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Federico Noris[1], William W. Delp[1], Kimberly Vermeer[2], Gary Adamkiewicz[3], Brett C. Singer[1] and William J. Fisk[1]

[1]Lawrence Berkeley National Laboratory
Environmental Energy Technologies Division
Indoor Environment Group
Berkeley, CA, USA

[2]Urban Habitat Initiatives Inc.
Boston, MA, USA

[3]Department of Environmental Health
Harvard School of Public Health
Boston, MA, USA

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PROTOCOL FOR MAXIMIZING ENERGY SAVINGS AND INDOOR ENVIRONMENTAL QUALITY IMPROVEMENTS WHEN RETROFITTING APARTMENTS

Federico Noris[1,*], William W. Delp[1], Kimberly Vermeer[2], Gary Adamkiewicz[3], Brett C. Singer[1] and William J. Fisk[1]

[1]Lawrence Berkeley National Laboratory, Indoor Environment Group, Berkeley, CA, USA

[2]Urban Habitat Initiatives Inc., Boston, MA, USA

[3]Department of Environmental Health, Harvard School of Public Health, Boston, MA, USA

Corresponding author: federico.noris@eurac.edu

ABSTRACT

The current focus on building energy retrofit provides an opportunity to simultaneously improve indoor environmental quality (IEQ). Toward this end, we developed a protocol for selecting packages of retrofits that both save energy and improve IEQ in apartments. The protocol specifies the methodology for selecting retrofits from a candidate list while addressing expected energy savings, IEQ impacts, and costs in an integrated manner. Interviews, inspections and measurements are specified to collect the needed input information. The protocol was applied to 17 apartments in three buildings in two different climates within California. Diagnostic measurements and surveys conducted before and after retrofit implementation indicate enhanced apartment performance.

Keywords: apartments, buildings, costs, energy, indoor environmental quality, protocol, selection, retrofits

1. INTRODUCTION

The U.S. is striving to improve the energy performance of housing in order to reduce carbon dioxide emissions, improve energy security, and reduce energy costs. Energy standards for new homes are being strengthened and various programs are underway to retrofit existing homes for energy savings. The largest retrofit program is the Federal Weatherization program targeting low-income populations that receive public assistance to pay energy bills. The Federal Weatherization program focuses on cost-effective retrofits, considering retrofit costs and energy savings; however, the legislation that initiated the program identified improved health as an additional goal [1]. Many energy retrofit programs are now underway, often implemented by energy utilities.

A variety of protocols, tools, and standards are available from energy utilities and state, federal and private energy organizations as well as from research projects to guide the selection and implementation of energy retrofits for homes [2-10]. Additionally, more sophisticated and time consuming algorithm-based approaches to identify retrofit strategies exist [11, 12]. The above-mentioned protocols, tools, and standards seek to maximize energy savings per unit expenditure, and often employ energy modeling, cost-benefit estimation, and engineering judgment. Ma et al. (2012) present an overview of methodologies widely used for selecting energy retrofits [13]. The existing protocols and tools, and much of the retrofit activity, emphasize single-family homes. If the U.S. is to meet energy policy goals, multi-unit housing, serving 20% of the U.S. population [14], must also be retrofit. Challenges faced include split incentives, with tenants paying energy bills and owners paying for retrofits. Additionally, many buildings have heating, ventilation, or water-heating equipment serving multiple apartments with associated costs split among residents – a disincentive to energy efficient behaviors. One approach has been to retrofit entire buildings; however, the required capital outlays can be prohibitive. Relatively few studies have focused on apartment-level retrofits.

