating, ventilation, and air conditioning repair and replacement. In the U.S., weatherization programs are funded by the federal government, states, and utility companies. Local non-profit weatherization organizations and private sector contractors provide weatherization services.

The primary goal of weatherization programs is to reduce energy burdens faced by low-income households by lowering their energy costs through energy saving investments. Here, we define energy burden as the percentage of household annual income spent on home energy (e.g., for space and water heating, appliances, lights). An energy burden of 10% or more is commonly used as a threshold for energy burden in the U.S. About one-third of American households face substantial energy burdens [1]. More generally, energy poverty is a serious issue in the U.S [2–5]. and internationally [6–19]. It can also be argued that access to affordable and reliable energy is a basic human right [20–22].

It has been long recognized that weatherization produces non-energy impacts (NEIs) (i.e., benefits beyond saving energy) [23–25]. These benefits include reducing environmental emissions associated with fossil fuel-based electricity production and home-based fossil energy consumption (e.g., natural gas for space heating) [26]. Weatherization programs themselves employ local workers, thereby promoting local economic development.

This research focuses on the potential health benefits attributable to

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[1] MF refers to apartment buildings that have 5 or more units. A MF building is considered 'affordable' if two-thirds or more of the households residing in the building have incomes at or below federal or state poverty standards.The thresholds are typically 200% of the federal poverty level or 60% of state median income, but these thresholds are subject to change.

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weatherizing affordable MF buildings. These benefits can be produced, in part, by improving indoor air quality [27–29]. Previous research involving single-family (SF) homes has identified several types of health benefits, such as reductions in un-controlled asthma [30–34] and reductions in thermal stress [35–39].

We do not believe that the results of previous studies on the health benefits attributable to weatherizing low-income SF homes are transferrable to the MF sector for several reasons. First, SF homes and MF buildings behave differently from a building science perspective. The latter have shared walls, common areas, central heating, and oftentimes shared ventilation systems. Stack effects can be more pronounced in high-rise buildings than in single floor SF homes.[2] Second, because of physical differences between SF homes and MF buildings, the frequency of weatherization measures installed is different between these home types. For example, SF homes more often receive air sealing and insulation measures while MF buildings are more likely to receive major HVAC replacements and new windows. For MF, insulation and air sealing measures are often installed only in common areas rather than at a unit-level. Lastly, the demographics of occupants differ between the two housing types. Residents of affordable MF buildings are older and more racially diverse [40]. Thus, evaluating the health benefits potentially accruable from weatherizing affordable MF buildings separate from SF health benefits is advisable.

Section 2.0 sets out a framework that explains why we believe that weatherization can lead to health improvements of occupants of MF buildings. The model encompasses a broad range of potential health issues that could be at least partially ameliorated by weatherization. Section 3.0 describes the quasi-experimental design of our study and the survey instrument administered. Methods and approaches used to analyze the survey data are presented in Section 4.0. Section 5.0 presents information that describes both the samples of buildings and respondents and their households encompassed in the study. Section 6.0 presents results that address changes in dwelling quality, general health, specific health issues, and miscellaneous issues of interest. Discussion of the results and potential policy implications are contained in Section 7.0.

2. Weatherization and health impacts

Previous research suggests that weatherization can positively impact human health in numerous manners. We summarize previous research into these five categories:

<u>*Direct and synergistic impacts on household finances*</u>– Research shows that low-income households whose single-family homes have been weatherized have improved household finances. This is primarily due to reductions in energy [41] and water costs [42–44]. Synergistically, also, depending on the household, fewer missed days of work due to illness, fewer interest payments associated with short-term, high-interest loans, fewer utility disconnection and reconnection fees, and reduced out-of-pocket costs associated with treatment of chronic health conditions can also improve household financial situations [43,45]. Improved household finances can synergistically reduce mental stress, as has been shown with decreases in energy burden [46]. It also has been found that households are better able to afford necessary prescriptions and nutritious food post-weatherization [43,45]. The latter, along with decreased stress and increased physical activity, could then lead to reductions in uncontrolled diabetes and cholesterol levels [47–51].

- <u>*Indoor air quality (IAQ)*</u> – Air sealing, repair and replacement of combustion appliances, improvements in ventilation [52,53], and the cleaning of furnace and dryer filters are among the weatherization measures that can improve IAQ [54–58]. Air sealing can keep pests and outdoor allergens out of homes [59–62]. Improvements in IAQ can then lead to improvements in chronic respiratory conditions, which include asthma and COPD [63–67]. Improved IAQ can also reduce migraines and chronic headaches [68–71].
- <u>*Indoor thermal comfort (ITC)*</u> – Insulation, air sealing, and HVAC system repair and replacement can keep homes warmer in the winter and cooler in the summer, which can greatly improve the health of occupants [72–80]. Preventing homes from being too cold or too hot can also reduce the incidence of low-birth-weight babies [81–84]. Improvements in ITC can improve rest and sleep [80,85–87]. Improvements in thermal comfort can reduce symptoms related to osteoporosis and rheumatoid arthritis. More comfortable indoor temperatures could also promote more physical activity [88,89], which could also help reduce obesity [80] and arthritis symptoms. Moderated thermal temperatures can also reduce instances of dehydration [90–93] and, further, reduce the incidence of kidney disease [94–96].
- <u>*Intrusion of outdoor noise*</u> – Wall insulation, primarily, as well as ceiling and attic insulation, new windows, and air sealing, can reduce noise levels in homes [97]. A direct result can be improvements in rest and sleep [98–100]. We hypothesize that reductions in noise might also benefit those who suffer from post-traumatic stress disorder (PTSD) [101], autism spectrum disorders [102–104], and hearing impairment [105,106].
- <u>*Synergistic impacts on mental health*</u> – Improvements in IAQ, ITC, and reductions in the infiltration of outdoor noise can improve rest and sleep, which can then lead to improvements in mental health [107–112]. Improvements in general health and physical activities can also lead to improvements in mental health [113–115]. Improvements in mental health can then reduce the impacts of chronic conditions such as hypertension [116–118], and ischemic heart disease [119–121].

The framework of results represented by these five categories is generic in that it can be applied to SF and mobile homes and MF buildings. However, most of the research in the literature is based on studies of SF homes. Only one previous study addressed the health impacts of weatherizing multifamily buildings [80], though it should be noted that the study also co-mingled single-family homes and small multifamily buildings (i.e., MF buildings with less than five units), was not limited to low-income properties, and had a much smaller sample size. As noted in the Introduction, there are numerous differences between the SF and MF contexts that could impact measurable health benefits of weatherization. Here are several hypothesized differences:

- <u>*IAQ impacts will be smaller*</u> – This is because less work is typically done in MF units that could improve IAQ. For example, air sealing and insulation are less frequently installed in medium size and large MF buildings. Many MF buildings have central heating and common laundry areas, which eliminates the potentially positive contributions to IAQ of cleaning in-home/unit heating system filters that are commonly done as part of the weatherization of SF homes.
- <u>*Thermal comfort impacts will be larger*</u> – This is because in the medium and large-sized MF buildings old and energy inefficient heating systems are replaced with new systems that are less likely to breakdown and are operated by building-wide energy management systems. Compared to the residents of SF homes, tenants living in MF buildings typically have less control over the temperatures in their units until new systems are installed that have in-unit energy management controls.

[2] A stack effect is created when hot air rises from the bottom of a building to the top, which then draws in cooler air into the building at the bottom. This creates air currents within the building. https://www.homepromatch.com/heating-air-conditioning/central-air-conditioning-installation-replacement/understanding-the-stack-effect.

