ENERGY IMPACTS OF ENERGY AND INDOOR ENVIRONMENTAL QUALITY RETROFITS OF APARTMENTS IN CALIFORNIA

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ABSTRACT

Monthly gas and electricity use data from a set of 13 study apartments and 20 control apartments from three apartment buildings (B1 –B3) in California were analyzed. The study apartments were retrofit with simultaneous energy savings and indoor environmental quality (IEQ) improvements as the goal. The control apartments were not retrofit. Pre-retrofit modeling indicated annual energy savings of 21%, 17%, and 27% for the study apartments in B1-B3, respectively. Based on a comparison of changes in energy use of study apartments to energy use changes of control apartments, total measured savings of gas energy plus site electrical energy were 28% in B1, 5% in B2, and 3% in B3. Given the small number of study apartments and the substantial changes in energy use within control apartments, the project yielded no conclusive evidence of energy savings. Apartment energy use increased with number of occupants and with floor area; however, the association with occupancy was most evident. Climate differences did not appear to be the major driver for the variability in energy use among apartments. Changes in occupant behaviors affecting energy use may have overwhelmed and obscured the energy savings in this small number of buildings. Much larger prior studies employing similar retrofits indicate that the retrofits usually do save energy.

BACKGROUND

The U.S. is implementing many energy retrofits in homes with the goal of reducing building energy consumption and carbon dioxide emissions, as well as improving national energy security. Several protocols and tools exist to help with the selection and implementation of housing energy retrofit measures [1]. These protocols are typically based on energy models, engineering judgment and cost-benefit analysis, rarely considering potential effects on indoor environmental quality (IEQ). Features of IEQ that may be affected by retrofits include thermal comfort conditions, indoor air pollutant concentrations, and acoustic and lighting conditions [2-4]. Although retrofit efforts provide an opportunity to simultaneously save energy and improve occupant's health and comfort, potential IEQ improvement opportunities are often not considered during selection of retrofits measures.

This paper provides the results of analyses of pre and post retrofit energy data from apartments retrofit using a unique retrofit selection protocol designed to maximize overall energy plus IEQ benefits. Although numerous prior papers (discussed subsequently) provide information on the energy savings of home retrofits, no data were identified from prior studies aiming to simultaneously save energy and improve IEQ.

The protocol used to characterize apartments and select retrofits, the selected retrofits and their costs, and the associated diagnostic data are presented in a prior paper [1]. The results of pre- and post-retrofit measurement of IEQ parameters are presented in a second prior paper [5]. The IEQ data indicate a general, but not universal, improvement in IEQ conditions after the retrofits [5].

METHODS

To be considered for inclusion in this study, apartment buildings needed to be located in California's coastal or central-valley regions, serve low income tenants, have four or fewer floors, have been constructed prior to 1990 with no subsequent major energy retrofits, have at least 15 apartments, and have no heating, cooling, or ventilation systems serving multiple apartments. Owners and managers of candidate buildings were contacted to determine if these criteria were met and to assess their interest in participating in the study. Three apartment buildings were selected. These buildings, denoted B1, B2, and B3, are located in Sacramento, Richmond, and Fresno, respectively. Sacramento and Fresno are located in central California where both winter heating and summer air conditioning are normally required. Richmond is located in the San Francisco Bay area, near the Bay, where air conditioning is generally not employed. Flyers were used to recruit 16 study apartments that were subsequently retrofit, and to recruit similar control apartments that are not retrofit. Study costs limited the number of apartments that could be retrofit and evaluated via pre-and post-retrofit diagnostic and indoor environmental quality measurements [1, 5]. Basic descriptive data for the study apartments included in the energy analyses are provide in Table 1. The study apartments had floor areas of 76 to 139 m^2, two to four bedrooms, and one to seven reported occupants. The study was approved by the Lawrence Berkeley National Laboratory (LBNL) Human Subjects Committee.

Table 1. Basic energy-related characteristics of study apartments.

Apartment	Bed-rooms	Floor Area (m^2)	Occu-pants	External Envelope Surfaces	Air Condition-ing	Cooking Fuel	Water Heating Fuel
B1A1	4	92	4	3	Yes	Gas	Gas
B1A4	3	85	4	3	Yes	Gas	Gas
B1A5	4	92	5	4	Yes	Gas	Gas
B2A2	2	76	2	3	No	Gas	Gas
B2A4	3	125	3	4	No	Gas	Gas*
B2A5	3	125	3	3	No	Gas	Gas
B2A6	4	139	7	4	No	Gas	Gas
B3A1	2	80	2	2	Yes	Electricity	Gas
B3A2	2	80	1	3	Yes	Electricity	Gas
B3A3	2	80	5	4	Yes	Electricity	Gas
B3A4	2	80	3	3	Yes	Electricity	Gas
B3A5	3	98	4	3	Yes	Electricity	Gas
B3A6	3	98	4	4	Yes	Electricity	Gas

*shared water heater’s gas use not part of energy bill

In study apartments, packages of retrofits were selected using a unique retrofit selection protocol [1] developed for this project and designed to maximize overall energy plus IEQ benefits. The protocol specifies a set of a-priori retrofits to be implemented whenever possible for compliance with the latest standards. These a-priori retrofits included installation of mechanical ventilation systems and installation of bathroom fans and range hoods vented to outdoors. In B1 apartments and three B3 apartments, small energy recovery ventilators were installed for continuous mechanical ventilation. In the remaining three B3 apartments (A1, A5, and A6), bathroom fans operated continuously at low speed, and then increased speed when occupancy was detected by an integrated occupancy sensor. Rates of continuous mechanical ventilation were set equal to 150% of the requirements of ASHRAE’s residential ventilation standard [6], recognizing that much of the “ventilation” entering apartments comes from surrounding apartments. In the B2 apartments, there was no continuous mechanical ventilation, but bathroom fans were installed that operated automatically for 20 minutes after occupancy was detected. Other a-priori retrofits included low-cost measures deemed cost effective in virtually all cases, such as replacement of incandescent bulbs with compact fluorescent bulbs. The remaining retrofits were selected after apartment inspections and diagnostic measurements. Candidate retrofits were ranked using a scoring system that assigned points based on how the retrofits were projected to affect energy use, indoor air quality (IAQ), and comfort. Each candidate retrofit received an energy score, an IAQ score, and a comfort score, and the summed score was divided by the projected retrofit cost. The retrofits with the highest cost-normalized scores were selected until the retrofit budget was expended. Table 2 lists all of the retrofits implemented in each apartment that are expected to influence building energy consumption. Most of the retrofits selected are typical of those used in many residential retrofit programs, for example envelope and duct sealing, refrigerator replacement, attic insulation, window replacement, replacement of heating and cooling systems and water heaters (only in B1), etc. Retrofits not typically a part of programs that consider only energy efficiency included the mechanical ventilation and range hood measures described above, replacement of gas stoves that had standing pilot lights in B1 (the pilots waste energy and emit pollutants), and installation of energy efficient wall-mounted particle filters in B2 and B3.

In each building, some of the retrofits were expected to reduce gas energy consumption, other retrofits were expected to reduce electricity consumption, and some IEQ improvement measures were expected to increase electricity and/or gas use. In B1, replacement of the water heaters, roof top gas and electric heating and cooling systems, and gas stoves should reduce gas use. Replacement of the refrigerator, incandescent light bulbs, and roof top units should decrease electricity use. The fans and additional ventilation of the energy recovery ventilators were expected to increase electricity and gas use (see related analysis in the discussion section). Apartments in B2 had no air conditioning, thus, only the replacement of the refrigerator and incandescent lights targeted electricity use, while envelope and duct sealing, attic insulation, water heater insulation, and sliding glass door replacements targeted gas consumption. No mechanical ventilation was added in B2 apartments, although, installation of a wall mounted filtration system was a small source of increased electricity consumption. In B3 apartments, envelope and duct sealing, attic insulation, and window replacements targeted both electricity and gas, while replacement of incandescent lights targeted only electricity. The continuous mechanical ventilation systems installed in the retrofit B3 apartments may have increased electricity and gas use, although the envelope tightening should have partially compensated for the increased mechanical ventilation. Installation of wall mounted filtration system was a small source of increased electricity consumption.

