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Health and financial benefits of weatherizing low-income homes in the southeastern United States

Bruce Tonn *, Erin Rose, Beth Hawkins, Michaela Marincic

Three [3], Inc., 520 W. Summit Hill Drive, Suite 1101, Knoxville, TN, 37902, USA

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ABSTRACT

The purpose of this research is to estimate the non-energy impacts that could be attributed to weatherizing low-income homes in Knoxville, Tennessee, USA. Commonly installed weatherization measures include insulation, air sealing, and heating system replacement. A hybrid quasi-experimental, cross-sectional research design was implemented. Under this design three samples of households were recruited for the project: Comparison homes that had been weatherized one-year previously; Treatment homes that were in the queue to be weatherized; and Control homes that were not going to be weatherized during the course of the project. Control homes were drawn from a lengthy waiting list. Homes were surveyed twice. The first phase occurred during four-month period when Treatment homes came up for weatherization. Comparison and Control homes were also surveyed during this four-month period. The second phase entailed surveying all households approximately one-year later. The phone survey contained questions about home conditions, health of occupants, and household finances. The cross-sectional analyses were much stronger, from a statistical significant viewpoint, than the quasi-experimental design approach because sample sizes were larger for the former and the latter was plagued by inexplicably large changes reported by the Control group. Post-weatherization homes were less likely to be kept at unhealthy temperatures, were less drafty and dusty, and had reduced levels of mold and intrusion of outdoor noise and odors. Respondents reported fewer bad days of physical and mental health. Households were better able to pay their energy bills and afford prescriptions.

1. Introduction

This paper addresses the non-energy impacts that improving the energy efficiency of homes can have on home conditions, human health, and household finances. Specifically, it evaluates the non-energy impacts that can be attributable to weatherizing low-income, single-family, electrically heated homes located a major city in the Southeastern United States. Weatherization programs install comprehensive sets of energy efficiency measures in homes that can substantially change their physical condition. Though these measures are largely designed to save energy, they can also directly impact health and improve indoor environments. Energy efficiency can also reduce consumption of fossil fuels, which can then reduce emissions of greenhouse gases and other air pollutants. As such, weatherization programs sit at the nexus of several important policy sectors: energy efficiency, health care, public health, climate change, environmental protection, and poverty reduction.

To demonstrate the link between weatherization and home and household non-energy impacts, this paper focuses on research conducted on a low-income weatherization program that was run in Knoxville, Tennessee, USA.[1] Knoxville is situated in the Southern Appalachian Mountains and has a moderate climate.[2] The weatherization program under study is called Knoxville Extreme Energy Makeover (KEEM). Details of this initiative and why studying this program contributes to our knowledge base on this topic are discussed in Section 5, which follows a short overview of weatherization in Section 2, a presentation of our theory of change in Section 3, and a brief discussion of how weatherization can reduce fuel poverty in Section 4. Section 6 presents our research approach, which features a hybrid quasi-experimental, cross-sectional design. The research results are presented in Section 7. Section 8 provides reflections on the results of this

* Corresponding author.
E-mail address: btonn@threecubed.org (B. Tonn).

[1] Coordinates: 35.9617°N 83.9232°W https://knoxvilletn.gov.

[2] Technically referred to as a mixed-humid climate as defined by the U.S. Department of Energy, which has on average 5,400 heating degree days https://www.energy.gov/eere/buildings/climate-zones.

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research, compares the results to similar research conducted in other regions of the country, and discusses the policy implications of this research.

2. What is weatherization?

In the U.S., the term *weatherization* is used to describe comprehensive energy retrofits to the homes of income eligible households and affordable multifamily buildings. To fall within this rubric, weatherization programs must install energy conservation measures that include: wall and ceiling insulation; air sealing around windows and doors; heating, ventilation, air conditioning (HVAC) repair and replacement; and door and window repair and replacement. Depending on their estimated ability to cost effectively save energy, many other measures can also be installed, such as lighting, water heater wraps, new refrigerators, and duct sealing. We also include in our definition weatherization programs that include non-energy-related health and safety measures, such as smoke detectors, carbon monoxide (CO) monitors, and minor repairs to roofs and electrical systems [1].[3] We do not consider programs that only focus on reducing secondary electricity loads (e.g., light bulb replacement programs) to be weatherization programs. Income eligibility is defined by a household's annual income in relationship either to the U.S. federal poverty level or to state median income.[4]

The weatherization process is straightforward. First, home energy audits are conducted by trained and certified energy auditors. The auditors determine which energy conservation and health and safety measures should be installed in homes. Every energy conservation measure needs to pass a cost-effectiveness test where the estimated energy cost savings over the lifetime of the measure must exceed the cost of the measure. Future energy price forecasts are used to estimate the numerator of this ratio, which is sometimes referred to as the Savings to Investment Ratio (SIR). Weatherization crews receive work orders from the auditors and then proceed to install the requisite measures. Quality inspectors visit homes post-weatherization to ensure that measures have been installed properly and that the flu gases from combustion appliances properly flow out of homes.[5]

The vast majority of weatherization programs in the U.S. fall into one of two categories. The first category of programs is funded by the U.S. federal government through the Weatherization Assistance Program (WAP), which is administered by the U.S. Department of Energy.[6] WAP provides grants to states, which then provide grants to local non-profit weatherization organizations to offer free weatherization services to income-qualified households. Most agencies directly employ their own energy auditors, weatherization crews, and quality inspectors, though many will instead hire outside contractors to install weatherization measures.[7]

In addition to paying for the energy conservation measures, WAP allows agencies to use up to 15% of funds to be spent on health and safety measures. WAP's annual funding appropriation from Congress varies considerably over time, though typically allows WAP to fund between thirty and one hundred thousand weatherization jobs per year.[8]

Electricity and natural gas utility companies offer the second category of programs. The reimbursement of costs to investor owned utilities for their weatherization programs from customer revenues are approved by their regulatory bodies (i.e., the public utility commissions). Utility-based weatherization programs might vary from WAP in the average amount of money that can be spent per weatherization job, and what funds can be invested in health and safety measures. Utilities can and do hire local agencies to implement their weatherization programs, though they just as often hire outside commercial contractors to implement their programs.

3. Impact of weatherization

Fig. 1 presents our theory of change and explains how weatherization can positively influence home conditions, health, and household finances. The model begins with physical changes to homes through the installation of energy efficiency measures. These measures have significant lifetimes: a decade or more for a new furnace and over twenty years for insulation, for example. The installation of these energy efficiency measures results in energy cost savings to households.[9] In addition, measures installed to reduce water heating energy demand by reducing water consumption (e.g., low-flow showerheads and facets) can also reduce water costs. When these cost savings allow households to better pay their utility bills on time and in full, they may also face fewer costs associated with arrearages and utility disconnections.

Weatherization can directly impact human health. For example, weatherization can improve indoor environmental quality [5–8]. More specifically, air sealing, insulation, and cleaning of furnace and dryer filters can prevent allergens from entering the home environment and more effectively filter allergens from the air [9–12]. Air sealing can also keep insects and other pests from entering homes. Insulation, air sealing and furnace replacement can also make homes more resilient to extreme weather events, which, in turn, can reduce thermal stresses experienced by occupants [13–16]. Burns to occupants can be reduced by reducing water heater temperatures, done ostensibly to reduce the amount of energy needed to heat water [17]. Furnace replacement and minor home repairs to electrical wiring and equipment can reduce home fires [18]. Installation of CO monitors can reduce CO poisoning events [18]. In every one of these cases, improved health can lead to reductions in medical costs, including visits to doctors' offices and emergency departments and hospitalizations [18].

Improved household financial situations can indirectly improve health by reducing psychosocial stressors, exemplified by reduced bad days of rest and sleep and fewer households having to trade off buying food or prescriptions to pay energy bills [18]. Improved health of households' primary wage earners and dependents can result in fewer missed days of work [18]. This is vitally important because almost three-quarters of lower-wage workers in the U.S. do not enjoy the benefits of paid sick days.[10] Improved financial situations could also allow households to avoid costly short-term predatory loans (e.g., payday loans, pawnshop transactions) [18].