- *Noise reductions will be larger* – Inefficient single pane windows are more often replaced with double pane windows during large MF weatherization projects. Window replacement in the SF sector is relatively rare because they are deemed less effective at reducing energy use than other measures. Another factor is that the majority of the MF buildings in the study are located in urban areas that have more noise pollution.
- *Synergistic impacts on mental health will be larger* – This is because thermal comfort and noise levels will be improved.
- *Synergistic impacts on household financial health will be smaller* – This is mainly because utility costs are included in the rents of many MF buildings. Thus, many MF households will not experience reductions in their energy costs nor avoid the costs of utility shut-offs and reconnection service fees. Also, MF households in our sample will not recoup the same level of lost wages from fewer missed days of work as their counterparts in the SF weatherization sector because more of the head of households are retired in the MF sector.

3. Research design

This study employed a modified quasi-experimental design and sample of convenience.[3] Affordable MF buildings were recruited into the project that had been weatherized in the previous five years (comparison with treatment (CwT) group), were scheduled to be weatherized within the initial stages of this 24-month project (treatment (T) group), and had not been weatherized and were not scheduled to be weatherized during the course of this project (control (C) group). In a conventional quasi-experimental design, a CwT group is not typically incorporated in the study. The most important reason we did this is that we were unsure what the post-treatment response rate would be for residents of affordable MF buildings who are typically renters that may have the propensity to move frequently. Thus, if the response rates dropped precipitously from pre-to post-treatment, we would still have had enough data for a cross-sectional study.

No national or even regional databases exist in the U.S. that contain lists of affordable MF buildings that contained the data necessary to establish building eligibility for this project. Additionally, there are no national or regional databases with lists of affordable MF buildings that have been or are scheduled to be weatherized. Lacking these resources, the research team directly reached out to over 100 organizations and individuals that work in the affordable MF building space in the Northeastern and Midwestern regions of the U.S. These included non-profit, commercial, and public sector owners of these buildings, housing authorities, state and local weatherization agencies, utility programs with MF weatherization programs, and energy efficiency and environmental non-profit organizations such as the Natural Resources Defense Council and Energy Efficiency for All. The team also reviewed publicly listed MF properties and development projects posted on-line by community and economic development corporations.

Recruiting property owners to allow their buildings to be part of this study was difficult. Most did not return phone calls or emails. Several did not want their residents to be surveyed about their health. The number of buildings in the queue to be weatherized was much lower than we expected as well. Taking all of this into account, we ultimately included every affordable MF building offered by property owners that had 5+ units. Buildings assigned to the CwT or T groups had or were expected to have installed major weatherization measures (i.e., air sealing, insulation, HVAC repair and replacement). We relied upon the property owners to judge the suitability of their buildings to be part of the control group.[4]

Buildings were recruited from the Northeastern and Midwestern regions of the U.S. (see Appendix 1). These regions were chosen for several reasons. First, these regions have similar climates zones (cold and very cold) and similar MF building construction practices. Thus, we believe that MF buildings from these regions are similar enough to compose a homogenous sample of buildings. Second, the majority of the MF buildings weatherized in the U.S. come from these regions. Third, one sponsor of this work is based in New York City and the other set of sponsors were utility companies in the Commonwealth of Massachusetts.

The research team also had to overcome the challenge of recruiting residents to complete the survey. Contact information for residents of MF buildings was unavailable to the research team. Due to this it was decided to hand deliver the phase 1 surveys, which entailed hanging clear plastic bags on apartment doorknobs that contained a cover letter describing the project, an informed consent form, a paper survey, and a postage pre-paid envelope. We contacted each property owner or manager to get permission to enter buildings to deliver the surveys. The paper surveys were translated into Spanish, Russian and Mandarin. Respondents were provided a gift card upon receipt of a completed survey. Approximately 25% of households approached by the project in this manner did complete the phase 1 survey.

Phase 1 of survey administration lasted from spring 2018 to summer 2019. For Phase 2, approximately one year later[5] from spring 2019 to winter 2020,[6] the same T and C group households were surveyed again. In this instance, respondents were called to complete the survey by phone if we had a phone number on record. Otherwise, the surveys were mailed to the respondents. The one year between survey administrations allowed for homes and households to experience all four seasons before again answering questions about the health of household members.

The survey itself took about 25 min to complete. One main respondent completed one survey instrument for their household that included questions that pertained to the household, the respondent, other adults in the household, and children in the household. The questions focused on health issues, such as asthma, thermal stress, headaches and arthritis, as reported below. The survey also included a battery of household budget and food security questions and questions about community cohesion and resilience. The survey also included a comprehensive array of demographic questions. Lastly, the survey included questions about the conditions of their dwellings pre- and post-treatment. Improvements in dwelling quality are a necessary though not necessarily a sufficient condition to produce the health benefits discussed above and reported on below. It should be noted that most of the questions used in the survey had previously been used on evaluations of the health benefits of weatherizing low-income SF and mobile homes. The preponderance of the questions was taken directly from previously fielded and well-regarded U.S. federal government surveys, such as the Behavioral Risk Factor Surveillance System[7] and the Residential Energy Consumption Survey.[8]

[3] The process for IRB approval for this study was waived because the study fell under the rubric of program evaluation.

[4] It should be noted that research team members did visit every comparison, treatment and control building to drop off surveys, interview property managers, and collect data about building construction and energy systems. In every case, the research team found that the buildings in these samples met expectations with respect to being categorized as affordable.

[5] The T group was surveyed approximately one-year after weatherization was completed. The C group was surveyed approximately one year after the Phase 1 survey.

[6] Survey administration ceased in March 2020 due to the COVID-19 pandemic.

[7] https://www.cdc.gov/brfss/data_documentation/index.htm.

[8] https://www.eia.gov/consumption/residential/.

4. Methods

This section presents approaches taken to analyze the survey data. The collection of comparison group data along with pre- and post-weatherization data from the treatment and control groups allows both cross-sectional analyses and differences-in-differences (DID) analyses. The former offer larger sample sizes and the latter are based in a more rigorous experimental design. Our approach is to use DID analyses for data related to changes in home conditions and chronic health conditions. In this context, the ability to track changes in health conditions for specific respondents living in specific apartments outweighs the benefits of larger sample sizes available for cross-sectional analyses. For these DID analyses, only households that completed surveys pre- and post-weatherization were included in the analyses. For several questions, the main survey respondents needed to be the same from one period to the next, too. No data were collected from apartments that had new occupants during the second survey period.

Cross-sectional analyses were performed with some variables that are not associated with chronic health conditions. These variables capture rare events that impact health, such as incidences of thermal stress and trips and falls, where larger sample sizes are needed. Most of the results reported below are based on DID analyses.

The data were not adjusted prior to analysis. The data could have been adjusted to account for cluster effects. This issue arises because in many instances more than one survey was collected from a building and, it could be argued, that weatherization would have had the same impact on every apartment in the building that completed a survey. This argument is rejected because it can be argued that weatherization does not have the same impact on every apartment in a multifamily building. For example, changes in apartment comfort pre-to post-weatherization are dependent upon where in the building the apartment is located, top-floor versus bottom-floor, south facing versus north facing, and/or corner versus in the middle of a floor. Changes in air flow from outside and within buildings due to weatherization also are dependent upon the location of the apartments in the buildings. It is also the case in many multifamily buildings that few weatherization measures are actually installed in units. For example, oftentimes because the way a MF building is constructed, insulation cannot be added to apartment walls that face outside but can be added to insulate the roof. In this instance, top floor apartments may be more impacted by the addition of roof insulation than lower floor apartments. It is for these reasons that the data have not been adjusted for clustering effects.

