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ORIGINAL ARTICLE

Watts-to-Wellbeing: does residential energy conservation improve health?

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Abstract Residential energy conservation has been increasing in number of houses treated, frequency, and scope, but few studies have examined whether modern energy conservation measures improve the health status of the occupants. We measured self-reported general, respiratory, cardiovascular, and mental health via structured telephone interviews using an adaptation of the National Health Interview Survey at baseline and follow-up in 2009–2012 [n=248 households in Boston, Chicago, and New York City (248 adults and 75 children)]. Housing included buildings with one to three units (n=106 units) located in Boston and buildings with >3 units/building (n=142) located in Chicago and New York. The energy conservation typically included insulation, heating equipment, and ventilation improvements. Adult respondents reported a 0.29-point improvement in the mean general health score (1 = excellent, 2 = very good, 3 = good, 4 = fair, 5 = poor) (3.07 to 2.78, $p<0.001$). Sinusitis, hypertension, overweight, and reduced use of asthma medication during asthma attacks showed 5 %, 14 %, 11 %, and 20 % differentials between improvement and worsening ($p=0.038$, $p<0.001$, $p<0.001$, and $p=0.077$, respectively). Forty-two adult respondents reported doctor-diagnosed asthma at baseline. Two measures of asthma severity worsened (days with problems sleeping—differential between improvement and worsening −28 %, $p=0.009$; and frequency of symptoms such as cough, wheezing, and shortness of breath—differential between improvement and worsening −26 %, $p=0.031$). Nitrogen dioxide, carbon monoxide, and carbon dioxide were low and showed no significant changes from baseline to follow-up in 41 housing units. This study found that residential energy conservation work conducted by trained professionals that balances energy efficiency and indoor environmental quality improves general health, sinusitis, and reduced asthma medication. Further research is needed to understand asthma-related outcomes.

Keywords Energy conservation · Weatherization · Health · Housing · Asthma

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Introduction

A centerpiece of the United States' energy policy since the 1970s has been technical and financial support for residential building improvements to reduce energy consumption. Residential building operations account for nearly a quarter of the nation's energy consumption (U.S. Department of Energy 2010). With the cost of energy increasing over the past decade, residential energy conservation has been increasing in size, frequency, and scope. This growth has also been bolstered by the promise of ancillary environmental health benefits for the building occupants. However, few studies have measured the actual health impact of residential energy conservation. The World Health Organization (WHO) has estimated the annual burden due to cold homes can be conservatively estimated at 30 % of excess winter deaths in Europe (Rudge 2011). Beyond the straightforward impact of thermal improvements, energy conservation can plausibly be related to health because it often includes the following: repair or replacement of heating and cooling equipment to increase efficiency and reduce the generation of pollutants such as carbon monoxide; improvement of ventilation to remove contaminants; air sealing and improvement of building envelopes, which can often reduce moisture leaks from the exterior; and reducing moisture from the dwellings. In this exploratory study, we examined the self-reported changes in a wide variety of physical, mental, and general health status of residents receiving energy conservation services from public- and utility-sponsored programs because such changes could be both direct and indirect. For example, it is plausible that energy conservation could improve thermal comfort, which could directly affect mortality, but could also reduce stress and improve mental health due to reduced household energy expenditures. This causal web of energy conservation, housing, and health interactions has been reviewed extensively by WHO (2005).

Spurred by the energy crisis of 1973, property owners sought to make their buildings better insulated and more air tight to reduce energy costs. Within a decade, research emerged documenting health problems associated with inadequate air exchange and increased indoor contaminant levels in these tightened buildings (Turiel et al. 1983; Sterling et al. 1983; Finnegan et al. 1984). These studies led to changes in standard energy conservation practices by balancing building tightening (e.g., insulation and sealing) with ventilation to improve indoor air quality. Although the research was primarily conducted on commercial office space, the balance of energy efficiency and indoor air quality became a principle of modern residential energy conservation as well (Bliss 1985). Concerns continue to be raised in the literature about energy conservation making buildings too tight (Engvall et al. 2003; Lawrence Berkley National Laboratory 2012; Manuel 2011), but another review found evidence suggesting that if the work is done properly, occupant health may improve (Brown et al. 1994).