It is argued here that these benefits are most achievable through comprehensive weatherization programs. For example, it takes a combination of measures to reduce asthma triggers, not simply the cleaning of furnace filters. Similarly, it takes several measures to improve home

[3] It must be noted that weatherization programs are not comprehensive home renovation programs. Weatherization programs will defer weatherization work if a home's physical condition is too poor to justify energy efficiency investments (e.g., roof needs major repairs) or conditions in the home might endanger weatherization workers (e.g., large amounts of mold) [2].

[4] The thresholds are typically 200% of the federal poverty level or 60% of state median income, but these thresholds are subject to change.

[5] Because weatherization programs always prioritize the safe venting of combustion gases from homes, we consider CO reduction a permanent and valuable non-energy benefit of these programs.

[6] https://www.energy.gov/eere/wap/weatherization-assistance-program.

[7] This report provides case studies of exemplary local weatherization programs and plenty of images of the types of homes weatherized and how measures are installed [3].

[8] This reason for the variation in funding is that WAP a subject of partisan politics in the United States.

[9] A summary of recent evaluations of WAP contain estimates for both energy costs savings and energy savings for single-family homes, mobile homes, and multifamily buildings that heat with a variety of fuels and are located across the U.S. can be found in Ref. [4].

[10] https://www.americanprogress.org/issues/economy/news/2012/08/16/12031/fact-sheet-paid-sick-days/.

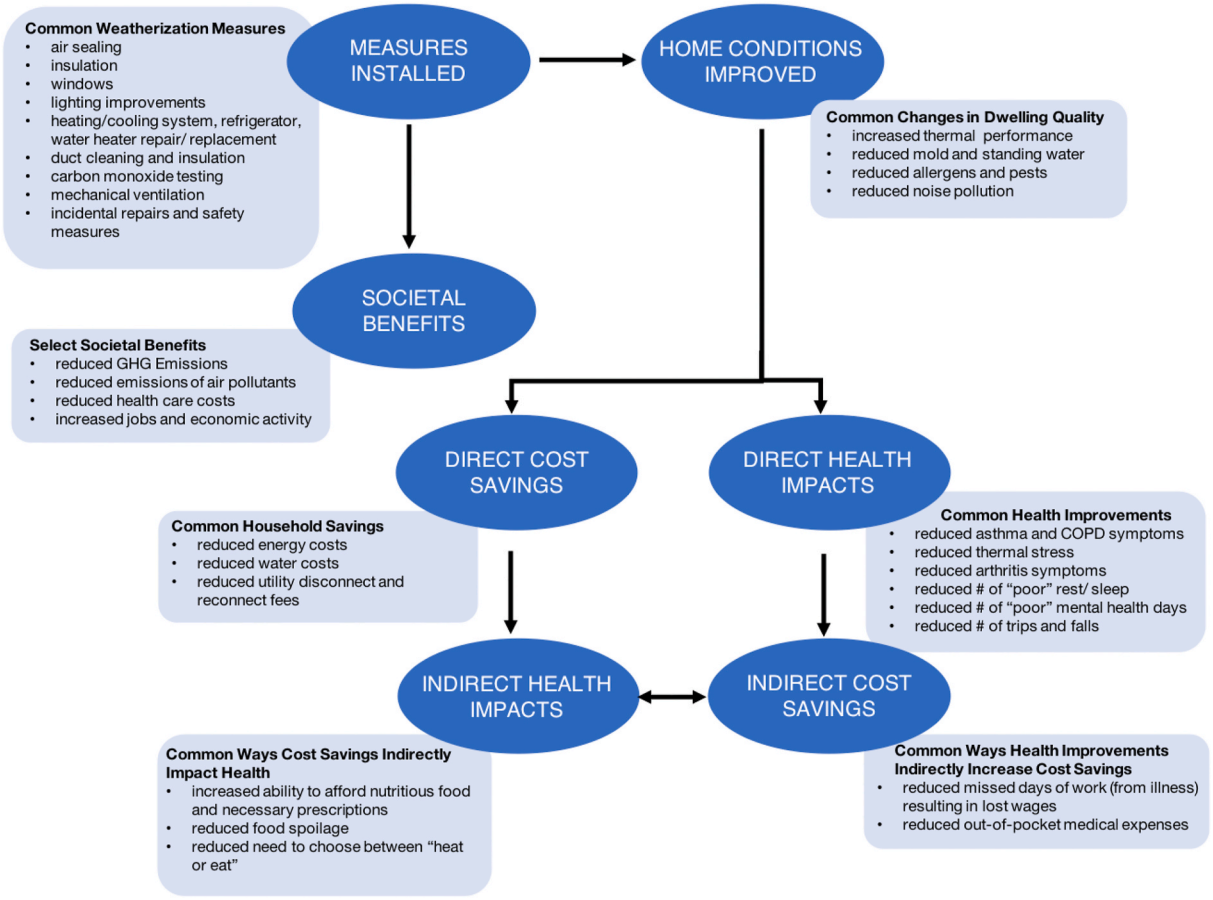

Fig. 1. How weatherization can produce non-energy benefits.

comfort and reduce dangerous incidents of thermal stress. Reduction in fire risk can be seen as an accumulation of risk reductions through furnace replacement, insulation, and minor electrical repairs [40]. It is only the rare case where a single measure can be mapped directly to a health benefit, such as the linkage of CO monitors to reduced CO poisoning.

4. The importance of evaluating the non-energy impacts of weatherization

4.1. Weatherization program administrator perspective

It is good practice to evaluate all of the outcomes of energy efficiency programs, not just the intended energy demand reduction outcomes. At the federal level, a fuller appreciation of the non-energy impacts could shore up support for Congressional funding and support collaborative interagency initiatives, for example between housing, indoor air quality, and residential energy efficiency programs. With respect to utilities, demonstrating the non-energy impacts of weatherization programs can help them meet their social contract as regulated utilities. Monetary estimates of the values of non-energy can be incorporated into rate cases to support using customer revenues for these programs. This is becoming particularly important in the U.S. because the success that utilities have had in installing LED lights in homes has left them with fewer cost effective measures to install in low-income homes [19].

4.2. Poverty reduction

Comprehensive energy retrofit programs targeting homes of low-income households are implemented across the Global North and can be found in the Global South where countries aim to reduce fuel poverty and mitigate climate change through improved energy efficiency and improve housing conditions [20–22]. In the U.S., weatherization programs are primarily driven by social equity concerns. As an example, the legislatively stated goal of WAP is to improve the ability of low-income households to afford their energy bills, which can be accomplished by making their homes more energy efficient.[11] Weatherization programs reduce an aspect of poverty that is commonly referred to as fuel poverty. This term broadly describes situations where households are unable to afford reasonable energy services (e.g., to afford to heat their homes to safe levels, to have sufficient lighting) and/or are unable to obtain clean, safe, and reliable sources of energy. Fuel poverty is a serious issue in the United States [23,24] and internationally [25–29]. This issue is exacerbated by poor housing conditions [30–32]. As this paper demonstrates, weatherization programs can directly improve adult health, and reduce material hardship, which can be defined to include utility cutoffs, housing hardship, and food insecurity [33–35].

The administration of weatherization programs in the U.S., however, is more narrowly conceptualized to view fuel poverty in terms of energy

[11] The U.S. Department of Energy's (DOE) Weatherization Assistance Program was created by Congress in 1976 under Title IV of the Energy Conservation and Production Act. The purpose and scope of the Program as currently stated in the Code of Federal Regulations (CFR) 10CRF 440.1 is "to increase the energy efficiency of dwellings owned or occupied by low-income persons, reduce their total residential energy expenditures, and improve their health and safety, especially low-income persons who are particularly vulnerable such as the elderly, persons with disabilities, families with children, high residential energy users, and households with high energy burden." (Code of Federal Regulations, 2011).

burden, which is defined as household energy expenditures as a percentage of annual household income. An energy burden of 10% or more is a commonly used threshold to determine whether a household lives in energy poverty [36]. A recent report from the U.S. Department of Energy's Energy Information Administration estimates that one-third of American households face substantial energy burdens based on energy expenditures as a percent of household income [37].