The data were not adjusted in response to observed differences in demographic characteristics between the samples. Exploratory regression analyses found that the demographic variables performed poorly. In other words, the demographic variables do not explain to a substantial degree variation in the impacts of weatherization on health outcomes. Of course, if the results presented below were used to estimate the health outcomes of weatherization across a region or state, then demographic differences which impact the incidence of pre-existing health issues would need to be considered.

Lastly, no data were available nor were any reports from research staff who visited sample buildings that suggested that it was unwarranted to accept the parallel trends assumption that underlies DID analyses. On the other hand, this does not mean that the results reported by the control group for many health issues met expectations. Indeed, in many instances, changes in control group results were quite large and unexpected. For this reason, statistical significances of changes in both the treatment group and control group results are presented separately, along with the DID statistical significances.

5. Sample characteristics

The research team collected data from a total of 382 buildings from a total of 186 sites.[9] As indicated in Appendix 1, the vast majority of the buildings were low-rise (i.e., <5 stories) and relatively few were high-rise, which was contrary to our a priori assumption we had about the MF sector that most buildings were high-rise. We generally found working with non-profit and public sector building owners easier than working with commercial sector property owner. Most of the buildings could be characterized as occupied by families or restricted for seniors. Overall, the sample of buildings is spread across the Northeast and Midwest, though most of the CwT and T buildings are located in the Northeast and most of the C buildings in the Midwest. The buildings were located in several major cities, including Boston, New York and Chicago and also in rural areas of those states.

Energy conservation measures that have the most potential to produce health-related non-energy impacts were installed in the T and CwT buildings at the following rates: air sealing (55%), heating equipment (52%), insulation[10] (50%), and mechanical ventilation (27%). Cooling equipment and windows were the least commonly installed measures, at 18% and 14% of buildings, respectively. Other installed measures include in-unit lighting (84%), refrigerators (52%) and water savings devices (47%). Structural repairs (20%) were the most reported health and safety measures. The common areas of one building only received asbestos, lead paint remediation, and smoke detectors. Seven percent of buildings received in-unit smoke detectors and 5% received some in-unit electrical repairs.

Table 1 indicates that a total of 1,912 households completed surveys in Phase 1, representing 2,964 persons. The average age of the main respondents was about 60 years, which is consistent with other research that has found that weatherization households tend to be found in the older demographic [40]. This finding is linkable to other findings that a high percentage of primary wage earners are retired and that the average household size is only about a person and a half [40].

Table 2 presents some additional context for the samples. It shows the self-reported incidence of four chronic diseases reported by main respondents for each of the three sample groups and the national incidence rates. For each chronic disease – asthma, diabetes, COPD, and arthritis – and each sample group, the incidence rates are much higher than the national incidence rates. The respondents reporting being afflicted with just over 1 of 4 of these chronic diseases. All in all, the baseline health of the residents of affordable MF buildings in this study is much worse than for the nation's population as a whole. It should also be noted that incidence of chronic disease across the three research groups is statistically significantly different for two diseases, COPD, and arthritis.

6. Results

Before presenting results with respect to changes in general health and then more specific health issues, results with respect to changes in dwelling quality are presented in Table 3. The results presented in this table are based on Treatment and Control households that completed the surveys pre- and post-weatherization. The column labeled "Diff." refers to post-weatherization changes reported by the treatment and control households and the column labeled "DID" refers to calculations using the classic differences in differences equation that includes results from both the T and C households.

Two important observations can be made about the results presented in Table 3. The first is that respondents reported high rates of numerous problems pre-weatherization with their buildings and units with respect

[9] A site is a property that has one or more multifamily buildings.

[10] Includes the following insulation types: above-grade wall, floor, rim/band joist, and foundation wall insulation.

Table 1
Sample demographics.

Respondent Demographics	Comparison with Treatment	Treatment		Control	
	Post-T	Pre	Post	P1	P2
Number of Households (N = 1,921)	612	417	198	892	553
Number of Persons (N = 2,964)	880	742	309	1,273	700
Age Main Respondent (mean) ***	64	58	60	57	60
Gender Main Respondent (female) (%) **++	70%	69%	73%	62%	60%
Primary Wage Earner Employed (%) *	20%	27%	25%	24%	21%
Primary Wage Earner Retired (%) ***	60%	46%	40%	42%	42%
Household Size (mean) ***+++	1.4	1.8	1.6	1.4	1.3
Single Person Household (%) ***+++	75%	58%	68%	76%	84%
Education – Some College or more (%) *	44%	38%	25%	33%	42%
Race – White (%) ***	63%	37%	39%	38%	38%
Race – Black (%) ***+++	20%	24%	26%	50%	54%
Hispanic or Latino ***+++	4%	14%	22%	3%	4%
*Is gas used for cooking in your home? (Yes/no)****++	26%	52%	36%	29%	25%
*Is smoking allowed inside the home (%No)****+++	84%	87%	89%	70%	71%

Phase 1
* Difference is statistically significant at the $p < .05$ level
** Difference is statistically significant at the $p < .01$ level
*** Difference is statistically significant at the $p < .001$

Phase 2
\+ Difference is statistically significant at the $p<.05$ level
++ Difference is statistically significant at the $p<.01$ level
+++ Difference is statistically significant at the $p<.001$ level

Table 2
Baseline health – chronic health conditions.

Health Indicators/Survey Group	CwT	T	C	National
Have asthma? (%Yes)	23.1% (n = 588)	25.4% (n = 404)	25.8% (n = 864)	7.7%[a]
Have diabetes? (%Yes)	28.0% (n = 603)	23.2% (n = 413)	24.1% (n = 881)	10.5%[b]
Have COPD? (%Yes)	16.2% (n = 561)	10.6% (n = 388)	17.8% (n = 847)	6.4%[c]
Have arthritis? (%Yes)	53.9% (n = 581)	49.7% (n = 394)	45.6% (n = 858)	23%[d]
Average Number of Reported Chronic Diseases	**1.21 (n=523)**	**1.06 (n=363)**	**1.14 (n=793)**	**N/A**

[a] https://www.cdc.gov/asthma/most_recent_national_asthma_data.htm.
[b] https://www.diabetes.org/resources/statistics/statistics-about-diabetes.
[c] https://www.cdc.gov/copd/basics-about.html.
[d] https://www.cdc.gov/arthritis/data_statistics/national-statistics.html.

to draftiness, dustiness, noise, odors, infestations, and mold. The second is that T group respondents reported improvements post-weatherization in ten of the twelve conditions listed in Table 3, with most of the changes being statistically significant. The DID results and statistical significance tests support the conclusion that dwelling quality improved post-weatherization. Notable IAQ-related improvements include reductions in drafts, dust, and insect and pest infestations. Respondents also indicated improvements in thermal conditions and reductions in the intrusion of outdoor noise.

The results in Table 3 lay the groundwork for observing beneficial impacts from weatherization. Table 4 presents the first group of health results, which are related to changes in general health. Only one health issue showed improvement, a reduction in new or more frequent headaches. The treatment group's sleep improved but not by a statistically significant degree. Decreases in mental health were unexpected, especially as seen in contrast with improvements reported by the control group. Also unexpected were decreases in vigorous physical activity by both treatment and control groups.