Study apartments in B1 were retrofit between August 1 and August 29, 2011. In B2, the retrofits took place between 1/3 and 2/1/2012. The retrofit period for B3 study apartments was 3/5 – 3/29/2012. There were two one-week periods of measurements of a range of IEQ parameters before and after the retrofits, and the resulting data indicate overall improvements in IEQ after the retrofits [5]. Residents of study apartments and of similar un-retrofit control apartments from the same apartment buildings provided access to utility web sites from which monthly electricity and natural gas energy use was obtained for a one year period before and after the retrofit periods. Moves by tenants reduced the amount of data available to less than a full year in several cases, and for a few apartments data were too limited for use. Also, data became unavailable for unknown reasons in some apartments, possibly because utility accounts were transferred to others. The loss of access to data was most pronounced for B1. Usable data were available from only three of five study apartments, and for some analyses usable data were available only for two of five study apartments.

Changes in energy use of study apartments, comparing post-retrofit energy use to pre-retrofit use, were compared to changes in energy use of control apartments. For analyses of annual energy use, energy data were analyzed from 12 monthly billing periods before the retrofits and from 12 corresponding (i.e., same range of dates) monthly billing periods after the retrofits. Data were excluded from any billing period that overlapped with the retrofit period by more than two days. When less than 12 months of data were available from either the pre- or post-retrofit periods, the analyses employed the same amount of data and same periods of data from before and after the retrofits. (Because billing periods varied slightly, the initial and final dates of pre-retrofit and post-retrofit data often differed by 1-3 days.) For inclusion in the annual analyses, data were required for at least 300 days before and after retrofits. Annual total gas and electricity use were calculated and divided by the elapsed days.

Summer and winter seasonal energy were also calculated, again employing data from matched pre- and post-retrofit billing periods and dividing total seasonal energy use by billing days. Energy data from billing cycles between October 31 and March 18 were totaled for winter, and energy data from billing cycles between the June 4 and October 3 were totaled for summer. Actual days of data within these time windows varied depending on the utility's billing dates and were nominally either 120 or 90 days. For inclusion in analyses, at least 90 of 120 days, or 57 of 90 days, of data were required from both the pre-retrofit and post retrofit period.

For every annual or seasonal calculation of energy use, the corresponding heating and cooling degree days for the study city were obtained from the Weather Underground web site <http://www.wunderground.com/history/>. This web site used 18.3 ^{o}C as the based for heating degree days and 29.4 ^{o}C as the base for cooling degree days. Degree days for Oakland, CA were used for B2, located nearby in Richmond, CA.

For each study and control apartment, the percent change in energy use (post-retrofit use minus pre retrofit use, divided by pre-retrofit use, multiplied by 100%) was calculated. Total pre-retrofit and post-retrofit energy use for each set of study apartments (e.g., B1 study apartments) or control apartments (e.g., B1 control apartments) were also calculated, divided by the number of apartments in the set, and the corresponding percent changes were calculated. These totals were used because simple averages of the percentage changes in the individual apartment energy use data were sometimes highly influenced by the large percentage changes from apartments with small energy use.

Pre-retrofit energy use, and changes in energy use, often varied highly among the apartments within each set of study or control apartments. Consequently, the previously described percentage changes in total energy use were often highly affected by outliers -- large changes in the energy use of individual apartments. Therefore, in "n-1" analyses, the percentage changes in total energy use were also calculated after excluding the data from the apartments with the largest percentage change in energy use within each set. This calculation was not performed for B1 apartments, because even before excluding data, energy use was available from only three (and in some cases only two) apartments.

Table 2. Retrofits implemented in each apartment.

Building 1, Apartment Numbers	A1			A4	A5	
Weather-strip entry doors	X			X	X	
Replace packaged heating and cooling system with more efficient unit	X			X	X	
Replace natural draft water heater with more efficient condensing unit	X			X	X	
Replace refrigerator with more energy efficient refrigerator	X			X	X	
Replace cook stove with standing pilot with electronic ignition stove	X			X	X	
Replace incandescent light bulbs with compact fluorescent bulbs	X			X	X	
Provide portable fan for air movement	X			X	X	
Replace kitchen range hood with higher flow unit	I			I	I	
Add continuous mechanical ventilation with energy recovery ventilator	I			I	I	
Replace bathroom fan with fan that operates automatically when high humidity	I			I	I	
Install better particle filter in heating and cooling system	I			I	I	
Building 2, Apartment Numbers		**A2**		**A4**	**A5**	**A6**
Seal leaks in building envelope		X		X	X	X
Replace HVAC ducts and seal return air plenum		X		X	X	X
Replace single pane sliding glass door with double pane door		X				
Add attic insulation		X			X	X
Weather strip door of vented closet containing water heater				X	X	
Replace refrigerator with more energy efficient refrigerator		X		X	X	X
Add water heater insulation jacket				X	X	X
Replace incandescent light bulbs with compact fluorescent bulbs		X		X	X	X
Replace kitchen range hood with higher flow unit		I		I	I	I
Replace bathroom fan with fan that operates when occupant detected		I		I	I	I
Provide portable fan for air movement*		I		I	I	I
Install more efficient particle filter in heating and cooling system		I		I	I	I
Install wall mounted fan-filter system		I		I	I	I
Building 3, Apartment Numbers	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
Seal leaks in building envelope	X	X	X	X	X	X
Replace HVAC ducts and seal return air plenum		X		X		X
Add attic insulation		X	X	X		X
Replace single pane window with double pane window	X				X	X
Replace refrigerator with more energy efficient refrigerator	X	X	X	X	X	X
Replace incandescent light bulbs with compact fluorescent bulbs	X	X	X	X	X	X
Replace kitchen range hood with higher flow unit	I	I	I	I	I	I
Add continuous mechanical ventilation with bathroom exhaust fan	I				I	I
Add continuous mechanical ventilation with energy recovery ventilator		I	I	I		
Provide portable fan for air movement	I	I	I	I	I	I
Install more efficient particle filter in heating and cooling system	X	X	X	X	X	X
Install wall mounted fan-filter system	I	I	I	I	I	I

Key: **X** is retrofit implemented and expected to generally reduce energy use, some of these retrofits may also improve IEQ; **I** is a retrofit implemented and intended to improve an aspect of IEQ that may increase energy use; shaded cell means apartment number not included in the study or insufficient energy data available; empty cell means the retrofit was not implemented; *will not save energy in B2 because B2 has no air conditioning

RESULTS
Tables A1 –A9 in the appendix provide pre-retrofit and post-retrofit gas and electricity energy use per day, for the annual, winter, and summer periods, for each study apartment and each control apartment. The corresponding days within the billing periods, heating degree days, and cooling degree days are provided. The tables also include the percentage change in energy use for each apartment, the percentage changes in total energy use, and the percentage changes in total energy use after omitting outliers via the “n-1” analysis process.

Figure 1 shows the percent changes in annual heating degree days (HDD) and cooling degree days (CDD) between the pre-retrofit and post-retrofit periods, for each set of study and control apartments. Cooling degree days for B1 and B2 are 26% to 27% higher during the post retrofit year. Cooling degree days are not shown for B2, because it had no air conditioning. Heating degree days for B3 apartments decreased in the post-retrofit year by 16% to 19%, and by a few percent for apartments in B1 and B2. The changes in degree days are nearly identical for study and control apartments. On average the changes in weather should have affected energy use similarly in study apartments and control apartments.

Figure A1 in the appendix shows the annual energy use data, for apartments in B1 through B3, respectively, and provides the associated percentage changes in energy use. Figure A2 provides analogous plots for winter gas consumption and summer electricity consumption. Figure A3 illustrates summer gas and winter electricity use; i.e., gas use from a period of essentially no HDD and electricity use from a period with essentially no CDD. In these figures, the letter “c” in the apartment code indicates that the apartment is a control apartment that was not retrofit. It is evident from the figures, and from Table 3, which combines pre-retrofit data from study and control apartments within buildings that there is a large range in the energy use of the rather similar apartments within the same building, particularly in B2 and B3 where the range is a factor of 2.5 to 4.0.