4.3. Weatherization and its relationship to health care

The major foci of this research are the health, housing condition, and household financial benefits of weatherization. We believe that the latter two concepts fall under the rubric of social determinants of health. This is a concept that has arisen recently in the literature and has been taken up by healthcare and public health sectors[12] in the U.S., due in part to the realization individuals' life expectancy varies tremendously simply based upon the neighborhood where they live [38]. This insight led to the conclusion that social and economic conditions can significantly impact health [39]. The Healthy People Program of the U.S. Department of Health and Human Services defines social determinants of health as "conditions in the environments in which people are born, live, learn, work, play, worship, and age that affect a wide range of health, functioning, and quality-of-life outcomes and risks."[13]

Demonstrating the links between weatherization and social determinants is critical for several reasons. Research on the social determinants impacts of weatherization is vital to broadening the perspectives of program administrators beyond energy burden to poverty writ large. Another important reason for demonstrating the link between weatherization and health in the U.S. context is that healthcare's financial resources dwarf those available to energy efficiency programs in general and low-income weatherization programs in particular. In the U.S., low-income weatherization is severely underfunded and waiting lists for weatherization are long [40]. It may take a year or more to get one's home weatherized. If it can be further demonstrated that healthcare costs could be reduced through investments in weatherization, then it could be a win-win policy solution for the energy efficiency and healthcare sectors. Even without financial contributions from healthcare, it is important to fully describe and document the positive non-energy impacts of weatherization programs to build and maintain support for programs funded by and administered by utility companies [41–43], as well as by state energy and federal energy programs.

5. Knoxville Extreme Energy Makeover (KEEM) project

5.1. KEEM

KEEM was a comprehensive weatherization program run in Knoxville, Tennessee between 2015 and 2017. Funding was provided by the Tennessee Valley Authority (TVA), which is a quasi-federal organization and is the largest electric power distributor in the U.S.[14] Because KEEM was funded by an electric utility, only homes that heat with electricity were recruited for weatherization.[15] Additionally, the homes were required to be owner-occupied, single-family homes. Close to 1300 homes were weatherized. The program was implemented by the non-profit Knoxville-Knox County Community Action Committee (CAC).[16]

KEEM had a specific energy savings goal per home, to reduce electricity consumption by at least 25%. Table 1 indicates the percentages of homes that received the most commonly installed measures as part of KEEM, with the most frequently installed measures being HVAC repair and replacement, and duct repair. An analysis of electricity bills collected one-year before and one-year after weatherization conducted by TVA estimated that annual electricity consumption in our sample weatherized homes was 16,112 kWh pre-weatherization and 12,245 kWh post-weatherization. The gross annual savings were estimated to be 3867 kWh and the net savings as 3236 kWh. Based on the gross savings estimate, electricity consumption in our sample homes was reduced by 24%.[17] In comparison, a rigorous evaluation of the energy savings attributable to WAP found that natural gas consumption was reduced about 19% in single-family homes that heat with natural gas [44].[18]

5.2. Contribution of this research to our knowledge of the non-energy impacts of weatherization

Rigorous evaluations of WAP were conducted between 2009 and 2015 [45,46]. In addition to estimating energy savings, the evaluations also conducted the first comprehensive evaluation of the home condition, health, and household finance impacts of a major U.S. weatherization program [18]. Since that time period, the WAP program has not significantly changed. Similar measures are installed guided by the same savings-to-investment ratio cost-effectiveness test. Given this situation, we believe it is reasonable and important to compare and contrast the WAP evaluation and the research reported herein.

The second column of Table 1 indicates the frequency that WAP installed that same set of weatherization measures across the U.S. during program year 2010 [47]. It is immediately clear that building fabric (also referred to as shell) measures (e.g., air sealing and insulation) were installed much more frequently by WAP and equipment measures were installed much more frequently by KEEM. Even though both WAP and KEEM are weatherization programs, they were administered quite differently. Thus, analysis of KEEM data could provide insights into the differential impacts of fabric versus equipment measures on home conditions and general health post-weatherization. For example, we hypothesize that the lower level of air sealing measures installed by KEEM will yield fewer impacts on chronic respiratory diseases such as asthma as compared to WAP.

Another major difference is that KEEM represents a program implemented in a moderate climate zone in the southeastern U.S. whereas the WAP evaluation encompassed homes weatherized across

Table 1
Measures installed by KEEM and WAP.

Measure	KEEM	WAP PY 2010
Air sealing	25%	89%
Attic Insulation	47%	65%
Wall Insulation	20%	24%
Duct Repair	59%	36%
Water Heater Replacement	30%	14%
Lighting Replacement	30%	n/a
HVAC Repair or Replace	79%	30%

[12] In the U.S., public health agencies work with their communities to improve general health and prevent the spread of disease. The healthcare sector is responsible for providing medical services to individuals on an as needed basis..

[13] https://www.healthypeople.gov/2020/topics-objectives/topic/social-determinants-of-health.

[14] https://www.tva.com.

[15] About two-thirds of homes in Knoxville heat with electricity, which enabled successful recruitment of participants for the program.

[16] http://www.knoxcac.org/newweb/.

[17] We note that the electricity savings estimates were not conducted by our research team. The energy savings estimates were based on weather normalized billing histories.

[18] The rebound effect was not estimated with respect to KEEM or WAP energy savings estimates. One can speculate that the reround effect would be small, at most, for low-income households. Any rebound with respect to heating or cooling would benefit occupant health.

the country, with a caveat. The sample of WAP homes surveyed was dominated by homes in the cold and very cold climates because that is where the substantial majority of funds were expended due to a Congressionally mandated funding allocation algorithm. Thus, this study offers the opportunity to compare weatherization impacts between a moderate climate zone and very cold and cold climate zones.

The household demographics were also different [48]. The KEEM household sizes were smaller – 2.11 persons per household in the KEEM program versus 2.38 in WAP and more racially diverse – 28% identified as Black in KEEM versus 18% for WAP. KEEM served an urban population whereas WAP covers rural areas as well. KEEM homes were in worse condition with respect to draftiness, infestations of insects and mice, and mold and mildew [48]. KEEM respondents reported worse health pre-weatherization with respect to bad days of physical and mental health and rest/sleep. This study aims to provide insights into whether the magnitude of changes in home conditions, health and household finances brought by weatherization could be greater for households experiencing worse baseline conditions.

The last point to be made in this section is that the national WAP evaluation results are not as useful to utilities and their regulators as are results from comparable local and regional research. They are reluctant to use national WAP evaluation results because they do not adequately represent their regions with respect to climate, program design, demographics, and housing. Thus, utilities such as TVA are much more apt to use the findings from a smaller study, such as KEEM, that is conducted in a similar climate zone than the national WAP evaluation results.

6. Research methods

A hybrid quasi-experimental, cross-sectional design was developed to estimate the non-energy impacts of KEEM. The treatment group sample frame consisted of all homes weatherized by KEEM between April and September 2017 (referred to herein as the Treatment group). The control group sample frame consisted of over 1,600 homes on CAC's wait list during that time period (referred to as the Control group). Drawing the Control group sample from the waiting list is appropriate because these households applied for KEEM in response to the same recruitment processes that yielded the treatment group, and also self-selected to have their homes weatherized. We also created a comparison group sample frame of homes previously weatherized between April and September 2016 (referred to as the Comparison group). Our sample size targets were: Treatment = 120, Control = 190, and Comparison = 150.

Data were collected for a comparison group for several reasons. First, comparison homes were readily identifiable and contactable. Second, treatment and control households could have had high moving rates and a reluctance to participate in surveys. Thus, collecting comparison group data would allow a cross-sectional assessment if required. Third, collecting data on comparison homes is a straightforward way to provide some preliminary results to stakeholders while also shepherding the quasi-experimental design through its post-intervention phase. Fourth, one can anticipate that sponsors, such as utility companies, may not have the financial resources to devote to large scale quasi-experimental design research projects, which makes smaller scale and less expensive cross-sectional studies more attractive. This approach provides insights into potential trade-offs between cross-sectional and quasi-experimental design studies in this area.

A fifth reason is that having a sizable N for the comparison group sample and a sizable N for a pooled sample of treatment and control homes pre-weatherization can help to overcome deficient sample sizes with respect to specific variables that may flow out of the quasi-experimental design. A sixth reason is that it was unknown how stable the control group results would be in different years. Indeed, as reported below, Control group results frequently changed.

Finally, if it is possible to collect comparison group data twice, at the beginning of the project and again when data are collected post-intervention, one might be able to begin to understand how non-energy impacts might change two years after weatherization, and, further, to understand how persistent these benefits are. The theory of change framework presented above posits a potentially strong positive feedback loop between improvements in health and household finances. An important hypothesis to begin to test is whether this feedback loop extends beyond one-year post-weatherization.