More directly related to the benefits of improved building performance through weatherization – and subsequently, thermal comfort – are the results presented in Table 5, which relate to changes in impacts of thermal stress. The results are presented at the individual level, not at the household level, as we did collect thermal stress answers about everyone in the household. These results are cross-sectional in nature (i.e., comparing CwT to T + C samples). This decision was made to increase sample sizes because the incidence of thermal stress is low compared to our sample size. It was also made because thermal stress is not considered a chronic health condition, which allows it to be studied at a population level rather than through a DID analysis.[11]

Respondents in the CwT group reported fewer medical encounters related to being too cold in their apartments than the T + C group. The difference is statistically significant with respect to emergency department and doctor's office visits. The frequencies of medical encounters for being too cold are higher than those reported for being too hot, which presently makes sense given our focus on very cold and cold climate zones but can be expected to change as temperatures continue to rise from the impacts of climate change.[12]

Conversely, arthritis is a chronic health condition and could be influenced by improved thermal conditions. Thus, the results presented in Table 6 are based on DID analysis. The first notable observation is the high percentage of respondents in both samples that reported having arthritis, over 40% in all cases. For comparison purposes, the incidence rate of arthritis in the U.S. population is 23%. Approximately three-fourths of the respondents reported having arthritis symptoms within the past 3 months. Urgent care and emergency department visits dropped for the treatment group post-weatherization, with the first being statistically significant. Arthritis symptoms increased in the control group. The reduction in urgent care visits in response to increases in symptoms may explained, in part, by increases in emergency

[11] Annual temperature patterns accessed for major cities in the Eastern and Midwestern U.S. did not change appreciably across our study periods.

[12] Several questions were included in the survey to explore relationships between ITC, weatherization, and low-birth-weight babies. The number of women in our sample of households that reported being pregnant during the study was too low to report anything meaningful in this paper.

Table 3
Changes in dwelling quality.

	Treatment		Diff.	Control		Diff.	DID
	Pre	Post		P1	P2		
During the past 12 months, how often was your apartment at a temperature that you felt was unsafe or unhealthy? (almost every month to some months)	50% (n = 182)	39% (n = 182)	−11%* (n = 182)	32% (n = 533)	26% (n = 533)	−6%** (n = 533)	−5% (n = 715)
During the past 12 months, how often have you or other members of your household found your home too drafty? (all of the time, most of the time)	60% (n = 156)	46% (n = 156)	−14%** (n = 156)	45% (n = 496)	36% (n = 496)	−9%*** (n = 496)	−5%* (n = 652)
During the past 12 months, how often have you or other members of your household found your home too dusty? (All of the time, most of the time)	71% (n = 136)	53% (n = 136)	−18%*** (n = 136)	64% (n = 468)	62% (n = 468)	−2% (n = 468)	−16%** (n = 604)
How much outdoor noise do you hear indoors when the windows are closed? (A great deal)	67% (n = 170)	60% (n = 170)	−7% (n = 170)	62% (n = 531)	61% (n = 531)	−1% (n = 531)	−6% (n = 701)
How much does outdoor noise interfere with your sleep at night? (Extremely, very much)	44% (n = 111)	35% (n = 111)	−11%* (n = 111)	26% (n = 403)	28% (n = 403)	+2% (n = 403)	−13% (n = 514)
How much does outdoor noise bother, disturb, or annoy you when you are inside your apartment? (A great deal, moderately)	33% (n = 171)	31% (n = 171)	−2% (n = 171)	32% (n = 499)	32% (n = 542)	0% (n = 499)	−2% (n = 670)
How infested is your home with cockroaches or other insects? (Extremely infested, somewhat infested)	26% (n = 187)	23% (n = 187)	−3% (n = 187)	15% (n = 543)	17% (n = 543)	+2% (n = 543)	−5%* (n = 730)
How infested is your home with rats, mice, or other rodents? (Extremely infested, somewhat infested)	27% (n = 183)	31% (n = 183)	+4% (n = 183)	12% (n = 524)	13% (n = 524)	+1% (n = 524)	+3%*** (n = 707)
Have you seen mold in your home in the past 12 months? (Yes)	31% (n = 164)	29% (n = 164)	−2% (n = 164)	15% (n = 481)	14% (n = 481)	−1% (n = 481)	−1%* (n = 645)
Have you seen standing water in your home in the past 12 months? (Yes)	11% (n = 159)	11% (n = 159)	0% (n = 159)	7% (n = 521)	6% (n = 521)	−1% (n = 521)	1% (n = 680)
How often do you smell odors from outside your home when the windows are closed?[4] *(very often, fairly often)*	24% (n = 165)	12% (n = 165)	−12%** (n = 165)	13% (n = 491)	11% (n = 491)	−2% (n = 491)	−10%*** (n = 656)
How often do you smell odors from other apartments or the hallway when you are inside your apartment?[4] (very often, fairly often)	38% (n = 147)	31% (n = 147)	−7%✧ (n = 147)	26% (n = 460)	24% (n = 460)	−2% (n = 460)	−5%* (n = 607)

* Difference is statistically significant at the p < .1 level. * Difference is statistically significant at the p < .05 level.
** Difference is statistically significant at the p < .01 level. *** Difference is statistically significant at the p < .001.

Table 4
Changes in general health.

	Treatment		Diff.	Control		Diff.	DID
	Pre	Post		P1	P2		
Thinking about your mental health, which includes stress, depression, and problems with emotions, for how many days during the past 30 days was your mental health not good?	7.06 (N = 119)	7.24 (n = 119)	+.18	5.86 (n = 394)	4.62 (n = 394)	−1.16**	+1.34 (n = 523)
During the past 30 days, for about how many days have you felt you did not get enough rest or sleep?	7.95 (n = 116)	7.74 (n = 116)	−.21	7.10 (n = 401)	6.73 (n = 401)	−.37	+.16 (n = 517)
In the past three months, have you had headaches that are either new or more frequent or severe than ones you have had before? (Yes/No)	36.6% (n = 175)	28.6% (n = 175)	−8.0% ✧	18.7% (n = 520)	17.1% (n = 520)	−1.6%	−6.4%***
How many days per week do you do moderate physical activities for at least 30 min?	2.77 (n = 132)	2.73 (n = 132)	−.06	3.04 (n = 434)	2.83 (n = 434)	−.21	+.15 (n = 566)
How many days per week do you do vigorous physical activities for at least 20 min?	1.56 (n = 119)	1.09 (n = 119)	−.47*	1.66 (n = 398)	1.18 (n = 398)	−.48***	+.01 (N = 517)

✧ Difference is statistically significant at the p < .1 level. * Difference is statistically significant at the p < .05 level.
** Difference is statistically significant at the p < .01 level. *** Difference is statistically significant at the p < .001.

department and hospitalizations.

Table 7 presents descriptive statistics with respect to asthma. Again, these results are presented for individuals, not households. Similar to arthritis, a higher percentage of residents in our samples report having asthma, around 19%, than is found nationally, which is about 8%. Only subjects who reported still having asthma are included in this analysis. The need for medical interventions related to asthma for the treatment group support our hypothesis that MF weatherization may not have a large impact on chronic respiratory conditions. Members of the treatment group reported slight increases in urgent care visits and hospitalizations and a slight decrease in emergency department visits, all statistically insignificant. Conversely, the control group reported major decreases in the need for medical interventions, which were all statistically significant.

We find insignificant impacts on asthma in treatment homes with persons with asthma despite reductions in many asthma triggers documented in Table 3, such as with respect to dustiness and draftiness. The use of natural gas for cooking dropped in these homes from 48% to 42%, though this reduction is statistically insignificant. The number these homes that allowed smoking increased from 7% to 11% but this increase is also statistically insignificant. We do not have data to establish whether smoking occurred in the homes, only on whether smoking was allowed or not. In any case, the preponderance of households with persons with asthma do not allow smoking in their homes. There were no changes in use of natural gas for cooking or allowance of smoking in homes in the control group.