The available literature on health improvements following energy conservation (energy retrofits) in existing housing is limited. A report on the US Weatherization Assistance Program, which provides energy conservation measures to low-income homes, found that clients reported feeling healthier following work, while control group respondents whose homes were not weatherized until after the study did not report health improvements (Brown et al. 1994). A study in New Zealand showed that insulating existing houses led to a significantly warmer, drier indoor environment and resulted in improved self-rated health and self-reported wheezing, reduced numbers of days off school and work due to illnesses, and reduced visits to general medical practitioners as well as a trend for fewer hospital admissions for respiratory conditions (Howden-Chapman et al. 2007). A study in Sweden found that residents of multifamily buildings where the owner had added mechanical ventilation in the past 10 years reported better health than buildings without the improvements while residents in buildings with multiple insulation or air sealing improvements in that period reported less throat problems and coughs but more nasal problems and eye irritation (Engvall et al. 2003). Other studies primarily from Europe offer valuable findings about the impact of central heating on thermal comfort and other health outcomes but are less applicable to energy retrofits in the United States where most dwellings already have central heating. We completed this study to help close that gap.

Methods

Residents of dwellings about to undergo energy retrofit work in Boston, MA; Chicago, IL; and New York, NY were recruited to participate in a two-phase telephone interview of their self-reported health and building condition in 2009–2012. Residents in Boston and New York received energy retrofits from contractors funded through the US Weatherization Assistance Program and had to meet their State's weatherization program criteria, e.g., household income was below 60 % of the state median income. Residents in Chicago received energy retrofits from contractors funded by the Energy Savers Program of CNT Energy that is supported by utilities and local charitable foundations. The program was available to multifamily rental property owners who maintain rents for households below 50 % of the area median income. Only residents with a working phone were eligible. Participating households were compensated for their time with a small monetary stipend for each survey completed.

We examined the impact of energy retrofits on health in buildings with one to three units and also in buildings with >3 units. Buildings with one to three units were in Boston and generally consisted of wood-frame construction, with attics and individual furnaces and separate heating systems for each unit. Buildings with >3 units were generally masonry construction with flat roofs and central heating systems serving multiple units and were located in Chicago and New York.

Each service provider prepared an individualized energy conservation plan for each building they served. There were common attributes of the energy retrofits by location (Table 2). Boston primarily installed insulation and dryer vents and upgraded heating; Chicago provided heating upgrades and air sealed units; and New York upgraded heating, installed windows and bath fans, fixed doors and added door weatherstripping, and repaired roof leaks, but added no insulation or air sealing. After recruitment, a professional telephone surveyor attempted to contact each interested household and if successful conducted a thoughtful informed consent before proceeding with the interview, which included a discussion about confidentiality of personal data, the purpose of the study, the voluntary nature of participation, and the study's risks and benefits, all as approved by the study Institutional Review Board.

Telephone surveyors interviewed one adult in each household, who provided information on themselves and for the youngest two children aged 5–15 years. The surveyors administered structured health interviews to assess self-reported health status of participating adults and children. The health interview was adapted from the U.S. Centers for Disease Control's (CDC's) annual National Health Interview Survey (CDC 2005), CDC's Behavioral Risk Factor Surveillance System (CDC 2010), and the U.S. Department of Housing and Urban Development (HUD)/National Institute of Environmental Health Sciences National Survey of Lead and Allergens in Housing (HUD/NIEHS 2001).

Baseline interviews were administered several weeks before energy retrofit work began (median = 2 weeks, maximum = 7 months) and follow-up interviews were administered 2 to 18 months after energy retrofits were complete. The original study design called for all follow-up interviews to be completed 1 year after the completion of energy retrofit work. Recruitment delays and funder constraints that did not allow for an extension of the research period prevented a full 1-year follow-up period for some households. A total of 99 households (40 %) had a follow-up period of 11 or more months (median 12 months), while the remaining 149 households (60 %) had a follow-up period of 2–10 months (median 3.5 months).