To recruit households to participate in the study, introductory calls were made to prospective households from CAC's premises using CAC's phones and phone numbers, essential to providing an introduction which would increase response rates while no personally identifiable information (PII) left CAC premises without the consent of the prospective participants. During the introductory calls, the goals of the project were explained and the potential respondents were asked if they were willing to participate in a phone survey and if they consented to allowing CAC to provide their contact information to the Center for Applied Research and Evaluation, University of Tennessee, Knoxville to conduct the phone survey.

As noted, all homes weatherized between April and September 2017 were contacted. Specifically, they were surveyed after the energy audits were complete, to ensure that the homes would not be deferred for weatherization, but before the weatherization work had begun. Control homes were selected from the top to towards the bottom of the waiting list under the assumption that those at the top were most likely to be most like the homes in our Treatment and Comparison group samples. Comparison homes were also randomly selected from those previously weatherized during the period April and September 2016 using a function in Excel. Approximately 90% of households we contacted agreed to participate in the survey. Here are the sample sizes after the first survey effort: Treatment = 99; Control = 152; and Comparison = 197. In total, approximately 23% of homes weatherized by KEEM were included in this project.

The follow-up survey of all three samples began in August 2018, over a year after the first survey. A time period of a year allows for the passage of all the seasons, which is important for many non-energy impacts related to home conditions, health, and household budgets. Most of the homes were surveyed during the same month they were surveyed in phase 1, plus or minus one month. The bulk of the follow-up surveys were completed by October 2018. A local community organization was engaged to contact in-person non-responsive Treatment homes. The number of households that completed the post-weatherization survey are: Treatment = 79, Control = 100, and Comparison = 141, for follow-up response rates of 80%, 66%, and 72%, respectively. Also, as shown in Table 2, the demographic make-up of each sample group did not change substantially from year 1–2.

The phone survey took about 30 min to complete and respondents

Table 2
Demographics.

Variable/Group (N=Pre/Post; Year 1/ Year 2)	Comparison (N = 197/141)	Treatment (N = 99/79)	Control (N = 152/100)
Respondent Gender: Female %	73/75	76/77	79/79
Respondent Age: Years (Average)	62/60	54/56	56/59
Average Household Size	2.03/2.04	2.04/2.08	2.16/2.11
Black or African American %	45/47	29/34	27/25
Employed %	35/33	34/35	37/35
Full-Time %	75/78	71/70	74/69
Retired %	31/33	20/23	26/31
Unable to Work %	26/28	31/34	29/31
Respondent Married %	20/17	25/24	26/31
Respondent Education: GED or Less %	50/51	42/39	58/57
Have Health Insurance %	96/93	87/89	92/95

were provided a $20 gift card as an incentive. The survey asked questions about respondent's perceptions of home conditions, general health and specific health conditions, and household budget issues. The KEEM survey questions were the same ones used in the WAP national occupant survey in order to facilitate comparisons between the results of the two studies [40].

7. Results

The results are presented in five subsections, beginning with demographic descriptive statistics. Section 7.2 presents the results emerging from the quasi-experimental design whereas the results from the cross-sectional research design are presented in Section 7.3. Then, in Section 7.4, the possible persistence of non-energy impacts is assessed, and the Comparison one-year post weatherization results are compared to the Treatment one-year post weatherization results. A summary of the results is presented in Section 7.5.

7.1. Demographics

Table 2 describes the demographics of our three samples. The majority of the main respondents were female and middle to older age. Because of this older demographic, household sizes were small, just over two occupants on average. This compares to an average household size of 2.53 nationally.[19] Only a third of household reported their primary wage earners as being employed at all, with only a quarter reporting that their primary wage earners were employed full-time. Over one-half of households report being retired or unable to work. The samples are racially diverse, in part because program recruitment focused on the most economically disadvantaged neighborhoods in Knoxville with high Black poverty rates.[20] No households in our samples reported being of Hispanic descent.

7.2. Quasi-experimental design results

The results from the quasi-experimental design are presented in Tables 3–5. As noted above, the survey was administered twice to all three samples at approximately the same times of the year. We refer to the phase one survey results of the Treatment group as Treatment-Pre (i.e., for pre-weatherization). The phase two survey results of the Treatment group are referred to as Treatment-post. The phase one survey of the Control group is referred to as Control Year 1 (i.e., survey administered during the first year of the project) and the phase two survey as Control Year 2. The phase one survey of the Comparison group is referred to as Comparison One-Year-Post (i.e., surveyed one year after being weatherized) and the phase two survey as Comparison Two-Years-Post. DIFF refers to the difference between the results two designated columns, as indicated in the legend for each table. DID refers to the difference in the Treatment group results minus the difference in the Control group results.

Table 3 presents survey results related to eight different household conditions for the Treatment and Control groups. To begin, it should be noted that the baseline results suggest that the Treatment and Control samples exhibit poor baseline conditions in many respects. About half of these households reported keeping their homes at unsafe temperatures the previous year. The vast majority report that their homes were too drafty and dusty. Respondents also reported high levels of intrusion of outdoor noise inside their homes and observations of mold.

The impacts of weatherization on home conditions are reviewed in three different manners. First, the differences reported only by the treatment homes pre-to post-weatherization are examined. Home conditions improved with respect to five of eight home condition variables, with reductions in draftiness, dustiness, mold, and keeping homes at unsafe temperatures being highly statistically significant. These results lay a strong groundwork for supporting the theory of change presented above that weatherization can lead to improvements in health and household finances.

Second, the Control Year 1 and Year 2 results are presented. The a priori expectation that the values for the eight home condition variables would not change a statistically significant amount from one year to the next was not met. The Control homes reported experiencing major and statistically significant improvements with respect to outdoor noise, keeping homes at unhealthy temperatures, and mice infestations. Improvements were also reported with respect to dustiness and draftiness.

Third, the Treatment group results pre- and post-are then compared to the differences between Year 1 and Year 2 reported by the Control group. Controlling for changes in the Control group, only three of eight changes in housing conditions met our standard for statistical significance, draftiness, mold, and unhealthy temperatures.[21] We believe that the changes in the Control group do obscure real and positive gains that can be attributed to weatherization with respect to dustiness and outdoor noise, which is supported by results presented in Sections 7.3 and 7.4.

The next question addressed is whether these mostly positive changes in home conditions correlate with changes in general health. Table 4 presents three variables that measure aspects of general health and pertain to physical health, mental health, and rest and sleep. We would expect that respondents would experience fewer bad days with respect to each of the components of general health. The results support this. Those living in the treatment homes report significant reductions in bad days of physical and mental health and rest and sleep. These results were less robust when changes reported by the Control group were factored in, though still notable with respect to physical and mental health.

The next five variables contained in Table 4 reflect self-reports with respect to specific health issues. As hypothesized above, the Treatment group results indicate that KEEM did not have a positive impact upon medical attention needed for the two respiratory conditions, asthma and COPD. Included under the rubric of medical attention are visits to doctor's offices, visits to emergency departments, and hospitalizations. The results were also null for thermal stress medical attention for being too cold or too hot in one's home. The only statistically significant change reported by the Treatment group is for a reduction in new or more frequent headaches. The Control group results did not change appreciably from Year 1 to Year 2 for most variables. No DID results were statistically significant for these five health variables.

Table 5 presents survey results for nine household finance related variables. As with home conditions, baseline household financial situations are very troublesome. Almost three-fourths of the treatment homes found it hard to pay their energy bills, almost one-half received disconnection notices and a quarter had their electricity disconnected. Substantial numbers of households had to trade-off buying food to pay for utility bills and could not afford prescriptions. Almost 20% had to take out short-term, high interest loans to make ends meet (e.g., payday loans, pawn shops). While the number of treatment households reporting it hard to pay their energy bills dropped quite significantly post-weatherization, the number is still above 50%. One conclusion is that weatherization helps but it cannot completely solve low-income households' financial burdens.

Indeed, the results presented in Table 5 suggest that the impacts on household budgets of weatherization are not as strong as the impacts on home conditions. With respect to the Treatment group, the only highly

[19] https://www.statista.com/statistics/183648/average-size-of-households-in-the-us/.