We have no other data available to us that helps us understand the changes in the control group, though we can speculate that the reasons might be tied to region (i.e., the treatment buildings are mostly located in the Northeast and the control buildings in the Midwest) or asthma control mechanisms being used in each sample that are unrelated to weatherization. Lacking an understanding for the large changes observed in the control group with respect to these asthma-related variables and small n's, we felt that it would be misleading to present

Table 5
Changes with respect to thermal stress.

Thermal Stress - Health Care Encounters Variables (Number of individuals in each sample)	T_Pre + C (n = 2008)	CwT (n = 879)	Diff
***During the past* 12 months ...**	**P1**	**P1**	
How many times because apartment was too COLD did anyone in the household have to:			
• stay overnight in the hospital (mean # of encounters)	0.019	0.013	−0.006
• go to the emergency department at a hospital (mean)	0.021	0.006	−0.016*
• visit a doctor's office (mean)	0.047	0.016	−0.031**
How many times because apartment was too HOT did anyone in the household have to:			
• stay overnight in the hospital (mean # of encounters)	0.006	0.002	−0.004
• go to the emergency department at a hospital (mean)	0.008	0.014	+0.006
• visit a doctor's office (mean)	0.012	0.009	−0.003

✧ Difference is statistically significant at the $p < .1$ level. * Difference is statistically significant at the $p < .05$ level.
** Difference is statistically significant at the $p < .01$ level. *** Difference is statistically significant at the $p < .001$.

DID results for this health issue.

The other chronic respiratory disease included in our study was COPD. The results, in Table 8, mirror those found with respect to asthma. A higher proportion of residents in our samples reported having COPD than nationally, about 20% and 6.4%, respectively. The treatment group reported decreases in doctor's office visits, emergency department visits, hospitalizations and number of medications used, with none of these changes being statistically significant. The control group reported substantive increases in emergency department and hospitalizations and decreases doctor's office visits and the number of medications used. The large decrease in doctor's visits and large increase in emergency department by the control group were very unexpected. There was one statistically significant DID result, increase in doctor's visits.

As noted in Section 2, one could hypothesize that weatherization could positively impact diabetes due to decreased stress, increased ability to afford nutritious food[13] and increased physical activity. The results presented in Table 9 support the importance of posing this hypothesis. Again, our samples report higher rates of diabetes, around 26%, than found nationally, which is approximately 11%. The treatment group reported decreases in diabetes symptoms, doctor's office visits, need for urgent care, and hospitalizations, and an increase in emergency department visits. The control group also reported a statistically significant decrease in doctor's office visits. None of the DID results are statistically significant, though three out of five moved in the direction suggested by the theory of change framework.

Similar to diabetes, one could hypothesize that reductions in stress, improved sleep and rest, more nutritious food and increases in physical activity could lower blood pressure and cholesterol. Results related to these two chronic health issues are presented in Table 10. Again, baseline rates of high blood pressure, around 55%, and cholesterol, around 37%, are high as compared to national incidence rates, which are 45% and 12%, respectively. The results do support these hypotheses as the treatment group respondents reported increases in being told that their blood pressure and that cholesterol levels went down to healthy levels, more so than the control group.

Table 11 presents a set of miscellaneous results that bear on the health of residents of affordable MF buildings. These results are based on the analysis of cross-sectional data. First, we see that the CwT sample reports fewer missed days of work because of illness or injury of self or another household member, consistent with the theory of change framework. Dental health, which could have improved due to better nutrition and less stress, did not differ between the two samples. Weatherization programs do replace energy inefficient and broken refrigerators, which may explain, in part, the decreases in reports of spoiled food. This is an important result because it may cost households $250 or more to replace food,[14] which is a considerable expense.

Of course, incidences of spoiled food could also be caused by power outages, which is something that conventional weatherization does not impact. We asked households whether any occupants relied on electrical medical equipment and refrigerated prescriptions. About 15% of households responded affirmatively to these questions. Then, about 50% of these households stated that it would be life threatening if their power went out for 4 or more hours. We were not expecting such dramatic results to these questions.

Fig. 1 presents a graphical summary of the forty-five results presented in Tables 3–11 that can be interpreted with respect to the theory of change framework presented in Section 2. Ten of the results were produced using the cross-section data and thirty-five were produced using the quasi-experimental design data. With respect to the latter, the results are assessed using only the treatment group, only the control group, and then using differences-in-differences. The results are assessed for consistency with the framework along a five-component scale. *Consistent-statistically significant* refers to a result that is consistent with the framework and is statistically significant at least at the $p < .10$ level. *Consistent* indicates that the result was in the expected direction but was not statistically significant. *No Measured Change* indicates that the measured change was <1% pre-to post. *Inconsistent* indicates that the resulted moved in the unexpected direction but was not statistically significant. *Inconsistent-statistically significant* refers to a result that did not move in the expected direction and was statistically significant. Our a priori assumption was that the control group results would not change appreciably from pre-to post time periods. Therefore, any measured changes were judged to be *Inconsistent* or *Inconsistent-Statistically Significant*.

There are two major observations to be made about the summary of results presented in Fig. 1. First, the preponderance of results is consistent with the theory of change framework. Seventy percent of the cross-sectional analysis results were consistent with the framework and seventeen percent or less were inconsistent. The results for the treatment group were similar. This broad view of the results provides confidence that weatherization does correlate with improvements in health, broadly speaking.

Second, almost one half of the control group results changed substantially from period 1 to period 2. There does not seem to be a pattern as to whether control group apartment conditions improved or did not improve pre-to post. The high variability of the control group results was also seen in a study on the health impacts of weatherization conducted in the single-family sector [45]. Unexpectedly, the variability of the control group results did not impact the percentage of differences-in-differences results that moved in the expected direction.

Fig. 2 plots statistical support for the impacts of weatherization on categories of variables. As expected, the most statistical support is provided about the positive impacts of weatherization on home conditions, followed by thermal stress and arthritis, two variables impacted by temperature conditions in the home. There was medium statistical support for general health. Into the low statistical support group fell cholesterol, high blood pressure, spoiled food and missed days of work. As expected, there was very low to no statistical support for the two

[13] 10.7% of treatment households and 7.7% of control households surveyed in Phase 1 reported a household member went an entire day and night without eating anything because there was not enough food and 15.0% and 13.1% of main respondents worried that household members would not have nutritious food to eat, respectively.

[14] https://www.kohlerpower.com/home/common/pdf/RES_Infographic.pdf.

Table 6
Changes with respect to arthritis (%yes).

Variable (Respondent Only)	Treatment		Diff.	Control		Diff.	DID
	Pre	Post		P1	P2		
Diagnosed as having arthritis	49.7% (n = 394)	50.8% (n = 189)	n/a	45.6% (n = 858)	48.3% (n = 546)	n/a	n/a
Had arthritis symptoms – past 3 months	79.7% (n = 74)	78.4% (n = 74)	−1.3% (n = 74)	82.1% (n = 196)	89.8%* (n = 196)	+7.7% (n = 196)	−9.0%* (n = 270)
Visited doctor for arthritis last 12 months	33.7% (n = 95)	20.0% (n = 95)	−13.7%* (n = 95)	31.4% (n = 236)	27.1% (n = 236)	−4.3% (n = 236)	−9.4% (n = 331)
Urgent care for treatment of worsening arthritis symptoms - last 12 month	9.8% (n = 102)	4.9% (n = 102)	−4.9% (n = 102)	10.7% (n = 243)	8.2% (n = 243)	−2.5% (n = 243)	−2.4% (n = 345)
Visited emergency department because of arthritis – last 12 months	7.8% (n = 102)	3.9% (n = 102)	−3.9% (n = 102)	5.8% (n = 243)	6.2% (n = 243)	+.4% (N = 243)	−4.3% (n = 345)
Stay overnight in hospital because of arthritis – last 12 months	6.9% (n = 102)	3.9% (n = 102)	−3.0% (n = 102)	4.9% (n = 243)	4.5% (n = 243)	−.4% (n = 243)	−2.6% (n = 345)

✧ Difference is statistically significant at the p < .1 level. * Difference is statistically significant at the p < .05 level.
** Difference is statistically significant at the p < .01 level. *** Difference is statistically significant at the p < .001.