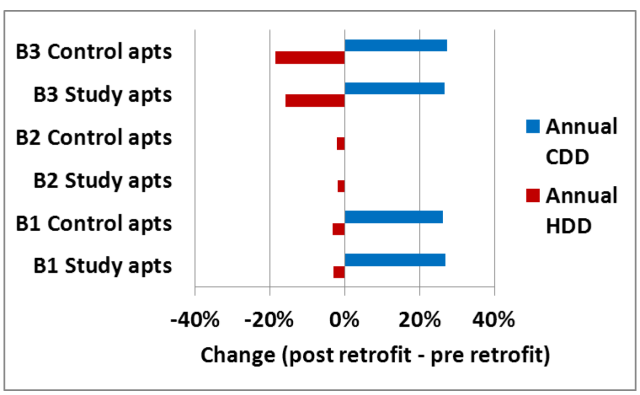

Figure 1. Changes in annual heating degree days (HDD) and cooling degree days (CDD).

Table 3. Range in pre-retrofit energy use among apartments within buildings

Apartments, Fuel (number)	Minimum kWh/d	Maximum kWh/d	Ratio (Max/Min)
B1, Gas (n = 8)	27.0	40.7	1.5
B1, Elec (n=8)	6.9	18.6	2.7
B2, Gas (n=11)	11.1	44.5	4.0
B2, Elec. (n=11)	4.7	17.4	3.7
B3, Gas (n=11)	20.5	50.4	2.5
B3, Elec. (n=11)	6.6	26.2	4.0

Figure 2. shows that pre-retrofit energy plotted versus occupancy, floor area, and number of external envelope surfaces (walls plus ceiling). Based on the values of R^2 the association with occupancy is most evident. The association of both gas and electricity use with number of external envelope surfaces is weak, with R^2 values 0.20 and 0.14.The building number is a proxy for climate, with B2 having the most moderate climate and B2 apartments having no air conditioning. However, apartments from B2 do not consistently use less energy than apartments from B1 or B3. Clearly, climate differences are not the major driver for the variability in energy use.

Pre-retrofit to post-retrofit differences in energy use in control apartments were substantial. Table 4 shows the ranges and average of the absolute values of the percent changes within the individual control apartments. Changes range from -40% to 102%, with averages of absolute values of percent changes ranging from 11% to 34%.

The overall energy savings, based on change in total energy use per apartment in study apartments minus the change in in total energy use per apartment in control apartments is illustrated in Figure 3. The data suggest gas energy savings, larger in the winter than annually or during the summer. Estimated annual gas energy savings are 25% in B1 but only 7% in B2 and B3. The data indicate a 41% annual electricity savings in B1, but this number is based on only two study apartments versus six control apartments. The data from B2 and B3 indicate 3% and 17% increases (as opposed to expected savings) in annual electricity use of study apartments relative to control apartments. For B3, the percentage increase in electricity use of study apartments versus control apartments is smaller during the summer air conditioning season than for the full year, indicating that increased air conditioning does not likely explain increased electricity use. There is a striking 49% increase in winter electricity use of B3 study apartments relative to B3 control apartments, driven substantially by the changes in electricity use in one study apartment and one control apartment, as discussed subsequently.

Figure 4 shows the alternate estimate of energy savings for B2 and B2 obtained via the “n-1” analysis. The data continue to indicate small annual gas energy savings and small annual increases in electricity use; however, some of the seasonal results have change dramatically. In place of the 49% increase in winter electricity use in B3, the “n-1” analysis, which excluded data from one study apartment and one control apartment, indicates a 6% savings. Also, the 3% summer gas energy savings for B2 in Figure 3 becomes a 31% savings in the “n-1” analysis. These large changes indicate that the study size is clearly too small to yield accurate estimates of average energy savings from the retrofits.

When gas energy and electricity site energy are combined, the data indicate annual savings of 28% in B1, 5% in B2, and 3% in B3. These savings are again based on of energy use changes in study apartments minus energy use changes in control apartments. The predicted energy savings were 21%, 17%, and 27% for B1-B3, respectively [1]. Only in B1 are the measured savings comparable to the predictions.

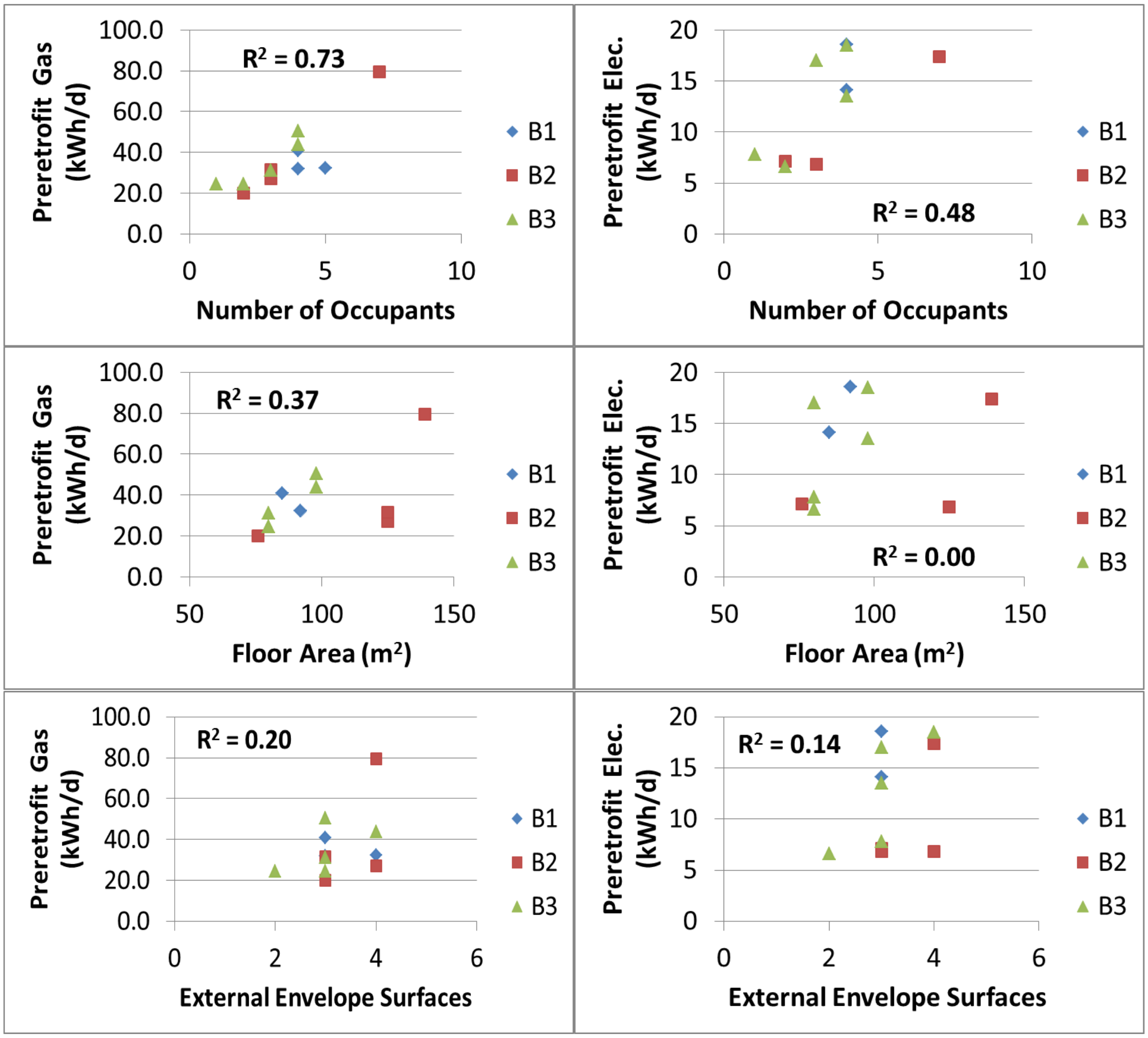

Figure 2. Pre-retrofit energy use of study apartments plotted versus number of occupants, floor area, and number of envelope surfaces (walls plus ceiling) exposed to outdoors.

Table 3. Changes in energy use in control apartments.