The health interview collected data on demographics, general health, respiratory health, cardiovascular health, and mental health. For example, adult respondents were asked during the baseline interview whether a doctor had ever diagnosed them with various medical conditions, including emphysema, hay fever, sinusitis, chronic bronchitis, asthma, overweight, hypertension, and other coronary conditions including heart disease, angina, and heart attack. During the follow-up interview, respondents were asked if conditions reported at baseline were worse, the same, better, or no longer present since the energy retrofit work was completed. Respondents were also asked if any of the listed conditions had been newly diagnosed since the baseline interview. We examined health effects separately for the adult and child subpopulations because children may respond differently to environmental changes than adults. The interviews also included non-health questions about housing characteristics/conditions and cleaning practices. Given the lack of previous studies of modern energy conservation measures, the present study was considered exploratory in nature, and multiple comparison adjustment was not conducted (Rothman 1990).

We also measured several air quality parameters in a convenience sample of housing units (n=65 units at baseline and 49 at follow-up). Paired samples for 41 dwellings were analyzed. Grab samples were collected for nitrogen dioxide (NO_2), carbon monoxide (CO), and carbon dioxide (CO_2). Short-term detector tubes (also known as length-of-stain detector tubes) were used to measure NO_2. CO was tested using either a real-time air monitoring instrument (QTRAK) or detector tubes. Researchers attempted to collect one air sample for each contaminant in the middle of the kitchen at breathing zone height in each of the selected units approximately 30 days before and after the energy retrofits.

Statistical analysis

Repeated measures logistic models were used to test that there were changes in certain housing conditions that could influence health from baseline to follow-up while controlling for season, such as presence of pests, water damage, smoking, and others. Paired *t* tests on log-transformed air sample concentrations were used to test that geometric mean concentrations changed from baseline to follow-up. McNemar's test was used to determine if the percentages of air sample concentrations below the detection limit were different at baseline and follow-up.

At baseline and follow-up interviews, adults reported their current general health on a five-point scale: excellent (1), very good (2), good (3), fair (4), and poor (5). We used the Cochran–Mantel–Haenszel mean score tests to determine if the general health score changed from baseline to follow-up. McNemar's test was used to determine if the percentages of adults with fair or poor general health were different at baseline and follow-up. For health-specific conditions, changes from baseline to follow-up were classified as improved (improvements in a specific health condition or that no longer had the condition at follow-up), same (no change in condition or did not have the condition at baseline or follow-up), or worse (the condition worsened or the individual developed the health condition after baseline). A weighted least-squares chi-squared test was used to test whether the percent of adults that experienced improvements in a specific health condition or that no longer had the condition at follow-up is different from the percent that were worse or who developed the health condition. For health conditions with some significant changes, we tested that effects differed by short (<11 months) or long (≥11 months) follow-up period. We used an ordinal logistic generalized linear model to determine if post-retrofit adult general health depended on the seven specific retrofit work categories (Table 1), total cost, or energy impact while controlling for post-retrofit time window (<11 months, 11 or more months), season, location, and key demographics (age, gender, race/ethnicity, and education). We used polychoric correlation to assess the associations between adult general health scores and satisfaction. We used an ordinal logistic regression model to test that satisfaction depended on post retrofit window, location, or their interaction.

Results

Of the 384 households that completed baseline interviews, 248 (65 %) completed follow-up (248 adults, 75 children). The demographics of the adult population varied by location (Table 2). Adult respondents in

Table 1 Weatherization work by dwelling unit

Location	*N*	Insulation[a]	Heating upgrade	Bath fan installation	Windows replaced	Health and safety[b]	Door weatherstrip[c]	Leak repair[d]
Boston	106	93 %	47 %	0 %	22 %	37 %	7 %	1 %
Chicago	60	45 %	75 %	2 %	2 %	0 %	0 %	2 %
New York City	82	0 %	92 %	100 %	70 %	100 %	100 %	98 %
All	248	50 %	69 %	34 %	33 %	49 %	36 %	33 %

[a] Air sealing, wall insulation, and/or attic insulation

[b] Dryer vent, CO alarm, and/or other health and safety (primarily door repair)

[c] Door weatherstripping and/or sweeps

[d] Roof repair or plumbing leak repair

Table 2 Adult/household demographics

Follow-up period of observation/location	N	Mean age	Percent with	
			Post high school education	Income above $20,000
Short follow-up (<11 months)	149	60	42 %	22 %
Long follow-up (≥11 months)	99	57	56 %	41 %
Boston	106	58	58 %	52 %
Chicago	60	49	45 %	15 %
New York City	82	67	36 %	11 %
All	248	59	45 %	30 %