[20] In 2017, pre-COVID 19, the Black poverty rate in Knoxville exceeded 40% https://www.welfareinfo.org/poverty-rate/tennessee/knoxville.

[21] We are using a $p \leq 0.1$ as our threshold for statistical significance. However, we have chosen to report all p-levels to be as transparent as possible.

Table 3
Quasi-experimental design analysis: Home conditions impacts (N).

Variable	Treatment		DIFF1	Sig.[a]	Control		DIFF2	Sig.[a]	DID	Sig.[b]
	Pre	Post			Y1	Y2				
How often home too drafty? (all to some of the time)	86% (79)	44% (78)	−42%	.000	77% (99)	68% (98)	−9%	.186	−33%	.000
How often home too dusty? (all to some of the time)	91% (79)	77% (79)	−14%	.013	92% (97)	86% (99)	−6%	.180	−8%	.322
How infested is home with mice? (extremely to somewhat)	9% (79)	9% (79)	0%	1.00	7% (99)	15% (98)	+8%	.057	−8%	.305
How infested is home with cockroaches, other insects, and spiders? (extremely to somewhat)	9% (79)	15% (79)	+6%	.227	18% (97)	21% (99)	+3%	.648	+3%	.434
Have seen mold in home? (yes)	42% (79)	25% (79)	−17%	.031	34% (100)	38% (100)	+4%	.523	−21%	.004
Outdoor noise when windows closed (a great deal to some)	70% (79)	58% (79)	−12%	.078	73% (100)	54% (100)	−19%	.001	+7%	.606
Kept home at unhealthy temperatures (yes)	55% (79)	14% (78)	−41%	.000	42% (100)	27% (100)	−15%	.004	−26%	.004
Odor from outdoors (great deal to some)	14% (79)	13% (79)	−1%	1.00	22% (100)	17% (100)	−5%	.405	+4%	.730

Legend: DIFF1 = T-pre minus T-Post; Sig. = p value statistical significance; DIFF2 = Control Year 2 minus Control Year 1; DID = (T-pre minus T-post) minus (C-pre minus C-post).

[a] Non-parametric 2-related samples McNemar Test or T-test.

[b] Pearson Chi-square test between (pre-treatment – post-treatment) and (pre-control – post-control).

Table 4
Quasi-experimental design analysis: Health impacts (N).

Variable	Treatment		DIFF1	Sig.[a]	Control		DIFF2	Sig.[a]	DID	Sig.[b]
	Pre	Post			Y1	Y2				
Thinking about physical health, which includes physical illness and injury, for how many days during the past 30 days was your physical health not good?	12.7 (76)	7.8 (79)	−4.9	.003	9.8 (95)	9.3 (97)	−0.5	.271	−4.4	.091
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?	10.6 (77)	6.4 (78)	−4.2	.025	7.9 (94)	7.7 (98)	−0.2	.910	−4.0	.079
During the past 30 days, for about how many days have you felt you did not get enough rest or sleep?	15.0 (78)	12.3 (78)	−2.7	.060	13.7 (98)	11.5 (100)	−2.2	.068	-.5	.686
Medical attention needed last year for asthma? (% yes)[c]	9% (11)	25% (8)	+16%	1.00	39% (13)	22% (9)	−17%	.625	+33%	.193
Medical attention needed past year for being too cold in home (% yes)	5% (79)	2.5% (79)	−2.5%	.687	6% (99)	1% (100)	−5%	.063	+2.5%	.281
Medical attention needed past year for being too hot in home (% yes)	1.3% (79)	1.3% (79)	0%	1.00	1% (100)	0% (100)	−1%	1.00	[b]1%	.521
In last three months, headaches that are either new or more frequent or severe than ones you have had before? (% yes)	36% (77)	16% (79)	−20%	.005	31% (100)	25% (99)	−6%	.458	−19%	.161
Medical attention needed past year for COPD, chronic bronchitis, or emphysema?[c]	67% (15)	62% (13)	−5%	1.00	65% (39)	67% (21)	+2%	1.00	−7%	.260

Legend: Diff = T-pre minus T-Post; Sig. = p value statistical significance; DIFF2 = Control Year 2 minus Control Year 1; DID = (T-pre minus T-post) minus (C-pre minus C-post).

[a] Non-parametric 2-related samples McNemar Test or T-test.

[b] Pearson Chi-square test between (pre-treatment – post-treatment) and (pre-control – post-control).

[c] Only included households whose main respondents reported having this chronic disease.

Table 5
Quasi-experimental design analysis: Household finance impacts.

Variable	Treatment		DIFF1	Sig.[b]	Control		DIFF2	Sig.[b]	DID	Sig.[a]
	Pre	Post			Y1	Y2				
Hard to Pay Energy Bills (yes)	73% (79)	51% (78)	−22%	.000	62% (99)	64% (99)	+2%	.850	−24%	.010
Did Not Buy Food to Pay Utility Bills (yes)	37% (79)	29% (76)	−8%	.263	46% (100)	40% (100)	−6%	.361	−2%	.814
Did Not Pay Energy Bills to Buy Food (yes)	19% (79)	18% (79)	−1%	1.00	22% (100)	19% (100)	−3%	.664	+2%	.731
Food Assistance (yes)	54% (69)	56% (70)	+2%	1.00	50% (97)	39% (91)	−11%	.021	+13%	.154
Short-term loans (yes)	17% (79)	19% (79)	+2%	.544	25% (100)	20% (100)	−5%	.405	+7%	.525
Could not afford prescriptions (yes)	43% (79)	32% (79)	−11%	.093	41% (100)	33% (100)	−8%	.170	−3%	.855
Received disconnection notice (yes)	47% (79)	39% (79)	−8%	.210	54% (100)	43% (100)	−11%	.013	+3%	.562
Electricity disconnected (yes)	27% (37)	27% (31)	0%	1.00	23% (54)	30% (43)	+7%	.581	−7%	.642
Missed Days of Work[c]	4.7 (19)	6.4 (19)	+1.7	.329	3.2 (23)	3.9 (23)	+0.7	.189	+1.0	.625

Legend: Diff = T-pre minus T-Post; Sig. = p value statistical significance; DIFF2 = Control Year 2 minus Control Year 1; DID = (T-pre minus T-post) minus (C-pre minus C-post).

[a] Pearson Chi-square test between (pre-treatment – post-treatment) and (pre-control – post-control).

[b] Non-parametric 2-related samples McNemar Test or T-test.

[c] Only included employed primary wage earners.

statistically significant improvement is with respect to fewer Treatment households finding it hard to pay their energy bills. On the other hand, electricity disconnections did not decrease, nor did reliance on food assistance and short-term loans. The food-energy tradeoff did not significantly diminish, either. It is notable that it appears that both the Treatment and Control households are much more likely to not buy food to pay their utility bills than they are to not pay their utility bills to buy food. Two variables describing the Control group decreased significantly from Year 1 to Year 2, food assistance and electricity disconnection notices. Only the decrease in hard to pay energy bills experienced by the Treatment group proved statistically significant after adjusting for the Control group results, which indicated an improvement in this variable. Overall, the weakness of these results was unexpected, although this changes when the cross-sectional results are assessed.

7.3. Cross-sectional research design results

Comparing results from the survey of Comparison group homes one-year post-weatherization to a combined sample of Treatment and Control homes surveyed during phase 1 (i.e., pre-weatherization for the Treatment group and Year 1 for the Control group) the differences in sample sizes between the quasi-experimental design and the cross-sectional design are highlighted. In the former, the matched pairs sample sizes were a maximum of 79 for the Treatment group and 100 for the Control group, while in the latter, the maximum sample sizes were 197 for the Comparison group and 251 for the Treatment + Control group.

The cross-sectional analyses suggest that the non-energy impacts of weatherization are much more robust than portrayed by the quasi-experimental results. This is clearly seen in Table 6, which contains the results of the home condition variables. In this case, all of the differences between the Comparison and Treatment + Control group move in the expected direction. Six differences are statistically significant, whereas only three were significant in the quasi-experimental case (See Table 3).

The pattern also holds with respect to health and household finances (see Tables 7 and 8). Five of the eight health related variables are statistically significant, all changing in the expected direction, compared to only two that were weakly significant in the quasi-experimental design

Table 6
Cross-sectional analysis: Home conditions.