Table 7
Changes with respect to asthma.

All household members)	Treatment Group		Diff.	Control Group		Diff.
	Pre-Wx (n = 785)	Matched Pair (208)		P1 (n = 1299)	Matched Pair (n = 611)	
Lifetime Asthma*: Ever been told […] you have asthma?*	18.7% (n = 147)	24.5% (n = 51)	NA	20.7% (n = 269)	17.8% (n = 109)	NA
Active Asthma*: Do you still have asthma?*	15.7% (n = 123)	22.0% (n = 46)	NA	17.8% (n = 231)	15.7% (n = 96)	NA
During the past* 12 months, *how many times *did anyone in the household have to:*	**n=46**			**n=96**		
• visit an urgent care center because of asthma (mean)	0.15	1.13	+0.98*	0.57	0.54	−0.03
• stay overnight in the hospital because of asthma (mean)	0.17	0.17	0.0	0.24	0.10	−0.14✧
• go to the emergency department because of asthma (mean)	0.43	0.41	−0.02	0.66	0.34	−0.32

✧ Difference is statistically significant at the p < .1 level. * Difference is statistically significant at the p < .05 level.
** Difference is statistically significant at the p < .01 level. *** Difference is statistically significant at the p < .001.

Table 8
Changes with respect to chronic obstructive pulmonary disease (COPD) (%yes).

Variable	Treatment		Diff.	Control		Diff.	DID
	Pre	Post		P1	P2		
Have you ever been told by a doctor or health professional that you have COPD, emphysema, or chronic bronchitis?	10.5% (n = 389)	20.3% (n = 182)	n/a	17.8% (n = 846)	24.0% (n = 451)	n/a	n/a
(If yes) Have you ever been given a breathing test to diagnose your COPD, chronic bronchitis, or emphysema?	92.3% (n = 39)	94.3% (n = 35)	n/a	91.1% (n = 146)	92.7% (n = 123)	n/a	n/a
Other than a routine visit, have you had to see a doctor in the past 12 months for symptoms related to shortness of breath, bronchitis, or other COPD, or emphysema flare ups?	36.4% (n = 22)	40.9% (n = 22)	+4.5% (n = 22)	64.6% (n = 96)	36.5% (n = 96)	−28.1%*** (n = 96)	+32.6%* (n = 118)
Did you have to visit an emergency room or be admitted to a hospital in the past 12 months because of your COPD, chronic bronchitis, or emphysema?	22.7% (n = 22)	9.1% (n = 22)	−13.6% (n = 22)	27.2% (n = 92)	18.5% (n = 92)	−8.7%✧ (n = 92)	−4.9% (n = 114)
How many different medications do you currently take each day to help with your COPD, chronic bronchitis, or emphysema?	2.73 (n = 15)	2.47 (n = 15)	−.26 (n = 15)	3.01 (n = 67)	2.33 (n = 67)	−.68 (n = 67)	+.42 (n = 82)

✧ Difference is statistically significant at the p < .1 level. * Difference is statistically significant at the p < .05 level.
** Difference is statistically significant at the p < .01 level. *** Difference is statistically significant at the p < .001.

respiratory issues contained in the study, asthma and COPD, as well as for dental health, trips & falls, and diabetes.

7. Discussion

The focus on the health benefits of weatherizing affordable MF buildings is well placed because occupants report higher incidences for all of the chronic health conditions assessed than the U.S. population. Overall, the results presented above support the conclusion that the weatherization of affordable MF buildings can improve the health of occupants. Setting the stage for the health improvements, many dwelling conditions improved, including thermal comfort and reductions in noise, dust, and drafts. Respondents reported improvements in rest and sleep and less need of medical interventions for being too cold in their homes. Headaches decreased. Improvements in thermal comfort had positive impacts on those suffering from arthritis.

As hypothesized, we did not see improvements with respect to two chronic respiratory conditions, asthma, and COPD. These findings are consistent with the only other assessment of the impacts on health outcomes of weatherization of MF buildings that general health and sleep improved but that more research is needed to understand relationships between asthma and weatherization [80].

Table 9
Changes with respect to diabetes (%yes).

Variable	Treatment		Diff.	Control		Diff.	DID
	Pre	Post		P1	P2		
Have you ever been told by a doctor or other health professional that you have diabetes?	24.0% (n = 400)	22.5% (n = 182)	n/a	25.2% (n = 841)	25.2% (n = 544)	n/a	n/a
How long has it been since you last had any symptoms of diabetes? (less than three months ago)	50% (n = 30)	50% (n = 30)	0.0% (n = 30)	54.7% (n = 117)	53% (n = 117)	−1.7% (n = 117)	+1.7% (n = 147)
During the past 12 months, did you see a doctor, nurse, or other health professional for urgent treatment of worsening diabetes symptoms?	35.3% (n = 17)	17.6% (n = 17)	−17.7% (n = 17)	29.2% (n = 72)	12.5% (n = 72)	−16.7%* (n = 72)	−1.0% (n = 89)
Urgent care for treatment of worsening diabetes symptoms - last 12 months	11.8% (n = 17)	5.9% (n = 17)	−5.9% (n = 17)	11.1% (n = 72)	4.2% (n = 72)	−6.9% (n = 72)	+1.0% (n = 89)
Visited emergency department because of diabetes – last 12 months	11.8% (n = 17)	5.9% (n = 17)	−5.9% (n = 17)	4.2% (n = 72)	1.4% (n = 72)	−2.8% (n = 72)	−3.1% (n = 89)
Stay overnight in hospital because of diabetes – last 12 months	5.9% (n = 17)	11.8% (n = 17)	+5.9% (n = 17)	5.6% (n = 72)	0.0% (n = 72)	−5.6% (n = 72)	+11.5%* (n = 89)

✧ Difference is statistically significant at the $p < .1$ level. * Difference is statistically significant at the $p < .05$ level.
** Difference is statistically significant at the $p < .01$ level. *** Difference is statistically significant at the $p < .001$.

Table 10
High blood pressure and cholesterol (%tes).

Variable	Treatment		Diff.	Control		Diff.	DID
	Pre	Post		P1	P2		
Has anyone in the household ever been told by a doctor, nurse, or other health professional that they have high blood pressure?	52.4% (n = 395)	59.0% (n = 188)	n/a	50.8% (n = 858)	57.7% (n = 544)	n/a	n/a
In the past 12 months, has anyone in the household been told by a doctor, nurse, or other health professional that their blood pressure went down to a healthy level?	54.7% (n = 75)	57.3% (n = 75)	+2.6% (n = 75)	63.5% (n = 230)	64.3% (n = 230)	+0.8% (n = 230)	+1.8% (n = 305)
Has anyone in the household ever been told by a doctor, nurse, or other health professional that their cholesterol is high?	38.9% (n = 380)	35.2% (n = 182)	n/a	37.2% (n = 847)	38.3% (538)	n/a	n/a
In the past 12 months, has anyone in the household been told by a doctor, nurse, or other health professional that their cholesterol went down to a healthy level?	36.1% (n = 36)	52.8% (n = 36)	+16.7% (n = 36)	44.0% (n = 134)	53.7% (n = 134)	+9.7%✧ (n = 134)	+7.0% (n = 170)

✧ Difference is statistically significant at the $p < .1$ level. * Difference is statistically significant at the $p < .05$ level.
Difference is statistically significant at the $p < .01$ level. * Difference is statistically significant at the $p < .001$.