Many energy retrofit measures will influence indoor environmental quality (IEQ), including thermal comfort conditions, acoustic conditions, and levels of indoor air pollutants that affect health [6, 7, 8, 15-17]. Changes in IEQ can be positive or negative, and some retrofits will not impact IEQ. Sealing leaks to outdoors without compensating measures, a widespread practice, reduces outdoor air ventilation and increases indoor air concentrations of indoor-generated air pollutants, while reducing indoor concentrations of some outdoor air pollutants. Sealing can also increase risks of pollutant backdrafting from natural draft vented combustion appliances when exhaust fans are operated. Caulking and insulation materials installed during retrofits can emit volatile organic pollutants. Replacing a gas stove with pilot light with a pilotless stove reduces natural gas consumption and eliminates the pilot light's emissions of nitrogen oxides and fine particles into indoor air. Adding insulation to exterior walls or replacing single pane windows with efficient windows reduces heating and cooling demands and improves thermal comfort by decreasing drafts and reducing thermal radiation to cold walls and windows. Table 1 lists the expected energy and IEQ impacts of several of the retrofits that are expected to significantly impact both energy and IEQ. The IEQ benefits are often not credited as benefits in the typical retrofit selection process.

Some of the existing protocols, tools, and guides for selecting or implementing energy retrofits [2-5, 10] specify diagnostic measures and associated procedures to prevent retrofits from causing combustion pollutant backdrafting or spillage from furnaces and water heaters. Some protocols caution about disturbance of lead-based paint and asbestos-containing materials. Some protocols require adherence to elements of the ASHRAE Standard 62.2 [18] or suggest this standard as a guide. The U.S. EPA provides protocols for maintaining or improving IEQ during home energy retrofits [10]. The EPIQR and TOBUS methods also considers IEQ aspects based on occupant survey answers [6 - 8]. However, IEQ improvement has not been a primary goal of most retrofit programs; consequently, the U.S. is not capitalizing on a potentially large opportunity to improve IEQ.

The objective of this project was to develop methods for selecting packages of retrofits that simultaneously save energy and improve IEQ conditions in apartments with independent space conditioning (heating and air conditioning, if present) systems. The project also sought to evaluate and demonstrate the energy savings and IEQ improvements realized through application of the protocol and implementation of the retrofits. This paper describes the retrofit selection protocol, its application in 17 apartments serving low-income populations, the selected retrofits and their costs, the projected energy savings, and the results of diagnostic measurements made before and after retrofits. Future publications will present measured impacts of the retrofits on IEQ and energy.

2. METHODS

2.1 Retrofit selection protocol

We developed a point-based protocol to account for retrofit costs and the expected impacts of retrofits on energy use, indoor air quality (IAQ), and comfort. Point assignments for specific retrofits, drawn from a list of candidate retrofits, were based on modeled energy savings, modeled changes in indoor air pollutant concentrations, and some professional judgments. Data obtained from apartment inspections and diagnostic measurements were used in the calculation of points. The sum of points assigned to each retrofit measure was divided by the estimated retrofit cost, yielding a cost-normalized benefit score. Retrofit measures were then ranked by their cost-normalized benefit scores.

In addition to the ranked retrofit measures, a set of *a-priori* retrofits was adopted for implementation whenever possible. The a-priori retrofits include measures selected to comply with elements of the ASHRAE residential ventilation standard [18] which is the basis for the associated California standard, measures to prevent safety hazards, and a few low-cost measures with benefits expected to nearly always exceed costs. These measures are described subsequently and the rationale for selecting them as a-prior measures is provided.

A retrofit budget was assigned for each apartment or apartment building. The a-priori measures were selected for implementation whenever applicable and acceptable to the building owner and tenants. The remaining retrofit budget was allocated to the ranked retrofit measures until the allotted budget was expended. To treat tenants equitably, we maintained the expenditure per apartment within a building within a small range.