Apartments (number)	Minimum	Maximum	Average Absolute Value Change
B1 Gas (n = 6)	-4%	28%	11%
B1 Elec (n=7)	5%	102%	34%
B2 Gas (n=7)	-18%	36%	13%
B2 Elec (n = 7)	-15%	22%	11%
B3Gas (n=6)	-40%	21%	19%
B3 Elec (n=6)	-15%	23%	17%

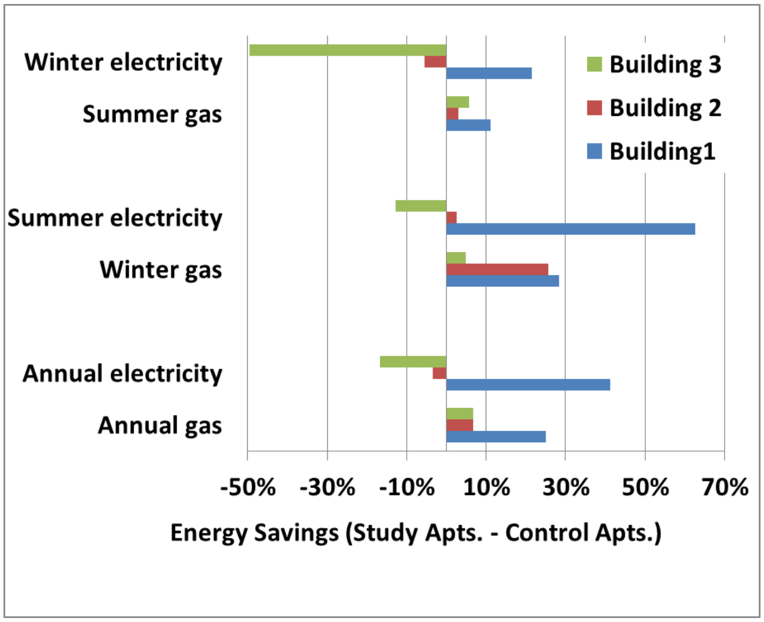

Figure 3. Estimated overall energy savings based on changes in energy use of study apartments minus changes in energy use of control apartments.

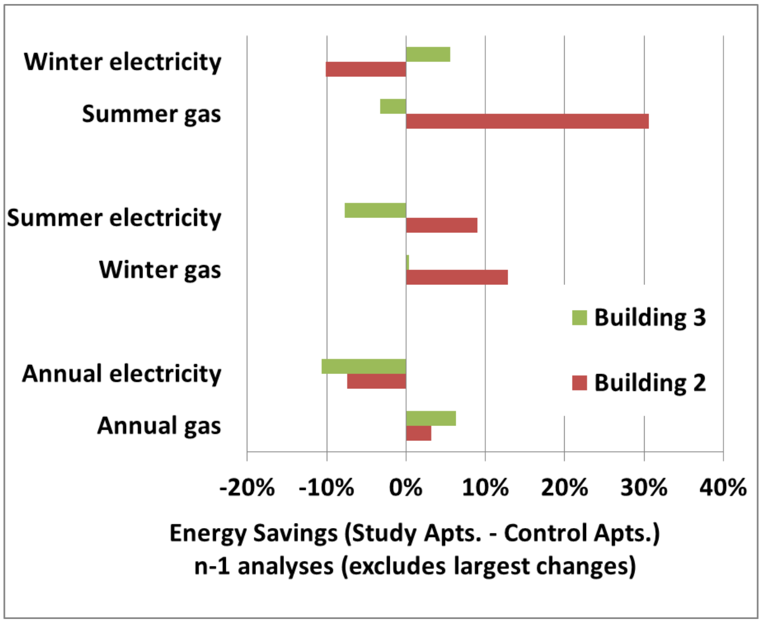

Figure 4. Estimated energy savings in B2 and B3 via the “n-1” analysis that excludes data from outliers.

DISCUSSION

Analysis of energy savings

The retrofits implemented in this study are widely believed to reduce energy consumption. Predicted energy savings were 21%, 17%, and 29% for B1 – B3, respectively [1], while measured energy savings were 28%, 5%, and 3%. Hypothetical explanations for the large discrepancy between predicted savings and findings from B2 and B3 are listed below and discussed in the following paragraphs:

H1. The selected retrofits, contrary to general belief, are ineffective in reducing energy consumption.

H2. Retrofit measures included to improve IEQ increased energy use and counteracted the energy savings of other measures.

H3. Changes in apartment use and occupant behaviors obscured the anticipated energy savings.

Relative to the first hypothesis, we note that the evidence of energy savings in B1, but not in B2 and B3, might be partially explained by differences in the retrofits implemented. In B1, the packaged rooftop heating and cooling systems, and the water heaters, were replaced with new more energy efficient units. Also, gas stoves with standing pilot lights were replaced. Analogous retrofits were not implemented In B2 and B3. Envelope sealing, attic insulation, and window or sliding glass door replacements were implemented in B2 and B3, but not in B1. Average spending on retrofits was higher in B1 ($12,700 per apartment) than in B2 ($7700 per apartment) or B3 ($9000) per apartment. An analysis of the national weatherization program found that attic insulation, insulating water heaters, installing low flow showerheads, and replacing inefficient heating systems were among the most effective energy savings measures [7]. Installation of storm windows and doors was less effective [7]. Overall; however, sufficient prior data are available from much larger studies to reject the hypothesis that these energy efficiency measures are ineffective. An analysis of measured data from retrofits of over 25,000 housing units [8] from multifamily dwellings indicated energy savings of 14% to 16%, although these retrofits took place prior to 1988 when savings opportunities were likely larger. A much more recent study of retrofits of more than 21,000 housing units in 231 properties in New York City reported a 19% reduction in fuel energy and 7% reduction in electricity [9]. In the milder California climate, smaller absolute but similar magnitude percentage savings would be anticipated. An analysis, published in 1995, of measured data from the National Weatherization Assistance Program (NWAP), which targets single family and multi-family homes of low income persons, indicated a 13.5% reduction in total energy use [7]. A subsequent meta-analysis of 17 state-level evaluations of the NWAP indicates a 23% reduction in natural gas use in gas-heated homes [10]. Each of these larger programs that reported energy savings employed retrofit measures that overlap highly with the retrofits in the present study. Thus, one can conclude that, on average, these retrofits save energy.

With respect to hypothesis 2, it is clear that that some of the retrofits included in the study to improve IEQ lead to energy consumption; however, the amount of energy consumed is moderate. The 23 W fans in the energy recovery ventilators installed in B1 apartments and in three apartments in B3 are projected to consume 0.55 kWh per day, if operated continuously. The automatic intermittent operation of bathrooms fans in apartments are projected to consume a negligible 0.01 kWh per day if operation is triggered 10 times per day with 20 minute operation periods. The exhaust fans operating continuously in three B3 apartments consume a projected 0.1 kWh per day. The wall-mounted air cleaners installed in B2 and B3, were projected to consume 0.22 kWh per day, assuming they were run in the automatic mode(as recommended) which employs a low fan speed most of the time (assumed 70% of time) and higher fan speeds when elevated indoor concentrations of particles are detected. Together, the added fans consume about 3% and 2.4% of total average pre-retrofit electricity consumption of B1 and B2 apartments, respectively. In the three B3 apartments with energy recovery ventilators and air cleaners, the added fans are projected to consume 5.7% of average pre-retrofit electricity. In the remaining three B3 apartments, with continuously operating bath fans and air cleaners, the added fans are projected to consume 2.4% of average pre-retrofit electricity. These calculations assume no change in range hood fan energy, as data indicated no increase in range hood use after retrofits [1].