Variable	Comparison	Treatment + Control	DIFF	Sig. [a]
	One Year Post	Pre-Wx		
How often home too drafty? (all to some of the time)	50% (195)	83% (250)	−33%	.000
How often home too dusty? (all to some of the time)	81% (196)	90% (251)	−9%	.004
How infested is home with mice? (extremely to somewhat)	6% (196)	8% (248)	−2%	.253
How infested is home with cockroaches, other insects, and spiders? (extremely to somewhat)	10% (196)	15% (248)	−5%	.126
Have seen mold in home? (yes)	30% (197)	39% (251)	−9%	.064
Outdoor noise when windows closed (a great deal to some)	60% (196)	73% (251)	−13%	.004
Kept home at unhealthy temperatures (yes)	13% (196)	47% (250)	−34%	.000
Odor from outdoors (great deal to some)	10% (197)	23% (250)	−13%	.000

Legend: Diff = Comparison one-year post minus (T-pre & Control Year 1); Sig. = p value statistical significance.

[a] Pearson Chi-square test between (Comparison one-year post) and (Treatment-pre & Control Year 1).

Table 7
Cross-sectional analysis: Health.

Variable	Comparison	Treatment + Control	DIFF	Sig.
	One Year Post	Pre-Wx		
Thinking about physical health, which includes physical illness and injury, for how many days during the past 30 days was your physical health not good?	7.2 (187)	11.0 (239)	−3.8	.001
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?	4.8 (189)	9.0 (238)	−4.2	.000
During the past 30 days, for about how many days have you felt you did not get enough rest or sleep?	9.7 (184)	14.5 (246)	−4.8	.000
Medical attention needed last year for asthma? (% yes)[a]	24% (37)	28% (39)	−4%	.701
Medical attention needed past year for being too cold in home (% yes)	0.5% (196)	5.6% (250)	−5.1%	.003
Medical attention needed past year for being too hot in home (% yes)	0.5% (197)	0.8% (251)	−0.3%	.709
In last three months, headaches that are either new or more frequent or severe than ones you have had before? (% yes)	19% (159)	33% (166)	−14%	.001
Medical attention needed past year for COPD, chronic bronchitis, or emphysema?[a]	23% (47)	25% (49)	−2%	.901

Legend: Diff = Comparison one-year post minus (T-pre & Control year 1); Sig. = p value statistical significance.
+ Pearson Chi-square test between (Comparison one-year post) and (Treatment-pre & Control Year 1).

[a] Only included households whose main respondents reported having this chronic disease.

Table 8
Cross-sectional analysis: Household finances.

Variable	Comparison	Treatment + Control	DIFF	Sig.[a]
	One Year Post	Pre-Wx		
Hard to Pay Energy Bills (yes)	51% (195)	70% (250)	−29%	.000
Did Not Buy Food to Pay Utility Bills (yes)	28% (196)	41% (251)	−13%	.002
Did Not Pay Energy Bills to Buy Food (yes)	12% (197)	21% (250)	−9%	.016
Food Assistance (yes)	56% (174)	51% (234)	+5%	.371
Short-term loans (yes)	14% (197)	24% (251)	−10%	.008
Could not afford prescriptions (yes)	35% (196)	43% (251)	−8%	.074
Received disconnection notice (yes)	37% (196)	56% (250)	−19%	.000
Electricity disconnected (yes)	8% (72)	25% (141)	−17%	.004
Missed Days of Work[b]	4.8 (62)	5.0 (79)	−0.2	.894

Legend: Diff = Comparison one-year post minus (T-pre & Control year 1); Sig. = p value statistical significance.

[a] Pearson Chi-square test between (Comparison one-year post) and (Treatment-pre & Control Year 1).

[b] Only included employed primary wage earners.

(See Table 4). Seven of the nine household finance variables are statistically significant, all moving in the expected direction. This is compared to only one in the quasi-experimental design case (See Table 5).

In both experimental designs, the food assistance and missed days of work variables were insignificant. The first may be explained by the fact that energy cost savings driven by weatherization do not count towards increasing household income. Neither do other cost savings with respect to reductions in water costs, short-term loans, arrearages and disconnection costs. Thus, post-weatherization, all things being equal, households will still income-qualify for food assistance programs. Given that missed days of work do not decrease in the context of the KEEM program as implemented in Knoxville, Tennessee, this means that household income is not increasing because more hours are not being worked, which could also explain why food assistance needs are not changing post-weatherization.

One the other hand, it is unclear why missed days of work are not decreasing post-weatherization even if the sample sizes are small for both the quasi-experimental design case and the cross-sectional cases. It is possible that because the unemployment rate was historically quite low in Knoxville, Tennessee during the study period, well below 5% for most of the time,[22] employees felt that their jobs were not as in jeopardy if they were able to miss a few days of work because of illness.

The cross-sectional results support the argument that weatherization can improve home condition, health and household finances. The cross-sectional analyses benefit from larger N's and are not impacted by changes in the Control group. It could be that the Comparison group homes came into the KEEM program in worse shape than the Treatment and Control homes. The first wave of homes recruited by the KEEM program were from the poorest and most historically underrepresented neighborhoods of color. This reflected in the demographics presented in Table 2; Black households comprise about 45% of the Comparison group whereas the percentage for the Treatment + Control group is nearer 28%. The homes in these neighborhoods are known to be in worse shape than other homes in Knoxville. Therefore, it could be hypothesized that KEEM had a greater impact on these homes and households because they started off in worse condition.

7.4. Persistence and convergence analysis results

Based on the statistical significance of comparisons of results, it can be concluded that the non-energy impacts seem to persist two-years post-weatherization but do not benefit from continued positive feedback loop effects while the Comparison and Treatment group results converge one-year post weatherization. Table 9 make the case for these observations. Only one of eight home conditions reported by the Comparison group households improved a statistically significant amount in year two; draftiness. Only small, statistically insignificant changes were reported for the other seven variables. There were no statistically significant differences between the eight variables between the Comparison and Treatment groups one-year post-weatherization. These results met our expectations.

Exactly the same pattern is found with the health and household finance variables in Tables 10 and 11, respectively. In only one case did the Comparison group report statistically significant changes from one year to the next, for the variable electricity disconnects, which continued to decrease in the second-year post-weatherization. The Treatment group continued to report high levels of disconnects one-year post weatherization, unfortunately. The only health-related variable associated with a statistically significant difference is between the Comparison group and the Treatment group, where the latter report more bad days of rest and sleep. One could speculate that worries about utility disconnections could lead to one's loss of sleep.

[22] https://data.bls.gov/timeseries/LAUMT472894000000004?amp%3bdata_tool = XGtable&output_view = data&include_graphs=true.

7.5. Graphical summary of research results

Fig. 2 presents a graphical summary with six panels of results. The equation used to estimate the results in each panel is presented underneath three stacked vertical bars. Each box in each bar represents the result of applying the equation to one of the variables in the categories of variables also noted at the bottom of the bar. Boxes appearing above the purple bar have negative values as calculated by the equations. Boxes appearing below the purple bar have positive values as calculated by the equations. Boxes further from the purple bar have higher levels of statistical significance. For example, Panel A's equation is the DID quasi-experimental design equation. The eight boxes in the leftmost column pertain to the home conditions category of variables. For five variables, the equation provided negative values and for three variables positive values.

For panels A, B, C, and D, negative values indicate expected results (i.e., the bad house conditions, health issues, and household financial issues are reduced). Positive values suggest that those problems became worse. The boxes filled with green and red are expected and unexpected results, respectively, both that are statistically significant with a p-value less than 0.1. The p-values for those boxes filled in grey are between 0.1 and 0.5, while the boxes with no fill color have p-values greater than 0.5. The first vertical bar in Panel A indicates that three home condition results with respect to the quasi-experimental design case were statistically significant in the expected direction (i.e., the three green boxes), two variables with negative equation results had p values between 0.1 and 0.5, two variables with p values above 0.5 had positive equation results, and one variable with a positive equation result had a p value between 0.1 and 0.5. Visually, Panel A suggests that weatherization yielded only a few statistically significant non-energy impacts and several results moving in unexpected directions, though none of those were statistically significant.