The a-priori retrofit measures included upgrading bathroom and kitchen ventilation to meet the requirements of the ASHRAE residential ventilation standard [18] and provision of 150% of the mechanical ventilation prescribed in this standard, recognizing that when exhaust ventilation is employed some of the air drawn into the apartment by the exhaust fan will come from surrounding apartments. Air sealing of the apartment envelope was an a-priori measure, because the cost is moderate and envelope sealing should save energy and reduce the inter-apartment tobacco smoke and odor transport that drive many complaints. When a combustion safety test and calculations accounting for the expected post-retrofit flow rates of kitchen and bathroom exhaust fans indicated a backdrafting risk, to mitigate this risk, replacement of natural draft combustion appliance, or isolation of the appliance from the occupied space, were a-priori measures. Additional a-priori measures, because of their low costs and anticipated larger benefits, included installing a high-efficiency filter in the forced-air heating system and reducing air bypass around the filter, installing a low-flow showerhead, adding insulation to the hot water tank and pipes, and replacing incandescent light bulbs with compact fluorescent bulbs. In addition, the a-priori measures included tenant education about improving IAQ, energy efficiency and comfort in their apartment, as well as education related to the appropriate use of the implemented physical retrofits. The education used the Department of Housing and Urban Development (HUD) Healthy Homes booklet, available at http://www.hud.gov/offices/lead/library/hhi/HYHH_Booklet.pdf, (accessed June 11, 2012), and documents developed as part of the current project. The education was implemented during a home-visit by a researcher. Written documents were provided and reviewed verbally and questions from tenants were answered. Protocols were reviewed and approved by Lawrence Berkeley National Laboratory's institutional review board and tenants provided informed consent.

In addition to the a-priori measures, a list of candidate retrofit measures was developed based on discussions with experts in the fields of building energy efficiency and IEQ (including both researchers and practitioners), prior literature, and retrofit guidelines describing how retrofits affect energy consumption and IEQ. Sample calculations of expected energy savings and IEQ changes facilitated the development of the list. Retrofits included in the list include the following: replacement of heating and cooling systems; duct sealing; addition of thermal insulation to walls and attics; replacing windows or sliding glass doors; replacement of refrigerators, gas stoves with pilot lights, and water heaters; and installation of energy efficient wall-mounted air particle filtration systems. The full list, and a detailed description of the retrofit selection protocol, are available through the project web site (http://apartmentenergy-ieqretrofits.lbl.gov/publications/, accessed June 11, 2012).

To estimate how the retrofits affect apartment energy consumption, we used Home Energy Saver Pro [9], a web-based retrofit selection tool developed for single-family homes and townhouses. The tool considers the initial condition of a residence, applies a building energy model, and suggests energy retrofits with their associated yearly energy savings and retrofit costs. For application to apartments, the townhouse option was used, as it was the best tool for our application available in Home Energy Saver Pro. A high level of attic insulation (R-60) was specified in Home Energy Saver Pro if there was another apartment located above. A majority of apartments in the study were equivalent to townhomes with independent entrances from the street, no dwelling above or below, and independent heating and space cooling systems. To estimate IEQ-related benefits, for each applicable retrofit measure, changes in indoor pollutant concentrations were calculated using a mass balance model. These calculations used indoor pollutant emission rates published in the literature.

The point-based system for ranking of retrofits assigned points on a -3 through +3 scale in three impact categories: energy; IAQ; and comfort. The point system is described briefly below with details provided at the project web site (http://apartmentenergy-ieqretrofits.lbl.gov/publications/, accessed June 11, 2012). In the energy category, a score of +1 was assigned for a projected apartment annual energy savings less than \$50, +2 for \$50 to \$100 annual savings, and +3 for greater than \$100 annual savings. If a retrofit increased energy use, negative energy points were assigned. In the IAQ category, positive points were allocated based on the projected reductions in indoor air concentrations of nitrogen dioxide (NO_2), and particles less than 2.5 μm in diameter (PM2.5). The category boundaries for IAQ scoring were based on 10% of the outdoor air pollution standard for that pollutant