The effects of envelope sealing plus operation of continuous mechanical ventilation systems (installed in B1 and B3 apartments) on space conditioning (heating and cooling) energy use are less readily estimated. The B1 apartments and three of the B3 apartments had energy recovery ventilators installed, with significant envelope sealing only in B3. The manufacturer reports 66% and 33% sensible and latent energy recovery by the energy recovery ventilator. The remaining three B3 apartments had envelope sealing and continuously-operating exhaust fans installed. Modeling of single family homes indicates that envelope sealing plus continuous mechanical ventilation at a rate sufficient to meet the requirements of ASHRAE Standard 62.2 [6] will decrease space conditioning energy consumption, particularly when the mechanical ventilation system includes energy recovery [11]. There are key differences between the modeled scenario and actual study. First, in the present study there was no significant envelope sealing in the B1 apartments, thus, the mechanical ventilation in B1 must have increased space conditioning energy use. However, the data from the B1 apartments still suggests energy savings. Second, sealing of envelopes in apartments may be less effective in reducing infiltration from outdoors than sealing envelopes in single family homes. Third, the mechanical ventilation rates in the present study were 150% of the rates prescribed in the ASHRAE Standard. However, in apartments much of the “ventilation” air comes from surrounding apartments, and these surrounding apartments are typically heated or cooled. Thus, the amount by which the mechanical ventilation systems increased ventilation from outdoors, imposing heating or cooling loads, may not have been larger than prescribed in ASHRAE Standard 62.2. The seasonal trends in changes in energy use suggest that space conditioning loads caused by mechanical ventilation do not explain the lack of energy savings. The data indicate savings in B1 despite continuous mechanical ventilation of all B1 apartments and no apartment envelope sealing. There was no continuous mechanical ventilation in B2, and still the measured energy savings were small. In B3, full year and winter time gas energy consumption decreased by a similar small amount. Also, full year electricity use in B3 apartments increased by more than summer electricity use, suggesting that ventilation-caused mechanical ventilation was not a major cause of the increase in electricity use in B3.

Considering the information provided in the prior two paragraphs, the energy consumption of IEQ improvement measures appears insufficient to explain more than a modest portion of the large discrepancy between predicted and measured energy savings in B2 and B3. However, uncertainties remain with respect to the effects of mechanical ventilation in B1 and B3 on apartment energy use.

The study data are consistent with hypothesis 3. The large variability in pre-retrofit energy use in apartments within the same building (Table 3), the large, both positive and negative, changes in energy use within control apartments (Table 4), and evidence that climate was not the major driver for variability in energy use (Figure 2), all suggest that changes in occupants behaviors strongly affected energy use. These findings plus a comparison of results of the "n-1" analysis to results of the primary analysis all indicate that the present study was too small to provide a reliable estimate of the effects of the retrofits on energy consumption. There is an increasing appreciation of the large effects of occupant behaviors on building energy consumption [12, 13]. Also, there is a recognized take-back or rebound effect, in which people use more energy, e.g., via increased space heating and cooling, after energy efficiency retrofits [14]. Finally, in these apartments, the number of occupants may have varied significantly over time and, as shown in Figure 4, occupancy was a fairly strong predictor of apartment energy use.

Relative to hypothesis 3, the large changes in winter electricity use in apartments B3A5 and B3A1c are notable. In study apartment B3A5, post retrofit winter electricity was 79% higher than pre-retrofit winter electricity use. Changes in this magnitude might be explained by use of electric space heating only in the post-retrofit year; however, at the start of the study tenants reported not having an electric space heater. Also, the increase in winter electricity use was accompanied by a simultaneous 27% increase in winter gas use; thus, electrical heat was not obviously substituting for gas heat. In control apartment B3A1c, winter electricity use was 69% lower in the post retrofit year while winter gas use increased 21%, suggesting the possibility that electrical space heating in the pre-retrofit period was partially replaced by gas heating in the post-retrofit period. However, the tenants of B3A1c also reported not having an electric space heater. The reasons for the large changes in winter electricity use of these two apartments are unknown.

Study strengths and limitations

Key strengths of this study include the reliance on a full year of pre-retrofit and post-retrofit measured energy data. Many studies have simply predicted energy savings. Also, the inclusion of numerous similar control apartments from the same apartment buildings is a strength. The main study weakness is the small number of apartments. The study size was cost constrained, much of the budget was expended to develop the retrofit selection protocol, implement the retrofits, and implement and analyze pre- and post-retrofit IEQ data [1]

CONCLUSIONS

Analyses of pre- and post-retrofit energy data from apartments receiving energy retrofits and from control apartments suggest small energy savings, driven by reductions in natural gas use. Because of the small number of retrofit apartments, the data provide no conclusive evidence of retrofit-caused energy savings. Much larger studies employing similar retrofits have shown that the retrofits usually save energy.

Apartment energy use increased with number of occupants. The associations of apartment energy use with apartment floor area and with number of external envelope surfaces were weak.

There were large and variable year-to-year changes in energy use in control apartments, potentially caused, in part, by changes in occupant behavior and occupancy. Given that magnitude of these natural changes in apartment energy use, the present study was too small to determine the energy impacts of the retrofits on energy consumption.

The study included retrofit measures designed to improve IEQ and some of these measures increased energy consumption. Although uncertainty remains, the energy consumption of the IEQ-improvement measures appears insufficient to explain why the measured energy savings in B2 and B3 are far smaller than the predicted savings.

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Appendix 1. Tables and plots of energy consumption.

Table A1. Annual energy use in B1

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	yr	**yr**	**yr**	**yr**	**yr**
Period		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**		Pre	**Post**	**Pre**	**Post**	**Post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	CDD/d (°C)	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B1A1	363	3.99	3.87	31.9	26.1	-18%	365	1.63	2.07	18.6	17.1	-8%
B1A4	363	3.99	3.87	40.7	26.7	-35%	365	1.63	2.07	14.1	11	-22%
B1A5	363	3.99	3.87	32.2	27.5	-15%	155	1.14	1.27			
B1 total				35.0	26.8	-23%				16.4	14.1	-14%
B1 "n-1" total						-16%						
B1A2c	363	3.99	3.87	29.9	38.4	28%	365	1.63	2.07	11.6	14.2	22%
B1A4c	331	4.36	4.17	37.5	36.0	-4%	365	1.63	2.07	6.9	9.6	40%
B1A5c												
B1A6c												
B1A8c	363	3.99	3.87	36.9	32.8	-11%	365	1.63	2.03	12.9	14.5	12%
B1A9c	304	4.78	4.62	27.0	25.2	-7%	336	1.41	1.73	13.3	13.9	5%
B1A10c												
B1A11c	363	3.99	3.87	33.7	34.6	3%	365	1.63	2.07	13.2	16.3	23%
B1A13c							362	1.60	2.07	6.5	13.1	102%
B1c total				33.1	33.6	2%				10.7	13.6	27%
B1c "n-1" total						-5%						21%

Table A2. Annual energy use in B2.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**	**yr**
Period		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	**CDD/d (°C)**	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B2A2	362	4.53	4.44	19.9	13.2	-34%	362	0.23	0.09	7.1	6.5	-9%
B2A4	362	4.53	4.44	27.2	27.8	2%	362	0.23	0.09	6.8	6.5	-5%
B2A5	362	4.53	4.44	31.4	28.1	-10%	362	0.23	0.09	6.8	6.9	2%
B2A6	362	4.53	4.44	79.4	85.8	8%	362	0.23	0.09	17.4	17.8	2%
B2 total				39.5	38.7	-2%				9.5	9.4	-1%
B2 "n-1" total						0%						0%
B2A2c	362	4.53	4.44	27.8	30.2	8%	362	0.23	0.09	9.2	9.7	6%
B2A3c	362	4.53	4.44	8.2	11.1	36%	362	0.23	0.09	4.7	5.7	22%
B2A4c	362	4.53	4.44	10.3	11.7	14%	362	0.23	0.09	8.8	7.4	-15%
B2A5c	362	4.53	4.44	16.7	13.8	-18%	362	0.23	0.09	5.4	5.3	-3%
B2A6c	362	4.53	4.44	35.7	39.6	11%	362	0.23	0.09	5.9	5.4	-8%
B2A7c	331	4.13	3.98	12.9	13.5	5%	331	0.26	0.1	6.9	5.8	-15%
B2A9c	362	4.53	4.44	44.5	44.0	-1%	362	0.23	0.09	10.2	9.3	-9%
B2c total				22.4	23.5	5%				7.3	7.0	-5%
B2c "n-1" total						3%						-8%