New York were older (mean age: 67), less well educated (36 % post-high school), and of lower income (11 % with income over $20,000) than adults at the other two locations. Respondents in Boston had a mean age of 58, and were more educated (58 % post-high school) and had higher incomes (52 % over $20,000) than the other two locations. Chicago respondents were younger (mean age 49) and had education (45 % post-high school) and income levels (15 % over $20,000) closer to the New York respondents. Children in the cohort ranged from 5 to 15 years of age (mean age 10). Fifty-seven (57 %) percent of the children were female. Of the 75 children, 39 lived in Boston [in 27 of 106 households (25 %)], 23 lived in Chicago [in 15 of 60 households (25 %)], and 13 lived in New York [in 10 of 82 households (12 %)].

Prior to energy conservation work, most households reported that that the temperature in their dwelling was uncomfortable in the summer (64 %) and/or in the winter (55 %) (Table 3). Households also reported that their homes had water leaks or dampness (52 %) and/or frequently had a mildew odor or musty smell (23 %) in the prior 12 months. Pest problems were less common, but households reported rodent problems in 27 % of dwellings and cockroach problems in 11 % of dwellings. Fifty-seven (57 %) percent of households reported smoke in their home in the past 12 months, with common sources being candles/incense (39 %) and tobacco smoke (22 %). More than half (51 %) of households did not use the exhaust fan over their stoves regularly when cooking, while 69 % did not use bath fans at least sometimes during showers or baths.

Table 3 Housing conditions

Housing condition	N	Percent of homes with condition[a]		p value[a]
		Baseline	Follow-up	
Temperature—uncomfortable in winter	199[b]	55 %	39 %	<0.001*
Temperature—uncomfortable in summer	239[c]	64 %	45 %	<0.001*
Water leak or dampness	246	52 %	42 %	<0.001*
Mildew odor/musty smell	244	23 %	18 %	0.109
Rodent problem	245	27 %	24 %	0.232
Cockroach problem	248	11 %	13 %	0.340
Smoke in home	99[d]	57 %	41 %	0.003*
Common source: candles/incense[d]		39 %	28 %	
Common source: tobacco smoke[d]		22 %	19 %	
Stove fan—never/rarely used during cooking or no fan	244	51 %	48 %	0.305
Bath fan—never/rarely used during showers/baths or no fan	240	69 %	62 %	0.023*

*$p<0.05$, statistically significant difference between baseline and follow-up

[a] Based on a repeated measures logistic model for each housing condition controlling for season

[b] Responses excluded for households that did not experience a winter season following energy retrofits

[c] All households experienced a summer season following energy retrofits

[d] Responses excluded for households that did not have at least 11-month follow-up period after energy retrofits because the question asked about the previous 12 months

[d] Raw percent of homes

Dwelling temperature was more comfortable in both the winter and summer after the energy work was completed (both $p<0.001$). There were also fewer problems with water leaks and dampness, bath fan usage increased, and the presence of smoke in the home declined ($p<0.001$, $p=0.023$, and $p=0.003$, respectively). There was no significant change in musty odors, use of stove fans, or rodent and cockroach problems ($p=0.109$, $p=0.305$, $p=0.232$, and $p=0.340$, respectively).

For all locations and follow-up periods combined, mean adult general health score improved by 0.29 points from baseline to follow-up (3.07 to 2.78, $p<0.001$) (Table 4). Respondents from New York (short follow-up period) and those in the longer follow-up groups in Boston and Chicago reported general health score improvements (0.29 points with $p=0.013$, 0.41 points with $p=0.001$ and 0.43 points with $p=0.060$, respectively).

New York respondents (short follow-up period) reported a significant improvement in the percent with fair/poor health ($p=0.007$), while respondents from the longer follow-up group in Boston reported a marginally significant improvement ($p=0.074$). For the 75 children in the study, their caregivers reported no significant change in their general health, with their average general health remaining between good and very good (data not shown).

For each of the adult health conditions that were reported at least 20 times at baseline, we analyzed the changes in outcomes after energy retrofit work (Table 5). Sinusitis, hypertension, and overweight showed 5 %, 14 %, and 11 % differentials between improvement and worsening ($p=0.038$, $p<0.001$, and $p<0.001$, respectively).