Comparing the number of green boxes between Panels A and B provides a strong visual picture of how many more statistically significant results emerged from the cross-sectional analysis than the quasi-experimental design analysis. Only one result moved in an unexpected direction. Panel C provides a similar picture if one only uses the Treatment-pre and Treatment-post results. How closely the Treatment group matches the Comparison group one-year post weatherization is seen in Panel F. One can also see in Panel E how unexpected changes in the Control group from year 1 to year 2 contributed to the underwhelming quasi-experimental design results (Note: the expected results for Panels E and F were to have non-statistically significant differences between the means. Thus, the green boxes cluster near the purple bars and the red boxes are at either end of the columns.) Panel D visually confirms that for the most part, the non-energy impacts attributable to weatherization did not change much for the Comparison group from one-year post to two-years post. There is only weak confirmation that these impacts may improve from one year to the next due to positive feedback effects.

Visually, the strongest consistent signal in the data across Panels A, B, and C is that weatherization has the most impact on home conditions, followed by health and then household finances. However, if one were to only focus on Panel B, then weatherization about equally and strongly impacts all three categories of variables.

An important question that is beyond the scope of this paper to resolve is which of the Panels A or B one should view as the most reliable and valid set of results. The research design underlying the former is more rigorous though suffers from small sample sizes and inexplicable changes in the control group. The research design underlying the latter is less rigorous but benefits from larger sample sizes. Results presented in Panels C and F also support the conclusion drawn from Panel B that weatherization conducted by KEEM had a positive impact on 18 of the 25 non-energy impacts addressed herein.

Table 9
Persistence and convergence analysis: Home conditions.

Variable	Comparison		DIFF1	Sig.[a]	Comparison	Treatment	DIFF2	Sig[b]
	One Year Post	Two Years Post			One Year Post	Post		
How often home too drafty? (all to some of the time)	46% (139)	37% (141)	−9%	.067	50% (195)	44% (78)	+6%	.358
How often home too dusty? (all to some of the time)	85% (141)	82% (141)	−3%	.458	81% (196)	77% (79)	+4%	.464
How infested is home with mice?(extremely to somewhat)	6% (140)	6% (140)	0%	1.00	6% (196)	9% (79)	−3%	.311
How infested is home with cockroaches, other insects, and spiders?(extremely to somewhat)	11% (141)	14% 141)	+3%	.405	10% (196)	15% (79)	−5%	.192
Have seen mold in home? (yes)	31% (141)	36% (141)	+5%	.281	30% (197)	25% (79)	+5%	.354
Outdoor noise when windows closed (a great deal to some)	57% (140)	55% (140)	−2%	.880	60% (196)	58% (79)	+2%	.823
Kept home at unhealthy temperatures (yes)	10% (140)	11% (141)	+1%	1.00	13% (196)	14% (78)	−1%	.766
Odor from outdoors (great deal to some)	12% (141)	9% (141)	−3%	.383	10% (197)	13% (79)	−3%	.545

Legend: DIFF1 = Comparison two-years post – Comparison one-year post; DIFF2 = Comparison One-year post minus Treatment-post; Sig. = p value statistical significance.
[a] Non-parametric 2-related samples McNemar Test.
[b] Pearson Chi-square test between (pre-treatment – post-treatment) and (pre-control – post-control).

Table 10
Persistence and convergence analysis: Health.

Variable	Comparison		DIFF1	Sig.[a]	Comparison	Treatment	DIFF2	Sig.[a]
	One Year Post	Two Years Post			One Year Post	Post		
Thinking about physical health, which includes physical illness and injury, for how many days during the past 30 days was your physical health not good?	7.3 (133)	9.5 (138)	+2.2	.109	7.2 (187)	7.8 (79)	−0.6	.652
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?	5.0 (134)	6.0 (140)	+1.0	.303	4.8 (189)	6.4 (78)	−1.8	.186
During the past 30 days, for about how many days have you felt you did not get enough rest or sleep?	10.9 (132)	11.5 (138)	+0.6	.507	9.7 (184)	12.3 (79)	−2.6	.091
Medical attention needed last year for asthma? (% yes)[b]	27% (26)	8% (26)	−19%	.219	24% (37)	20% (10)	+4%	.774
Medical attention needed past year for being too cold in home (% yes)	0.7% (140)	0.7% (141)	0%	1.00	0.5% (196)	2.5% (79)	−2%	.144
Medical attention needed past year for being too hot in home (% yes)	0.7% (141)	0.7% (141)	0%	1.00	0.5% (197)	1.3% (79)	−0.8%	.502
In last three months, headaches that are either new or more frequent or severe than ones you have had before? (% yes)	17% (141)	20% (141)	+3%	.617	81% (197)	84% (79)	−3%	.584
Medical attention needed past year for COPD, chronic bronchitis, or emphysema?[b]	47% (35)	45% (38)	−2%	1.00	53% (47)	62% (13)	−11%	.592

Legend: DIFF1 = Comparison two-years post – Comparison one-year post; DIFF2 = Comparison One-year post minus Treatment-post; Sig. = p value statistical significance.
[a] Pearson Chi-square test between (pre-treatment – post-treatment) and (pre-control – post-control).
[a] Non-parametric 2-related samples McNemar Test or T-test.
[b] Only included households whose main respondents reported having this chronic disease.

Table 11
Persistence and convergence analysis: Household finances.

Variable	Comparison		DIFF1	Sig.[b]	Comparison	Treatment	DIFF2	Sig.+
	One Year Post	Two Years Post			One Year Post	Post		
Hard to Pay Energy Bills (yes)	52% (140)	58% (141)	+6%	.291	51% (195)	51% (78)	0%	1.00
Did Not Buy Food to Pay Utility Bills (yes)	27% (140)	30% (141)	+3%	.671	28% (196)	29% (76)	−1%	.818
Did Not Pay Energy Bills to Buy Food (yes)	11% (141)	11% (141)	0%	1.00	12% (197)	18% (79)	−6%	.227
Food Assistance (yes)	55% (125)	50% (125)	−5%	.332	56% (174)	56% (70)	0%	.996
Short-term loans (yes)	15% (141)	15% (141)	0%	1.00	14% (197)	19% (79)	−5%	.323
Could not afford prescriptions (yes)	37% (140)	27% (141)	−10%	.040	35% (196)	32% (79)	+3%	.629
Received disconnection notice (yes)	38% (140)	28% (137)	−10%	.026	37% (196)	39% (79)	−2%	.698
Electricity disconnected (yes)	3% (51)	7% (38)	+4%	1.00	8% (72)	23% (31)	−15%	.046
Missed Days of Work	5.8 (33)	5.7 (33)	−0.1	.931	4.8 (62)	6.4 (26)	−1.8	.376

Legend: DIFF1 = Comparison two-years post – Comparison one-year post; DIFF2 = Comparison One-year post minus Treatment-post; Sig. = p value statistical significance.
+ Pearson Chi-square test between (pre-treatment – post-treatment) and (pre-control – post-control).
**Only included employed primary wage earners.
[b] Non-parametric 2-related samples McNemar Test or T-test.