Table A3. Annual energy use in B3.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**	**year**
Period		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	**CDD/d (°C)**	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B3A1*	304	3.51	3.13	24.6	26.4	7%	364	3.20	4.07	6.6	9.0	36%
B3A2	363	3.47	2.79	24.3	15.8	-35%	363	3.20	4.07	7.8	6.4	-18%
B3A4	332	3.36	2.87	31.1	27.8	-10%	332	3.48	4.38	17	20.1	18%
B3A5	333	3.36	2.87	50.4	45.1	-10%	333	3.48	4.38	13.5	19.9	47%
B3A6	363	3.47	2.79	44.0	33.1	-25%	363	3.20	4.07	18.5	22.2	20%
B3 total				35.0	29.5	-16%				12.6	15.3	22%
B3 "n-1" total						-10%						14%
B3A1c	363	3.47	2.79	28.7	30.8	7%	363	3.20	4.07	26.2	22.4	-15%
B3A2c	363	3.47	2.79	34.3	28.4	-17%	363	3.20	4.07	13.6	13.9	2%
B3A3c	363	3.47	2.79	23.4	28.4	21%	363	3.20	4.07	11.2	15.9	42%
B3A4c	335	3.33	2.87	24.9	24.0	-4%	335	3.42	4.38	18.8	23.2	23%
B3A8c	363	3.47	2.79	25.5	19.3	-24%	363	3.20	4.07	15.8	17.9	13%
B3A9c	363	3.47	2.79	20.5	12.3	-40%	363	3.20	4.07	24.5	22.8	-7%
B3c total				26.2	23.9	-9%				18.3	19.3	5%
B3c "n-1" total						-3%						3%

Table A4. Winter gas and summer electricity use in B1.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**win**	**win**	**win**	**win**	**win**	**win**	**sum**	**sum**	**sum**	**sum**	**sum**	**sum**
Period		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**		**Pre**	**Post**	**Pre**	**Post**	**Post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	**CDD/d (°C)**	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B1A1	120	8.84	8.63	43.7	39.8	-9%	120	4.50	5.22	27.9	17.1	-39%
B1A4	120	8.84	8.63	68.0	32.8	-52%	120	4.50	5.22	23.6	19.7	-17%
B1A5	120	8.84	8.63	43.7	41.3	-5%	120	4.50				
B1 total				51.8	38.0	-27%				25.8	18.4	-29%
B1 "n-1" total						-7%						
B1A2c	120	8.84	8.63	46.9	60.7	29%	120	4.50	5.22	15.2	21.3	40%
B1A4c	120	8.84	8.63	61.8	56.0	-9%	120	4.50	5.22	8.1	13.5	67%
B1A5c												
B1A6c												
B1A8c	120	8.84	8.63	41.6	36.0	-13%	120	4.50	5.08	13.8	17.6	28%
B1A9c	120	8.84	8.63	36.0	31.4	-13%	91	4.62	4.96	17.0	18.3	8%
B1A10c												
B1A11c	120	8.84	8.63	46.6	51.3	10%	120	4.50	5.08	20.3	25.5	26%
B1A13c	120	8.84	8.63	37.8	40.4	7%	115	4.50	5.30	13.4	20.6	54%
B1c total				45.1	46.0	2%				14.5	19.5	34%
B1c "n-1" total						-4%						31%

Table A5. Winter gas and summer electricity use in B2.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	win	win	win	win	win	win	sum	sum	sum	sum	sum	sum
Period		Pre	Post	Pre	Post	Post-Pre		Pre	Post	Pre	Post	Post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B2A2	87	5.33	7.51	31.9	19.0	-40%	90	0.31	0.06	7.0	6.2	-11%
B2A4	88	5.33	7.51	39.8	44.5	12%	90	0.31	0.06	6.9	5.9	-14%
B2A5	88	5.33	7.51	56.5	40.1	-29%	90	0.31	0.06	6.8	6.4	-6%
B2A6	88	5.33	7.51	105.2	120.4	14%	90	0.31	0.06	18.4	18.9	3%
B2 total				58.5	56.1	-4%				9.8	9.4	-4%
B2 "n-1" total						-1%						-5%
B2A2c	88	5.33	7.51	27.8	61.8	122%	90	0.31	0.06	8.8	10.3	17%
B2A3c	88	5.33	7.51	16.4	21.7	32%	90	0.31	0.06	4.3	4.9	14%
B2A4c	88	5.33	7.51	14.7	21.1	44%	90	0.31	0.06	8.9	6.9	-23%
B2A5c	88	5.33	7.51	27.8	18.8	-33%	90	0.31	0.06	5.6	5.8	3%
B2A6c	88	5.33	7.51	48.6	57.7	19%	90	0.31	0.06	5.5	5.2	-4%
B2A7c							90	0.31	0.06	6.1	6.8	11%
B2A9c	88	5.33	7.51	68.3	66.5	-3%	90	0.31	0.06	9.6	8.1	-15%
B2c total				33.9	41.3	22%				7.0	6.9	-2%
B2c "n-1" total						12%						4%

Table A6. Winter gas and summer electricity use in B3.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	win	win	win	win	win	win	sum	sum	sum	sum	sum	sum
Period		Pre	Post	Pre	Post	Post-Pre		Pre	Post	Pre	Post	Post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B3A1*	121	8.61	7.09	32.5	42.2	30%	121	8.60	9.83	11.8	16.9	43%
B3A2	121	8.17	7.09	34.6	21.1	-39%	121	8.63	9.82	11.1	7.6	-32%
B3A3	91	6.15	4.29	34.6	31.4	-9%	121	8.63	9.82	28.6	44	54%
B3A4	121	8.17	7.09	45.7	44.2	-3%	121	8.63	9.82	28.5	32.3	13%
B3A5	121	8.17	7.09	50.4	45.1	-10%	121	8.63	9.82	18.8	23.8	27%
B3A6	121	8.17	7.09	78.8	51.6	-35%	121	8.63	9.82	35.4	41.2	16%
B3 total				46.6	39.6	-15%				22.4	27.6	24%
B3 "n-1" total						-6%						16%
B3A1c	121	8.17	7.09	46.9	56.3	20%	121	8.6	9.83	27.6	33.4	21%
B3A2c	121	8.17	7.09	38.4	40.1	5%	121	8.63	9.82	19.3	19.8	3%
B3A3c	121	8.17	7.09	35.2	35.2	0%	121	8.63	9.82	16.4	25.4	55%
B3A4c	121	8.17	7.09	43.7	40.4	-7%	121	8.63	9.82	30.7	37.6	22%
B3A8c	121	8.17	7.09	33.4	19.0	-43%	121	8.63	9.82	27.0	28.2	4%
B3A9c	121	8.17	7.09	31.9	14.9	-53%	121	8.63	9.82	47.3	42	-11%
B3c total				38.2	34.3	-10%				28.1	31.1	11%
B3c "n-1" total						-5%						8%

*Omitted data from Aprils, reported pre-retrofit gas use in April was extremely high (161 kWh/d), is suspect data.

Table A7. Summer gas and winter electricity use in B1.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	sumr	sumr	sum	sum	sum	sum	win	win	win	win	win	winter
Period		Pre	Post	Pre	Post	post-Pre		Pre	Post	pre	pre	post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B1A1	90	0.02	0.04	24.4	15.0	-39%	123	0.01	0.00	14.3	12.7	-11%
B1A4	90	0.02	0.04	20.5	24.7	21%	123	0.01	0.00	9.1	4.4	-52%
B1A5	90	0.02	0.04	25.1	21.5	-14%	94	0.01	0.00	17.4	16.0	-8%
B1 total				23.3	20.4	-13%				13.3	10.6	-20%
B1 “n-1” total						3%						-10%
B1A2c	90	0.04	0.04	17.4	16.9	-3%	123	0.01	0.00	10.6	9.2	-13%
B1A4c	89	0.02	0.04	15.1	18.5	22%	123	0.01	0.00	7.3	8	10%
B1A5c							123	0.01	0.00	8.8	8.2	-7%
B1A6c							117	0.01	0.00	9.6	5.7	-41%
B1A8c	90	0.02	0.04	30.3	27.0	-11%	123	0.01	0.00	14.6	12.8	-12%
B1A9c							123	0.01	0.00	12.1	12.1	0%
B1A10c							95	0.01	0.00	10.5	11.5	10%
B1A11c	90	0.02	0.04	24.1	23.1	-4%	123	0.01	0.00	10	11.7	17%
B1A13c							123	0.01	0.00	3.8	9.3	145%
B1c total				21.7	21.4	-2%				9.7	9.8	1%
B1c “n-1” total						-6%						-5%