For asthma, the results were mixed. On the one hand, significantly more people worsened than improved in asthma severity, as measured by days with problems sleeping (differential −28 %, $p=0.009$) and frequency of symptoms such as cough, wheezing, shortness of breath, chest tightness, and phlegm production (differential −26 %, $p=0.031$). On the other hand, for a third measure of asthma severity (use of prescribed rescue medicine during an attack), there was marginally more improvement than worsening (differential 20 %, $p=0.077$).

The improvements in hypertension and overweight status were significant for both the long-term and short-term follow-up observation periods. The trends in the improvements for sinusitis were the same for each of the observation periods, but neither the findings for the long-term nor short-term periods were statistically significant ($p=0.127$ and $p=0.141$, respectively). The trends for asthma outcomes were also similar for both observation periods, but changes in days with problems sleeping was only significant for the long-term period ($p=0.002$ vs. $p=0.357$ for short term) and changes in the frequency of symptoms was only marginally significant for short-term period [$p=0.269$ (long) and $p=0.052$ (short)].

Table 4 Adult general health score

Location and follow-up period of observation[a]	*N*	Mean general health score[b]				Fair or poor general health			
		Baseline	Follow-up	Change	*p* value[c]	Baseline	Follow-up	Change	*p* value[d]
Boston—short	28	2.86	2.46	−0.40	0.124	32 %	21 %	−11 %	0.257
Chicago—short	39	2.97	2.97	0.00	1.0	33 %	26 %	−7 %	0.405
NYC—short	79	3.32	3.03	−0.29	0.013**	48 %	32 %	−16 %	0.007**
Boston—long	74	2.96	2.55	−0.41	0.001**	32 %	22 %	−10 %	0.074*
Chicago—long	21	3.00	2.57	−0.43	0.060*	29 %	19 %	−10 %	0.414
All	241	3.07	2.78	−0.29	<0.001**	37 %	25 %	−12 %	<0.001**

*Marginally significant difference ($0.05\leq p<0.1$) between baseline and follow-up, **statistically significant difference ($p<0.05$) between baseline and follow-up

[a] Short = 10 or fewer months follow-up; long = 11 or more months follow-up (no long-term follow-up for NYC)

[b] General health: excellent (1), very good (2), good (3), fair (4), and poor (5)

[c] The Cochran–Mantel–Haenszel mean score test was used for each location and follow-up period

[d] McNemar's test that the percent with fair or poor health differed for baseline and follow-up

Table 5 Specific adult health conditions

Health condition	*N*	Baseline *n* (% with condition)	Follow-up				*p* value[a]
			Improved/no longer had	Same/never had	Worsened/ developed	Differential	
Sinusitis	246	39 (16 %)	9 %	86 %	4 %	5 %	0.038**
Hay fever	243	34 (14 %)	6 %	90 %	5 %	1 %	0.548
Chronic bronchitis	248	28 (11 %)	5 %	92 %	3 %	2 %	0.178
Hypertension	243	115 (47 %)	18 %	79 %	3 %	14 %	<0.001**
Overweight	243	100 (41 %)	17 %	77 %	6 %	11 %	<0.001**
			Improved	Same	Worsened		
Asthma	248	42 (17 %)					
Symptoms	42		21 %	31 %	48 %	−26 %	0.031**
Missed days of work	36		22 %	56 %	22 %	0 %	1.000
Days w/difficulty sleeping	40		13 %	48 %	40 %	−28 %	0.009**
Times at urgent care	42		10 %	71 %	19 %	−10 %	0.241
Days using preventive medicines	42		17 %	60 %	24 %	−7 %	0.483
Days using rescue medicines	40		38 %	45 %	18 %	20 %	0.077*

*Marginally significant difference ($0.05 \leq p < 0.10$) between improved or no longer had and worsened or developed the condition, **statistically significant difference ($p < 0.05$) between improved or no longer had and worsened or developed the condition

[a] Based on weighted least-squared chi-squared tests that the percent of adults that experienced improvements in a specific health condition or that no longer had the condition at follow-up is different from the percent that were worse or who developed the health condition

For the children in the study, the respondents reported only one doctor-diagnosed condition for at least 20 of the children at baseline: eczema or skin allergy. Twenty-five of 74 children (34 %) had eczema/skin allergies at baseline; at follow-up, 14 (19 %) had the condition get better or go away; 54 (73 %) remained the same or never had the condition, and six (8 %) developed the condition. The difference in eczema or skin allergy in children improving compared to getting worse after energy retrofits was marginally significant ($p=0.067$).