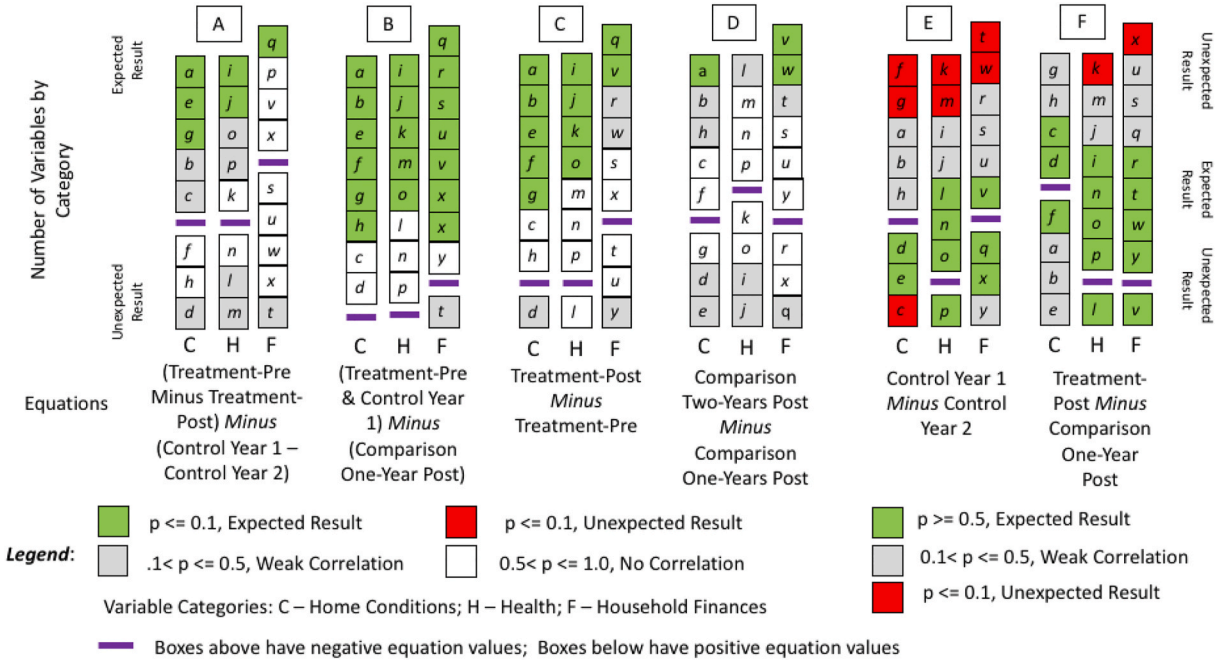

Fig. 2. Summary of statistical results.
Home conditions: *a* – draftiness; *b* – dustiness; *c* – mice; *d* – insects; *e* – mold; *f* – noise; *g* – unhealthy temps; *h* – odors. Health: *i* – physical health; *j* – mental health; *k* – rest/sleep; *l* – asthma; *m* – thermal stress cold; *n* – thermal stress hot; *o* – headaches; *p* – COPD. Household Finances: *q* – hard to pay energy bills; *r* – do not buy food; *s* – do not pay energy bills; *t* – food assistance; *u* – short-term loans; *v* – no afford prescriptions; *w* – disconnect notices; *x* – disconnected; *y* – missed days of work.

8. Discussion

8.1. Reflections on results

Having Comparison group data facilitated cross-sectional analyses and provided insights into the persistence of the non-energy impacts of weatherization. Collecting Comparison group data also allowed the research team to meaningfully engage stakeholders in Knoxville and throughout TVA's service territory throughout the project. Based on these experiences, we will seek to implement this hybrid approach in other assessments of non-energy impacts attributable to low-income home weatherization programs.

One insight gained during this research project is that matched pairs analysis may not always be preferred for all non-energy impact variables. Let's compare asthma, a chronic disease, and thermal stress, which is not a chronic disease. With respect to the former, it does seem preferable to learn through matched pairs analysis whether weatherization reduced asthma symptoms and medical intervention needs for specific respondents who have asthma. Conversely, weatherization can reduce the probability that anyone in any household will suffer a thermal stress event. There are no pre-existing conditions with respect to thermal stress that absolutely require a matched pairs analysis. In the case of thermal stress, cross-sectional analyses or quasi-experimental design analyses using the full pre-treatment samples that have higher N's might be supportable.

Another insight gained during our analyses also pertains to the thermal stress variables. Waiting one-year to collect post-weatherization data is sufficient for non-energy impacts that take only a few months to a year to present themselves. Thermal stress is different because extreme temperature events do not occur every year throughout the U.S. Knoxville did not experience a heat wave during the course of this project. However, climate change is expected to increase the frequency and severity of heat waves. Hence, weatherization would be expected to have a positive effect in reducing thermal stress.

The last point of reflection relates to data collection tools and approaches. The survey tool employed in this research contained a broad set of questions. Many of the questions required respondents to provide their subjective judgements, such as with respect to unsafe temperatures. Future research could benefit from directly collecting data on indoor temperatures and humidity, which could reduce reliance on subjective reports. More detailed data could also be collected from medical records databases on the incidences of medical interventions and their costs. Direct health data could also be collected, such as blood pressure data to help measure stress levels pre-and post-weatherization. The surveys themselves could also be modified to focus on fewer issues but with more precision. For example, additional questions could be added to help characterize asthmatics and better understand mental health.

8.2. Comparing KEEM and WAP results

It is important to revisit hypotheses about potential differences in results between the WAP and KEEM non-energy impact studies. One hypothesis was strongly supported by the KEEM results was that KEEM might not have had significant impacts on chronic respiratory diseases, asthma and COPD, because of the low rate of air sealing. It is possible that this lack of impact is also explained by the lack of use of fossil fuels for heating and cooking in the all-electric KEEM homes[23] as combustion appliances can emit indoor pollutants that can cause asthma flare-ups.

KEEM and WAP had similar substantial positive impacts on home conditions, such as fewer homes were kept at unhealthy temperatures, and there were similar reductions in mold and outdoor noise intrusion. Other similarities included positive impacts on physical and mental health, and greatly improved abilities to pay utility bills. As an example, the KEEM respondents reported a decrease of 4.2 bad mental health days in the past month, compared to a reported decrease of 3.4 days by the WAP respondents. Overall, there were enough differences between the KEEM and WAP results to warrant caution in generalizing results from the national WAP evaluation to a local weatherization program situated

[23] About two-thirds of WAP single-family homes heat with natural gas [44].

in the Southeastern United States.

8.3. Policy implications

The research results lead to several policy observations. First, weatherization programs that intend to emphasize non-energy impacts, especially with respect to home conditions and health, need to ensure that air sealing and HVAC measures are both frequently installed.[24] Second, it is important for assessments of the non-energy impacts of weatherization to be as granular (i.e., program and location specific) as possible. This is because key demographic differences, such in as household size [48] and racial diversity, could substantially affect patterns of non-energy impacts. Third, neither the KEEM nor WAP results can be generalized to the affordable multifamily (MF) sector. This is because the demographics of multifamily residents differ even from the KEEM household (e.g., MF households are even smaller, older, and more racially diverse [4]) and the building science that typifies MF buildings, and therefore the portfolios of measures installed, is quite different from single-family homes. Fourth, care also must be taken when considering generalizing these results to an international context. Homes, climate, weatherization programs and demographics would all need to be comparable to the KEEM context.

Fifth, weatherization has both individual-level and health care/public health benefits. The healthcare sector should be interested in how weatherization can address prescription non-adherence, for instance, which cost the U.S. economy almost $300 billion annually,[25] or reduce hospitalizations related to thermal stress. Public health officials should be interested in how households can use energy cost savings to purchase food and also reduce their need for food assistance. Placing monetary values on these benefits could then possibly justify healthcare and public health contributions to weatherization programs, which is needed because most local weatherization programs cannot meet demand [40].

If these paths of collaboration are opened, then other opportunities for collaboration between the energy efficiency and healthcare and public health sectors could be pursued as well. For example, each time a weatherization program touched a home, important observations about the home and occupants could be shared with healthcare [49,50]. Another area for cooperation surrounds near-elderly households. It has been shown that significant proportions of the KEEM and WAP samples can be designated as near-elderly (50–64 years old) and that their homes, general health, and budget situations are worse than other households [48]. It might be beneficial for weatherization programs and their healthcare and public health partners to work together to find ways to better serve near-elderly households and use weatherization to reduce health and energy inequities [51]. One value of having local agencies conduct weatherization in the U.S. is that representatives of these agencies can straightforwardly refer households to other agency services, such as energy assistance.

9. Conclusion

This research shows that low-income weatherization can improve home conditions, human health and household financial conditions. Homes were less frequently kept at unsafe temperatures, measures of general health improved, and households were better able to pay their energy bills. Weatherization by itself is not able to rectify all of these issues but can be seen as an important component of programs that address fuel poverty.

The project employed a hybrid quasi-experimental/cross-sectional research design. This approach was taken in response to several practical concerns about the quasi-experimental design and also because a sample of comparison homes was readily available. The cross-sectional analyses produced stronger statistically significant results and also showed that 1) the non-energy benefits did not change much two-years post-weatherization and 2) that the Treatment group and Comparison group results ended up being quite similar one-year post-weatherization.

This research has several policy implications. One is that it is important to install comprehensive sets of weatherization measures to produce measurable non-energy impacts. A second is care must be taken when generalizing results from studies such as this because weatherization program, climate, home type, and demographic differences can greatly change non-energy impacts. Lastly, given that weatherization can produce substantial health impacts, it should be a goal of the energy efficiency sector to convince the health care and public health sectors to also invest in weatherization programs.

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.

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