Table A8. Summer gas and winter electricity use in B2.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	sum	sum	sum	sum	sum	sum	win	win	win	win	win	winter
Period		Pre	Post	Pre	Post	post-Pre		Pre	Post	pre	pre	post-Pre
Parameter	days	HDD/d (°C)	HDD/d (°C)	kWh/d	kWh/d	change	days	CDD/d (°C)	CDD/d (°C)	kwh/d	kwh/d	change
B2A2	90	2.03	1.75	10.0	8.5	-15%	88	0.01	0.00	7.4	7.2	-3%
B2A4	90	2.03	1.75	19.3	18.2	-6%	88	0.01	0.00	7.6	8.0	6%
B2A5	90	2.03	1.75	17.3	20.2	17%	88	0.01	0.00	6.9	7.2	4%
B2A6	90	2.03	1.75	67.7	61.8	-9%	88	0.01	0.00	17.4	17.9	3%
B2 total				28.6	27.2	-5%				9.8	10.1	2%
B2 “n-1” total						-10%						1%
B2A2c	90	2.03	1.75	16.4	5.6	-66%	88	0.01	0	12.2	9.8	-19%
B2A3c	90	2.03	1.75	2.9	4.1	40%	88	0.01	0	5.4	8.1	49%
B2A4c	90	2.03	1.75	6.2	6.2	0%	88	0.01	0	9.2	7.8	-15%
B2A5c	90	2.03	1.75	9.7	10.5	9%	88	0.01	0	5.4	5.5	1%
B2A6c	90	2.03	1.75	26.4	29.9	13%	88	0.01	0	6.5	5.4	-18%
B2A7c	90	2.03	1.75	5.3	8.5	61%						
B2A9c	90	2.03	1.75	28.1	28.4	1%	88	0.01	0	10.2	10.8	7%
B2c total				13.6	13.3	-2%				8.2	7.9	-3%
B2c “n-1” total						21%						-9%

Table A9. Summer gas and winter electricity use in B3.

Energy type	gas	gas	gas	gas	gas	gas	elec	elec	elec	elec	elec	elec
Season	**sum**	**sum**	**sum**	**sum**	**sum**	**sum**	**win**	**win**	**win**	**win**	**win**	**win**
Period		**Pre**	**Post**	**Pre**	**Post**	**post-Pre**		**Pre**	**Post**	**pre**	**pre**	**post-Pre**
Parameter	**days**	**HDD/d (°C)**	**HDD/d (°C)**	**kWh/d**	**kWh/d**	**change**	**days**	**CDD/d (°C)**	**CDD/d (°C)**	**kwh/d**	**kwh/d**	**change**
B3A1*	121	0.03	0.01	13.8	14.9	9%	121	0	0.09	4.6	4.9	9%
B3A2	121	0.03	0.01	16.1	12.0	-25%	121	0	0.07	7.0	5.8	-17%
B3A3	121	0.03	0.01	12.6	12.9	2%	62	0	0.14			
B3A4	121	0.03	0.01	19.6	16.7	-15%	121	0	0.07	10.0	10.0	1%
B3A5	121	0.03	0.01	36.9	32.2	-13%	121	0	0.07	11.6	20.8	79%
B3A6	121	0.03	0.01	19.3	19.3	0%	121	0	0.07	10.5	10.9	4%
B3 total				19.7	18.0	-9%				8.7	10.5	20%
B3 “n-1” total						-3%						-1%
B3A1c	121	0.03	0.01	12.0	17.0	41%	121	0	0.09	41.8	13.0	-69%
B3A2c	121	0.03	0.01	24.3	21.4	-12%	121	0	0.07	10.9	11.5	5%
B3A3c	121	0.03	0.01	14.7	14.4	-2%	121	0	0.07	8.7	10.3	19%
B3A4c	121	0.03	0.01	11.1	11.7	5%	121	0	0.07	10.6	10.2	-3%
B3A8c	121	0.03	0.01	20.2	18.8	-7%	121	0	0.07	11.4	10.9	-4%
B3A9c	121	0.03	0.01	12.0	10.0	-17%	121	0	0.07	8.7	9.14	6%
B3c total				15.7	15.5	-1%				15.3	10.8	-29%
B3c “n-1” total						-7%						5%

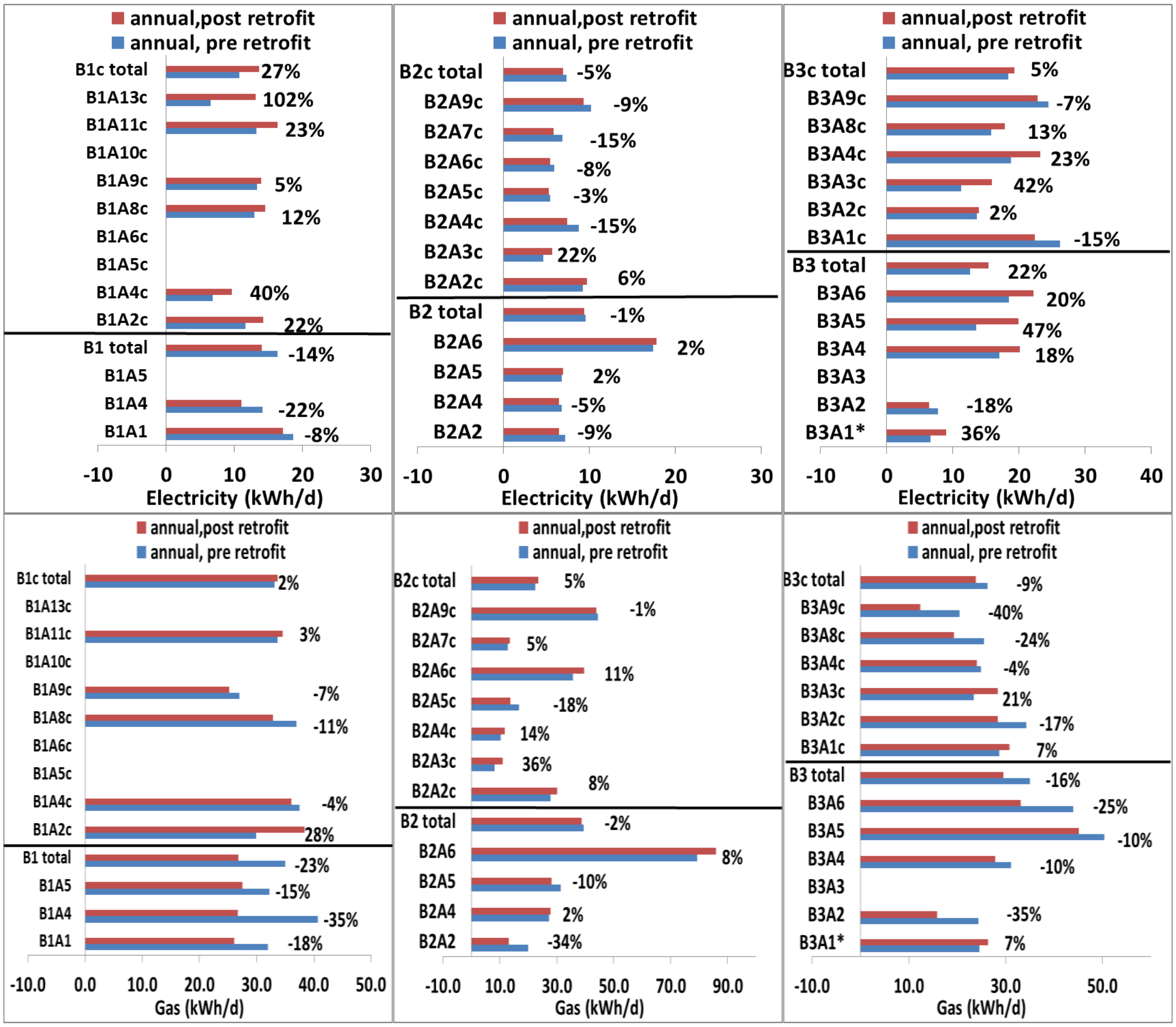

Figure A1.Plots of annual pre- and post-retrofit energy use in study apartments and control apartments