[19]. Thus, for NO_2 with an outdoor air standard of 56 μg/m^3, scores were +1 for a reduction in indoor concentration less than 5.6 μg/m^3, +2 for reductions of 5.6 to 11.2 μg/m^3, and +3 for indoor concentration reductions greater than 11.2 μg/m^3. Negative IAQ scores would have been assigned for projected increases in NO_2 or PM2.5 concentrations; however, we did not encounter such cases. If a retrofit was projected to affect both NO_2 and $PM_{2.5}$ concentrations, scores for each of the affected IAQ parameters were summed but the total category score was constrained within the -3 to +3 range. Comfort scores, considering of retrofits effects on noise and thermal comfort, were based on reported benefits in the literature for the various retrofits, but necessarily relied on engineering judgment due to the scarcity of quantitative data. Noise and thermal comfort points were assigned for replacement of noisy kitchen and bathroom fans with quieter fans, provision of portable fans that help keep people cool during warm weather, and improvement of wall insulation or windows which are associated with reduced drafts and radiant discomfort when it is cold outdoors. The sum total score for each retrofit, constrained between -9 and +9, was initially divided by a preliminary estimate of retrofit's cost available from the Home Energy Saver Program Pro tool and from a table of costs obtained through consultation with several individuals with extensive retrofit experience. For the final stages of retrofit selection, apartment-specific costs provided by the retrofit contractor were utilized. To simplify protocol use, tables were developed that provide points allocated to retrofit measures and changes in IEQ parameters and energy costs.

As an example of the process, replacement of the gas range with pilot light with a pilotless range received a +3 score. The energy score was +1 based on an annual energy cost savings of $38. The IAQ score was +2, with +1 based on an indoor NO_2 reduction of 3 μg/m^3 plus another +1 based on an indoor $PM_{2.5}$ reduction of 0.2 μg/m^3. Dividing the +3 benefit score by the installed cost of $680, resulted in a normalized score of 4.4/$1,000. In another example, addition of a wall mounted particle air cleaner received a -1 energy score based on the projected annual electricity cost of $18 (assuming half time operation) and a +3 IAQ score based on a projected decrease in PM2.5 greater than 11.2 μg/m^3. With the installed cost of $813, the cost-normalized benefit score was 2.5/$1,000.

2.2 Collection of apartment data for retrofit selection

To collect data to input into the retrofit selection protocol, buildings and apartments were characterized via building manager interviews, inspections using checklists, and diagnostic measurements. The parameters determined via diagnostic measurements included the following: air flow rates and sound levels for bathroom and kitchen exhaust fans; envelope air leakage; ventilation system duct leakage; and the results of a combustion appliance zone (CAZ) worst-case depressurization test. Bathroom exhaust fan airflow rates were measured with a rotating vane anemometer within an integrated flow hood (TESTO 417, Testo Inc, Sparta NJ) or a powered flow hood. The powered flow hood uses a calibrated fan (Minneapolis Duct Blaster fan and a DG700 pressure control from Energy Conservatory, Minneapolis), with zero pressure drop maintained across the hood so that flow rates are unaffected by the measurement system [20]. Kitchen range hood airflows were also measured with the powered flow hood. Envelope air leakage was measured using a blower door test according to ASTM E779-10 [18]. To measure duct leakage, the delta Q test method was employed according to ASTM E1554-07 [22-24]. The test provides supply and return duct leakage based on a blower door test while operating and not operating the HVAC system. The data obtained when the HVAC was off was used to determine envelope leakage. Blower door tests utilized a Minneapolis Blower Door and the DG700 pressure control from the Energy Conservatory (Minneapolis, MN). In apartments with combustion appliances inside the apartment, the combustion appliance zone (CAZ) worst-case depressurization test was performed [25]. Additionally, the likelihood of failing the CAZ worst-case depressurization test after retrofitting bathroom fans and range hoods was estimated using the results of the blower door test to model apartment depressurization as a function of exhaust air flow rate.