Adults were also asked about their mental health before and after work was conducted. They were asked questions such as: in the last 30 days, how often do you feel (1) nervous, (2) restless or fidgety, (3) hopeless, (4) worthless, etc. No significant changes in mental health status were observed (data not shown).

There were no significant changes in the quality of the indoor air between baseline and follow-up sampling (Table 6). All NO_2 samples and most CO samples were below detection limits at baseline, with no significant changes at follow-up. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) has generated a guideline noting that indoor air concentrations of CO_2 should not exceed about 700 ppm above outdoor air concentrations or a concentration of 1,000 ppm (ASHRAE 2010). Both baseline and follow-up geometric mean CO_2 levels were below this benchmark. Outdoor air typically contains approximately 350 ppm CO_2 (Apte et al. 2000).

Using the individual work categories presented in Table 1, the relationship between the specific types of energy retrofit work and self-reported adult general health after energy work was explored, but none had a statistically significant relationship with general health ($p=0.722$). Total cost and anticipated energy impact were also not significantly related ($p=0.828$ and $p=0.312$, respectively) to post-work general health.

Respondents were also asked about their general satisfaction about the energy work on a five-point scale (1=very satisfied to 5=very dissatisfied). Adult general health at follow-up was significantly associated with satisfaction with energy work (polychoric correlation=0.205, $p=0.002$). However, baseline adult general health was not significantly associated with satisfaction (polychoric correlation=0.043, $p=0.512$). In other words, respondents who were healthier at

Table 6 Air sampling results (n=41 dwellings)

Gas	Detection limit (ppm)	Percent below detection limit			Geometric mean (ppm)[b]		
		Baseline	Follow-up	p value[a]	Baseline	Follow-up	p value[c]
Nitrogen dioxide	0.05	100 %	98 %	–	–	–	–
Carbon monoxide	1.00	85 %	78 %	0.405	–	–	–
Carbon dioxide (indoor)	5.00	0 %	2 %	–	679.3	657.5	0.821

[a] McNemar's test that the percent below the detection limit differed for baseline and follow-up. The p value could not be calculated for most of the gases because only one unit had different results at baseline and follow-up

[b] Geometric mean not reported when more than half of results below detection

[c] Paired t test that geometric mean air concentrations were different at baseline and follow-up

baseline were not necessarily more satisfied with the work, but those who were more satisfied with the work were more likely to feel healthier after the work was complete. Satisfaction did not depend on post retrofit observation period, the location of the work (Boston, Chicago, or New York), or their interaction (p=0.535).

Discussion

We found that the self-reported general health of the residents improved after energy retrofits, similar to the New Zealand (Howden-Chapman et al. 2007) and the Department of Energy studies (Brown et al. 1994). For this study, the respondents were asked the same questions about their current health at both baseline and follow-up. Similar to the study by Leech et al. of new energy efficient homes, the interviewer and the interviewee at follow-up were both blinded to the general health responses provided at baseline (Leech et al. 2004). The health of participants at large and of those who were originally in fair or poor health significantly improved.

The respondents also reported that symptoms related to sinusitis and hypertension both were more likely to improve than worsen after energy retrofits. These two health factors have previously been associated with an improved energy efficiency or heating. The New Zealand study reported that the incidence of symptoms or conditions related to sinus congestion, morning phlegm and winter colds, decreased significantly following the insulation of homes (Howden-Chapman et al. 2007). An earlier study documented the relationship between improved indoor heating and reductions in blood pressure among an older adult population (Woodhouse et al. 1993).

Prior studies have not documented a relationship between energy efficiency and being overweight. One study explored the effect of home energy assistance on children's nutrition and overweight status (Frank et al. 2006). The study found that young children whose family received home energy assistance for at least a year were less likely to be underweight than children who did not receive assistance, but there was no difference in the overweight status between the two cohorts. That study suggested a theoretical framework for energy efficiency and nutrition, but more research is needed to establish causality.