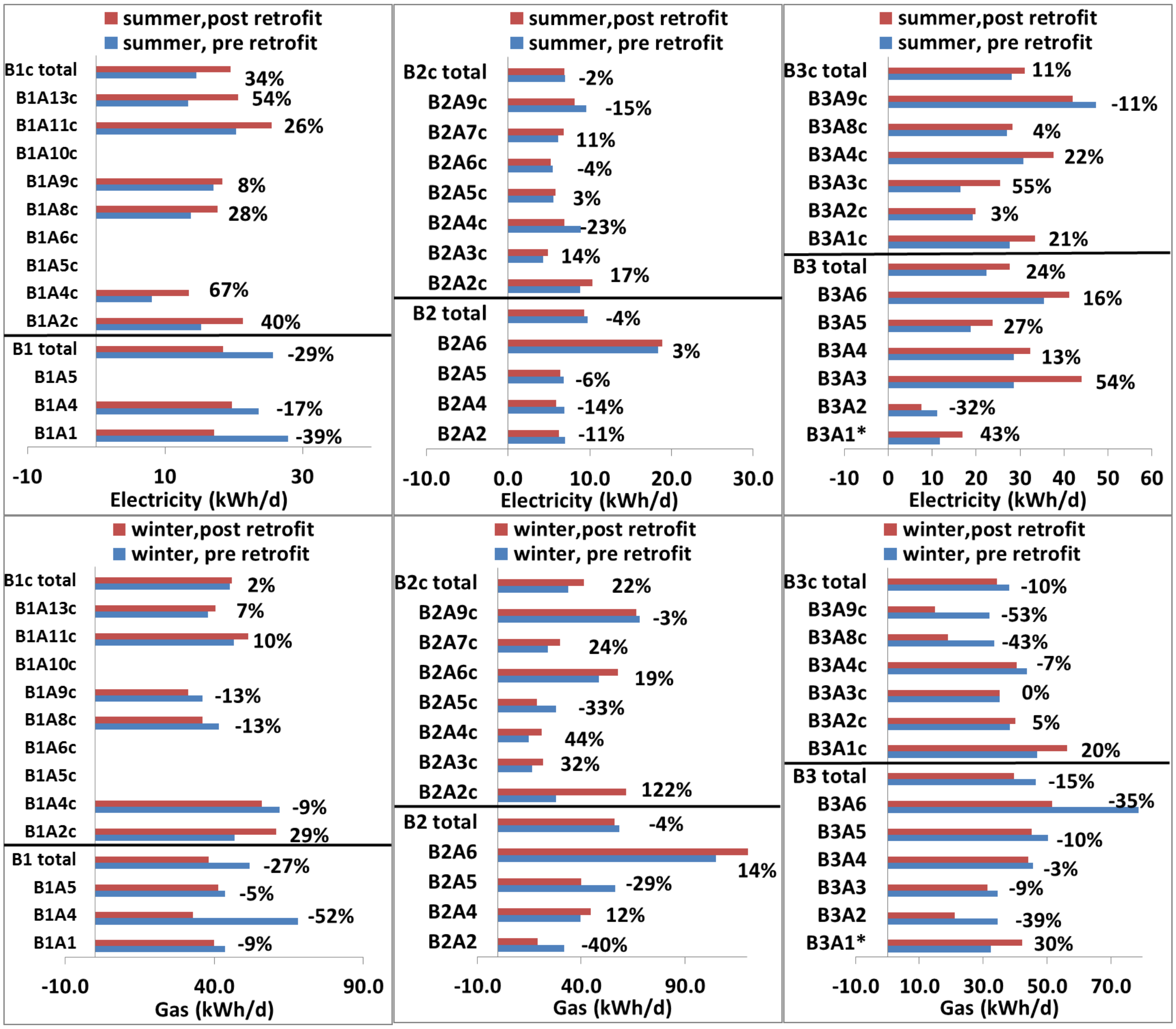

Figure A2. Plots of winter pre- and post-retrofit gas use and summer pre- and post-retrofit electricity use in study apartments and control apartments.

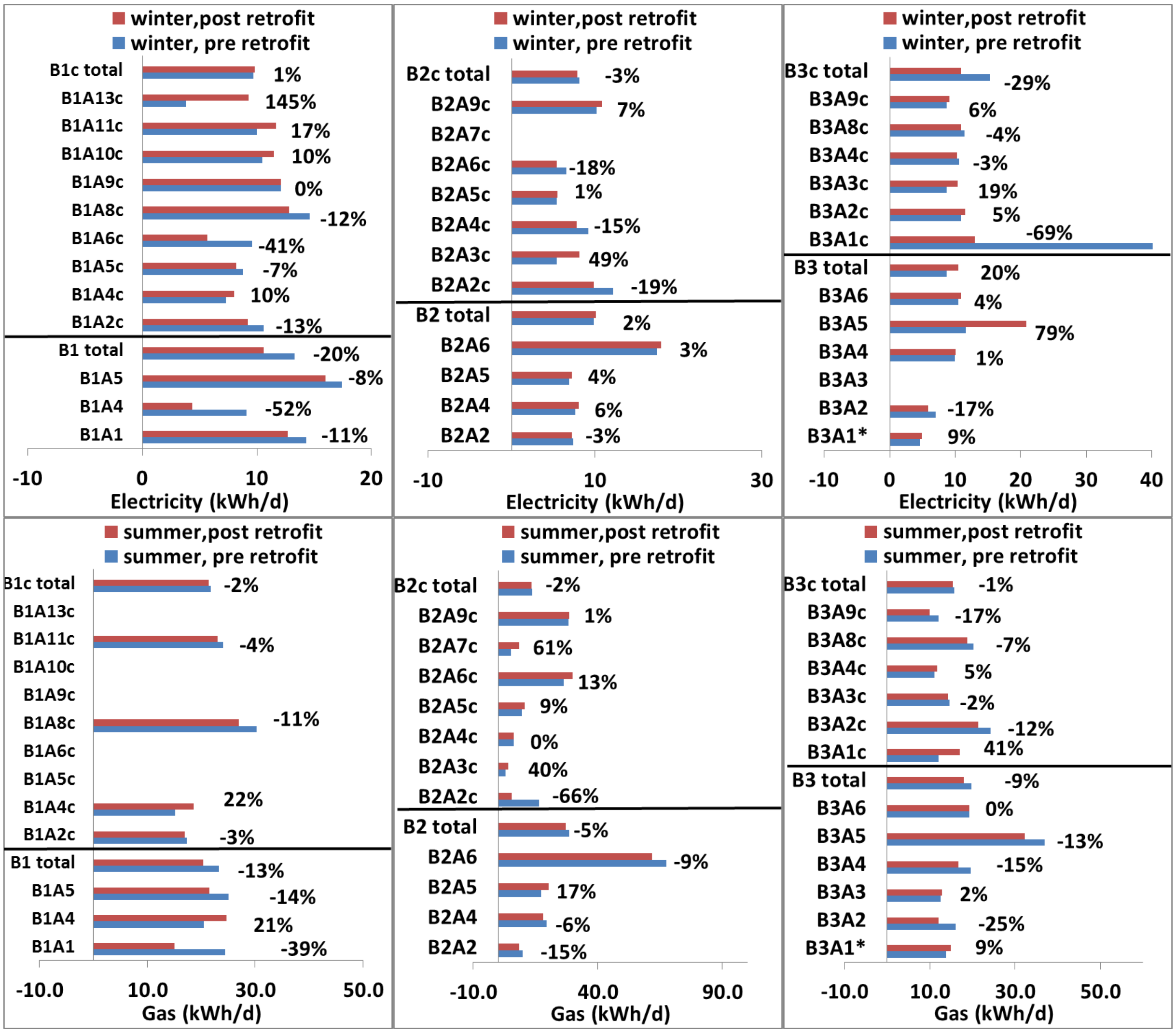

Figure A3. Figure A2. Plots of summer pre- and post-retrofit gas use and winter pre- and post-retrofit electricity use in study apartments and control apartments.