2.3 Application of the protocol

The retrofit selection protocol was applied to three properties in two California climates (coastal Bay Area and Central Valley). The Bay Area is characterized by a mild Mediterranean climate, while the Central Valley has a more severe climate with colder winters and hot summers (heating and cooling degree days are provided in section 3.1). We refer to these as “buildings” B1, B2, and B3 even though each property had multiple structures. These properties provided subsidized housing, buildings were low-rise, and were older than 20 years. Each apartment had meters for electricity and gas, an independent heating system and, if present, an independent air conditioning system. Flyers were distributed to invite residents to participate. Approximately 12 apartments in each property were recruited for the initial inspection with diagnostic measurements. Via implementation of the retrofit selection protocol, retrofit package recommendations were developed for each inspected apartment. Apartments with greater improvement opportunities and with cooperative occupants were given priority. In case of equal improvement opportunities, study apartments were selected randomly. The retrofit recommendations were discussed with building owners and tenants and, in nearly all cases, the suggested retrofit measures were acceptable to both tenants and owners. In each of the three properties, five or six apartments were retrofit with an $8,000 – $10,000 budget per apartment.

2.4 Evaluation of the retrofits

The diagnostic measurements described above were repeated after retrofit implementation. Portions of the post-retrofit data were used to check for correct retrofit implementation, e.g., to determine if fan flow rates were within specifications. By comparing pre- and post-retrofit diagnostic data, measures of retrofit impact were assessed. Additionally, after the retrofits, the times of operation of bathroom exhaust fans and kitchen ranges hoods were monitored using differential pressure sensors (Model: 265, Part: 2651-R25WD-2D-T1-C, Setra Sensing Solutions, Boxborough, MA) and Onset HOBO data loggers (Parts: U12-012 or U12-013, Onset Corp., Bourne, MA). A variety of parameters were measured to quantify the energy savings and IEQ changes associated with the apartment retrofits and the results of those measurements will be documented in future publications. These parameters include, among others, gas and electricity consumption, temperature and humidity, and concentrations of a range of air pollutants. Occupant surveys were administered to at least one adult in each household at enrollment, pre-retrofit and one month post-retrofit. These surveys addressed aspects of apartment conditions, occupant behavior and occupant satisfaction.

3. RESULTS

3.1 Buildings and apartments selected for retrofits

Major characteristics of the study properties and apartments are summarized in Table 2. The buildings were located in Sacramento (B1), Richmond (B2) and Fresno (B3). Climate conditions for these cities – specified in terms of heating and cooling degree-days are provided in Table 2. B1 apartments were retrofitted in summer; retrofit of B2 and B3 apartments occurred in winter.

In B1, we selected 3-bedroom (3BR) and 4-bedroom (4BR) apartments because they had gas heaters (a target characteristic) and they were more common within the building. The apartments were all two-stories with similar layouts except for the bedroom configuration. All apartments had rooftop packaged units for heating and cooling, natural draft gas water heaters in an internal closet on the second floor, and double-pane windows. The kitchen range hoods were not vented to outdoors and the gas cooking ranges had pilot lights. Visible mold or moisture damage in a few of the bathrooms suggested inadequate airflow in bathroom exhaust fans.

The size, layouts, and energy-related features of apartments in B2 varied. We selected one 1BR (B2A1 for building 2 apartment 1), one 2BR (B2A2), three 3BR (B2A3, B2A4, B2A5) and one 4BR apartment (B2A6). Apartment B2A1 had a gas wall furnace, while all other apartments had gas forced-air central furnaces located in an internal closet. B2A1 had no bathroom exhaust fan; all other bathrooms had fans. B2A4, B2A5 and B2A6 had individual natural-draft gas water heaters, while the other apartments shared a water heater with other apartments. The 3BR and 4BR apartments had two stories; 1BR and 2BR apartments had one story. B2A1 and B2A2 had single-pane sliding glass doors. All windows were double pane. The attic insulation in four of the five top-floor apartments was missing or only a few centimetres thick. None of the apartments had air-conditioning.

In B3, four 2BR apartments (B3A1, B3A2, B3A3, B3A4) and two 3BR apartments were selected. All had rooftop packaged heating and cooling systems, natural-draft gas water heaters in outdoor closets, and electric cooking ranges. They also all featured single-pane sliding glass doors and windows that sometimes did not seal properly as well as kitchen and bath exhaust fans with inadequate flows.