Adult participants with doctor-diagnosed asthma reported that some symptoms were worse following the energy retrofit work while one measure of asthma severity marginally improved. This differs from the New Zealand study of insulation of housing which observed consistent improvements in asthma symptoms among people with prior respiratory problems (Howden-Chapman et al. 2007). The findings are possibly influenced by differences between the two studies. At least one household member in every home in the New Zealand study had a respiratory problem, while only 17 % of the adult population in our study reported that they had asthma. The New Zealand study added moisture barriers to all homes and reports of non-condensation dampness and mold were resolved in 34 % of homes, with mold dropping from 72 % to 38 % of homes and dampness dropping from 64 % to 30 % of homes. Local agencies in our study did not systematically address dampness in all dwellings, and the improvement in wetness/dampness was smaller [dampness improved in 10 % of homes from 52 % to 42 % while mildew/musty odor remained unchanged (20–22 % of homes)].

Another possibility is that aeroallergens in ductwork could be re-entrained during weatherization if the ductwork is disturbed. Future studies should consider measuring aeroallergens during weatherization to determine if this is a significant source of exposure. The impact of exposure to other asthma triggers in our study, e.g., smoking, could conceivably have a larger influence on asthma outcomes compared to the energy improvements.

Key factors that energy retrofits could improve are thermal comfort, humidity, contaminants, and air exchange (U.S. EPA 2012). Our findings documented that contaminants such as CO and NO_2 were low before work began and remained low after work was completed. Our study could have benefited from long-term measurement of all analytes to get a better picture of people's overall exposure to the contaminants. For example, continuous monitoring of temperature and humidity was done in a subset of the New Zealand study homes. However, given the variation in treatments between locations and between buildings, developing a cost-effective sampling plan was not possible. Some local agencies provided indoor temperature readings and air exchange rate data at baseline, but not enough data were available to include them in our analysis. Future studies would benefit from the collection of these data.

Another limitation of this observational study is that we did not have a control group to observe possible health changes in dwellings that did not receive energy retrofits, which makes it possible that some health changes could have been associated with other non-building related factors. At the same time, this study's pre-test/post-test design allowed subjects to be matched and observed for changes in health status. The population in this study was all low-income because this is the sector of the population targeted by many energy conservation programs in the United States. While health status in such populations can be influenced by other non-building related factors, such as access to medical care, nutrition, and other factors, the pre–post design employed here attempted to control for these factors since they were unlikely to change at follow-up. Future studies would benefit from employing both a pre–post design and an external comparison or control group.

This study also did not dictate the treatments that the local agencies implemented, so there is treatment variation by location, building type, and by follow-up observation period. When sample sizes were large enough, we were able to use statistical modeling to control some of these effects, but for outcomes such as asthma symptoms that had smaller sample sizes, modeling was not possible. Had we been able to observe additional dwellings and households for a full 1-year period, the power of our findings may have been strengthened. However, the shorter follow-up period allowed us to find that many of the outcomes including general health, sinusitis symptoms, hypertension, and thermal comfort were significantly better in both the short and long follow-up periods.

Using a questionnaire that was successfully used in prior peer-reviewed studies, we found that homes became more thermally comfortable and less damp while general self-reported health improved from an average score of "good" at baseline toward "very good" at follow-up. Although the ability to assert a causal connection between specific housing actions and health is limited by the study design, the findings complement earlier studies that documented improved health status after energy retrofits.

Conclusions

When residential energy conservation work is conducted by trained professionals following procedures that balance energy efficiency and indoor environmental quality, this study suggests that energy retrofits may have a positive effect on the health of the occupants of the dwellings. This study showed statistically significant improvements in general health, asthma medication use, and sinusitis. Residents were most likely to feel healthier in dwellings where they were satisfied with the energy work. Asthma symptom outcomes were mixed, suggesting that the necessary moisture controls were not consistently applied or other actions beyond heating upgrades and insulation measures may be needed to improve asthma. Future research on residential energy conservation measures should gather data on quantifiable temperature, dampness, and air exchange levels associated with improvements in occupant health.

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Conflict of interest The authors declare they have no competing interests. This study was approved by an Institutional Review Board.

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