Table 11
Miscellaneous results.

	Variable (Respondent Only)	T_Pre + C	CwT	Diff
		P1	P1	
Missed Days of Work	*In the past* 12 *months, about how many days of work did the primary wage earner miss because of illness or injury of self or another household member? (Mean)*	3.63 (n = 214)	3.16 (n = 83)	−0.47
Trips & Falls	*In the past* 12 *months, did anyone in the household suffer a trip or fall inside the home that required them to see a medical professional? (Yes)*	5.4% (n = 1218)	8.3% (n = 577)	+3.9%*
Dental Health	*During the past* 12 *months, was there a time when you or other household members needed dental care but could not afford it? (Yes)*	24.4% (n = 1118)	24.8% (n = 532)	0.4%
Spoiled Food	*In the past* 12 *months how many times did you have to throw away food because your refrigerator was broken or lost power? (Mean)*	0.37 (n = 1101)	0.24 (n = 526)	−0.13
Electrical Medical Equipment	*Do you or does anyone else in your household rely on medical equipment that would stop working if the power goes out? (Yes)*	14.1% (n = 481)	14.0% (n = 1211)	N/A
	Would it be life threatening if your electric medical equipment was unable to be powered for an extended period? (Yes)	55.2% (n = 152)	66.4% (n = 67)	N/A
Refrigerated Prescriptions	*Do you or anyone else in your household take prescription medicines that need to be kept in the refrigerator? (Yes)*	17.4% (n = 579)	15.6% (n = 1257)	N/A
	Would it be life threatening if the medicines were not refrigerated for an extended period because of a power outage? (Yes)	48.1% (n = 81)	44.8% (n = 154)	N/A

✧ Difference is statistically significant at the $p < .1$ level. * Difference is statistically significant at the $p < .05$ level.
** Difference is statistically significant at the $p < .01$ level. *** Difference is statistically significant at the $p < .001$.

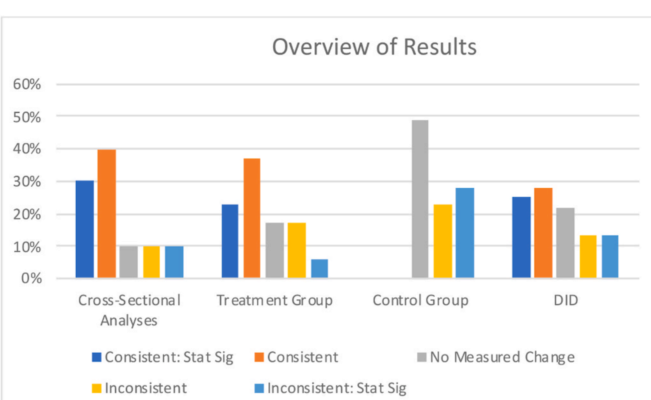

Fig. 1. Overview of results.

This study enrolled more buildings and surveyed more residents than any previous study of MF weatherization. The samples were diverse in race, building function, state, and region. However, a few qualifications need to be offered. Convenience sampling was used to build the sample of MF buildings, instead of random sampling. This limitation, in part, led to there being a regional imbalance between the treatment buildings and control buildings, which were located in the Northeast and Midwest, respectively. There are demographic differences between samples, though secondary regression analyses did not indicate that these variables are highly correlated with health outcomes that could be attributed to weatherization. Though sample sizes were robust, samples sizes for the DID analyses of chronic health issues, such as asthma and COPD, were smaller than desired. Lastly, due to the research design, we are not able to describe longer-term impacts of weatherization on chronic health issues and health risks that may arise from weatherization, such as with respect to chronic heart disease, and radon and lead exposure.

In comparing results from a national evaluation of WAP and evaluations of weatherization programs in the Tennessee Valley in the U.S., it is clear that SF homes come into weatherization programs in worse shape than do MF buildings [40]. For example, SF homes are much draftier and more inflicted with mold and standing water. We hypothesize that MF buildings are in better condition because they are regularly inspected by municipal authorities whereas SF homes are not. It could also be that the MF buildings in our study are in better condition because of the property owners that self-selected into this study, as noted above.

The results reported above may underestimate actual and potential health benefits attributable to residential energy efficiency programs in the affordable MF space. One reason is that, as mentioned, the buildings in our samples were probably in better physical shape than those not in our sample. Our outreach efforts to some property owners were rebuffed – we speculated that they might not want any light shown on the condition of their buildings and on the subsequent health conditions of the occupants.

We also believe that the thermal stress benefits are under-represented. In the best of worlds, weatherization programs replace inefficient or faulty heating systems before they fail and through their failure create a serious risk of cold stress on occupants. We believe that systems are routinely replaced so that the vast majority of residents are not placed in harm's way, especially with the group of property owners represented in our samples. Our resident survey was not designed to capture the benefit of keeping residents safe with the timely replacement of heating systems. Our survey only captured which we believe are outlier events where systems were not replaced in a timely fashion and/or buildings that actually were not healthy for residents prior to weatherization.

The same benefit can be extended to cooling systems. If energy inefficient systems are replaced before they fail, then residents are not at risk of being too hot in their apartments. In many regions within the cold and very cold climate zones, cooling systems are still not common. To the extent that weatherization programs add cooling systems to existing buildings, such as through the installation of air source heat pumps (ASHPs), these programs are currently reducing heat stress risks. As climate change continues to heat up the environment, especially in urban areas that suffer from urban heat island effects, the benefits of new and replacement cooling systems should be anticipated to increase even further.

This study was not able to capture the benefits attributable to ASHPs due to the very small number installed in the study sample. Installation of ASHPs is one path for the electrification of the affordable multifamily sector. However, as electrification makes inroads, then we anticipate health benefits associated with reduced exposure to indoor CO with respect to apartments that have their own space and water heating systems that burn fossil fuels. We also anticipate a reduction in emissions and exposures to nitrogen oxides (NOx) from combustion cook stoves in apartments in larger MF buildings that do not have adequate or any kitchen ventilation.

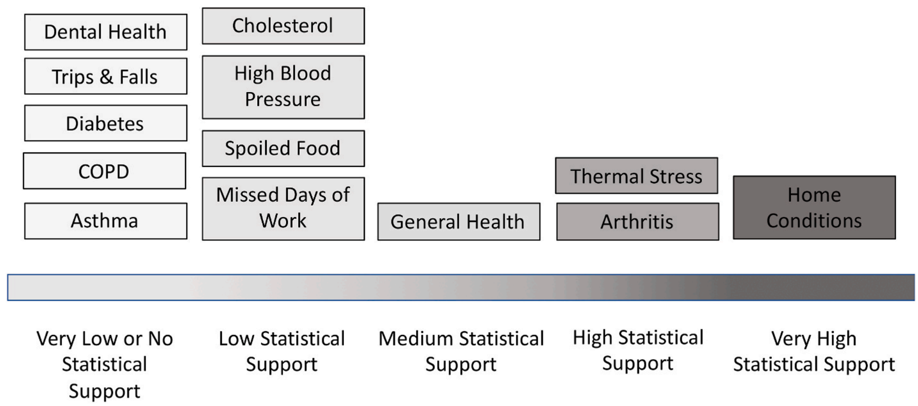

Fig. 2. Assessment of statistical results by variable category.