3.2 Selected retrofits and their costs

Table 3 summarizes the retrofit measures implemented and provides the cost-normalized benefit scores based on the actual billed costs. Normalized scores are heavily influenced by the cost of the measure. Some inexpensive measures (e.g., replacing incandescent light bulbs) have the highest scores, whereas costly measures often show lower scores despite much larger energy savings.

To provide whole-apartment ventilation, small energy recovery ventilation systems (ERVs) were installed in the living room of each apartment in B1 and in half the apartments in B3. This ERV has slightly larger exhaust airflow than supply airflow. However, compared to an exhaust ventilation fan, use of the ERV should result in less air transport from surrounding apartments into the subject apartment. In all the apartments in B2 and the remaining three apartments in B3, continuously operating bathroom exhaust fans were selected for whole-apartment ventilation. ERVs were not used in B2 to avoid disturbance of asbestos in ceilings and because the projected energy benefits of an ERV were small in B2’s mild Bay-Area climate. ERVs were installed in three apartments in B3, and exhaust fans in the other three apartments, to enable a performance comparison. The existing kitchen range hoods and bathroom exhaust fans were replaced in all apartments since they did not meet the requirements of ASHRAE Standard 62.2 [18]. B2A1 did not have a bathroom exhaust fan, only an operable window; however, the resident refused installation of an appropriately located exhaust fan.

Installation of kitchen and bath fans in B1 and B2 created a situation in which the apartments were predicted to fail the worst-case depressurization test designed to protect against combustion appliance backdrafting. Even without additional air sealing, the higher flows of the new exhaust fans were predicted to cause depressurization levels exceeding the 2 Pa limit specified by Building Performance Institute (BPI) for natural draft water heaters in some of the apartments. In B2, the water heaters were located in closets adjacent to external walls that had vents to outdoors. The backdrafting risk was eliminated by weather-stripping the closet doors to isolate the appliance from the occupied area of the home. This approach was not applicable in B1 apartments, which had water heater closets located far from external walls. Installation of power vent water heaters, which use a blower to establish draft and therefore are less sensitive to house depressurization, was deemed unsuitable because the blowers are noisy and the water heaters were located close to bedrooms. Options in B1 were additionally constrained by air quality regulations that limit nitrogen oxides emissions from new water heaters to 10 ng J^{-1} for storage water heaters with burners up to 22 kW (75,000 Btu/h). We decided that the best option was to install 76,000 Btu/h, 90% efficient condensing water heaters. The high cost of this retrofit option ($3280 installed) resulted in a low cost-normalized benefit score. Our experience highlights a need for better products to meet this challenge. There is a need for energy efficient water heaters that are power-vented and quiet enough to be located in closets within the occupied space. Additionally, as more areas impacted by outdoor air pollution require ultra-low NO_X burners, the need and the market for products that also feature these burners will increase.

Several different measures were undertaken to improve the apartment envelopes. In all apartments in B2 and B3, caulks and foams were used to seal accessible penetrations in the envelope created by plumbing, gas lines, electrical boxes and outlets, and at other penetrations through the building envelope such as at the perimeter of window or door frames. To not aggravate the combustion pollutant backdrafting risk in B1 apartments, only the entry doors were weather-stripped. For the apartments in B2 and B3 on the top floor with missing or only a small amount of attic insulation, the attic insulation was upgraded to R-38 by blowing in cellulose. In B2, we originally contracted for addition of external wall insulation based on inspections with a 1.9 mm boroscope indicating that insulation was absent. However, when the contractor crew drilled the larger holes to inject insulation, they discovered that the majority of the walls had a low level of insulation. Because adding blown-in insulation into wall cavities with existing insulation is challenging (e.g., numerous holes must to be made in walls to homogeneously fill each cavity) and anecdotally considered ineffective, the measure was dropped. This experience suggests that presence of insulation may not be accurately assessed using a small boroscope and that several walls should be checked. In B2A1 and B2A2 with single-pane sliding glass doors, the doors were replaced with double-pane sliding glass doors. In B3, all the windows and sliding doors were single pane. However, due to budget constraints, only selected bedroom windows were replaced. Window and sliding door replacement should both save energy and improve comfort (reducing drafts and radiant heat loss), but their high cost lowered their cost-normalized benefit scores.