Lastly, over time the population of the U.S. can be expected to continue to skew older, even with the devastating impacts of COVID-19 on the U.S. population over 65. As such, the health conditions of the typical residents of affordable MF buildings, which are already worse than the average population, will probably worsen. As a result, the health impacts of weatherization could be even more beneficial for this population.

This all said, conventional weatherization cannot be expected to completely remedy chronic health conditions. Though chronic health symptoms and need for medical interventions decreased post-weatherization, they did not disappear. In this light, it is valuable to ask whether weatherization programs could be improved to produce more substantive positive impacts on health. One path that is slowly gaining traction in the U.S. weatherization world is to blend conventional weatherization with 'healthy homes' programs. The latter encompass measures that are not energy conservation measures but can improve respiratory health. For example, asthma flare-ups can be reduced by removing old, dusty carpets and installing air purifiers. Program blending can be cost-effective because work crews only need to visit homes once and economies of scale can be achieved by consolidating administrative functions.

Another path on the near horizon would be to add a third set of measures that improve climate resilience. These measures include cool and green roofs and walls, planting shade trees, and additional ventilation and insulation. These additional measures would further reduce the impacts of heat stress by increasing a building's passive survivability during power outages caused by extreme weather and temperature events, which are forecast to substantially increase in the near future.

The U.S. energy efficiency sector aspires to work with the healthcare sector in the U.S. to co-fund low-income weatherization. It is natural to also desire to have healthcare contribute to installation of healthy homes measures. More and better evidence is needed to support this partnership. Healthcare needs to know with more certainty what the health benefits would be for specific patients that have specific diagnosed health conditions. Healthcare also needs to know more about the cost implications. Along these lines, more research is needed to link weatherization and health databases so that researchers could establish actual healthcare cost reductions for actual patients.

An attractive aspirational model would be to allow physicians to issue prescriptions or 'doctor's orders' to have the homes of their patients weatherized. This model is plausible if their patients live in SF homes that they own. The model is less plausible if their patients rent their homes because property owners would need to give their approval for their homes to be weatherized. This model is also problematic because renters frequently relocate and because housing conditions improved by weatherization could lead property owners to raise rents, thereby increasing moving rates even higher. The model is especially problematic in the MF sector because in many cases it is not possible to weatherize only one unit in MF building. A physician could probably not write a prescription to weatherize a 40-unit affordable MF building.

We believe that the theory of change, research design, and survey instrument can be used in other countries. Care must be taken to generalize these results to international contexts. It is fair to suggest that SF results cannot be generalized to the MF sector holds elsewhere, too. It is tempting to say that our results could be generalized to similar climate zones and MF buildings. However, it is possible, maybe even very likely, that baseline building conditions will be different. It is also very likely that baseline health conditions will be different. Lastly, it is very likely that demographic characteristics will be different, especially with respect to race.

We acknowledge that the overall health benefits found with respect to weatherizing affordable MF buildings is less that we expected and also less than measured from the weatherization of low-income single-family homes. We wish to emphasize that this paper only addresses one category of the potential benefits of weatherizing affordable MF buildings. Weatherization also reduces energy use and emissions of GHG and other pollutants. Families benefit financially from reductions in energy costs and reduction in a number of other expenses. Weatherization programs are labor intensive and typically hire locally, which also yields beneficial economic multipliers. Weatherization can also benefit utilities and ratepayers by reducing costs associated with disconnections and bill payment assistance programs.

8. Conclusion

Weatherization of affordable MF buildings is correlated with the improvement of the health of occupants in our study sample. Respondents reported living in a healthier environment with safer indoor temperatures and improved indoor environments. General health improved, as did specific chronic health conditions, such as arthritis. As expected, there were no demonstrable positive impacts on respiratory conditions, such as asthma. Overall, the health effects were weakly positive. Blending weatherization and healthy homes programs could produce greater health impacts. Additional research is needed to measure the longer-term impacts of weatherization and establish cost reduction benefits to the healthcare sector. Consideration should be given to blending weatherization, healthy homes, and climate resilience programs to jointly address climate change mitigation and adaptation.

CRediT authorship contribution statement

Bruce Tonn: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Beth Hawkins:** Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Erin Rose:** Writing – original draft, Formal analysis, Conceptualization.

Michaela Marincic: Project administration, Formal analysis, Data curation. **Scott Pigg:** Formal analysis, Conceptualization. **Claire Cowan:** Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix 1. Sample of Affordable MF Buildings

Characteristic	Comparison with Treatment	Treatment		Control	
	Post-T	Pre	Post	P1	P2
No. of Households	612	417	198	892	553
Rise***$^{+}$					
Low-rise (<5 stories)	78%	54%	66%	59%	58%
Mid-rise (5–9 stories)	16%	24%	33%	34%	37%
High-rise (10+ stories)	5%	20%	0%	6%	6%
Size (housing units)***$^{+++}$					
5–12 units	22%	30%	41%	14%	12%
13–39 units	30%	21%	20%	22%	20%
40 or more units	48%	49%	39%	64%	69%
Ownership***$^{+++}$					
Apartments, condominiums, and private	42%	27%	33%	45%	44%
Non-profit and public	54%	51%	57%	33%	35%
Unknown	4%	22%	10%	22%	22%
Housing Function***$^{+++}$					
Family	14%	26%	17%	22%	19%
Mixed Use	6%	2%	0%	8%	7%
Senior	56%	12%	17%	30%	27%
Supportive	5%	7%	5%	27%	31%
Unknown	20%	53%	60%	15%	15%
State***$^{+++}$					
Illinois	16%	0%	0%	60%	64%
Wisconsin	11%	8%	6%	5%	5%
Vermont	4%	3%	5%	0%	0%
New York	11%	32%	10%	3%	2%
Rhode Island	11%	31%	47%	8%	7%
Pennsylvania	12%	1%	0%	5%	3%
New Hampshire	2%	5%	7%	0%	0%
Massachusetts	34%	20%	25%	19%	20%
Primary Heating***$^{+++}$					
Boiler	50%	67%	57%	65%	68%
Furnace	14%	9%	10%	17%	16%
Mini Splits	1%	12%	19%	0%	0%
Packaged Thermal Air Conditioner (PTAC)	7%	0%	0%	9%	10%
Air Source Heat Pump (ASHP)	<1%	0%	0%	3%	2%
Electric Baseboard	27%	12%	13%	5%	3%
Electric (Unspecified)	0%	0%	0%	1%	<1%
Other	0%	1%	1%	<1%	<1%
Primary Cooling***$^{+++}$					
Central A/C	13%	2%	1%	25%	27%
Window/Wall Units	60%	70%	69%	51%	49%
Mini Splits	1%	14%	20%	1%	1%
PTAC	11%	0%	0%	23%	23%
ASHP	<1%	0%	0%	0%	0%
Mixed	4.4%	1.4%	0%	0%	0%
None	10%	13%	11%	1%	1%
Other	1%	0%	0%	0%	0%

Phase 1
* Difference is statistically significant at the $p < .05$ level
** Difference is statistically significant at the $p < .01$ level
*** Difference is statistically significant at the $p < .001$

Phase 2
$^{+}$ Difference is statistically significant at the $p<.05$ level
$^{++}$ Difference is statistically significant at the $p<.01$ level
$^{+++}$ Difference is statistically significant at the $p<.001$ level

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