In all the apartments with central forced-air HVAC systems, the existing particle filters were replaced with filters having minimum efficiency reporting value (MERV) equal or greater to MERV-11 as determined by ASHRAE Standard 52.2 [26]. The HVAC duct leakage rates in all the apartments in B2 and some apartments in B3 were high; therefore, the return plenum was sealed and accessible ductwork replaced. For B2 and B3, locations where outdoor particle concentrations are frequently elevated, the installation of High-Efficiency Particulate Air (HEPA) filters received a good cost-normalized benefit score despite their energy use (6 - 47W depending on fan speed), thus, HEPA filters were installed in all the apartments and mounted on walls. The occupants of all the apartments were provided portable fans. For the apartments with air-conditioning (B1 and B3), the air movement achievable with the fans may lead the tenants to reduce the use of the air conditioning and save energy during the cooling season, while in B2 (no air-conditioning) the fans may improve comfort. In B1, the rooftop packaged heating and air-conditioning systems were replaced to enable qualification for a utility rebate, conditional to a Home Energy Rating System (HERS) rating predicting at least 20% energy savings. We replaced all incandescent light bulbs with fluorescent light bulbs that use less energy. In B1, the gas ranges with pilot ignition (that are both an energy waste and a pollution source) were replaced with an electronic ignition gas ranges. In all apartments, existing refrigerators were replaced with Energy Star refrigerators. We added external tank insulation to three existing water heater tanks in B2 and insulated accessible hot water piping.

A distinctive feature of this retrofit selection protocol, compared to other available energy retrofit protocols, is that it gives equal importance to energy, comfort and IAQ. The implemented measures that traditional energy retrofit protocols would have not recommended include installation of HEPA filter units for particulate reduction, enhancement of filtration in HVAC systems, replacement of gas ranges with pilot lights, upgrades of bathroom and kitchen exhaust fans, and the addition of whole-apartment ventilation systems.

The mean predicted energy savings, based on the Home Energy Saver tool and additional estimates, for the apartments in B1, B2 and B3 were 21%, 17% and 27%, respectively. The greater predicted savings for B1 and B3 were partially due to the more severe weather in Sacramento and Fresno (see HDD and CDD data in section 3.1), compared to Richmond. As a consequence of warmer weather, the apartments in B1 and B3 have central air-conditioning providing more energy saving opportunities. The measures that promised the greatest energy savings in B1 were the replacement of the rooftop packaged units for heating and air conditioning and the replacement of the water heater. In B2 and B3, the largest projected energy savings were from addition of attic insulation and HVAC ductwork replacement. Where implemented, window and sliding door upgrades were projected to save significant energy.

The total retrofit cost for B1 was approximately $63,400 (average of $12,700 per apartment). This amount exceeded the initial budget target for this building but the inclusion of additional measures increased projected energy savings above the threshold for a utility rebate. The total cost of the retrofits in B2 was $46,100 (average of $7,700 per apartment). The total cost for the retrofits implemented in B3 was $54,000 (average of $9,000 per apartment). Overall, the prices for the different retrofit measures were within the industry typical range. The costs may have been modestly increased due to research project requirements. We used Building Performance Institute (BPI)-accredited contractor companies because they must comply with industry voluntary work standards and were expected to be more skilled. Contractors were selected based on quotes, availability to meet the project schedule, and a check of references. We needed contractors that could complete the retrofit work within a small window of time to meet the goal of conducting pre- and post-retrofit IEQ sampling during the same season.

3.3 Retrofit performance based on pre-and post-retrofit diagnostics

Figure 1 shows the pre- and post-retrofit envelope leakage from all apartments. The mean pre-retrofit air exchange rate at 50 Pa (ACH_{50}) and normalized leakage at 4 Pa (NL_4) for the apartments that received envelope sealing were 9.7 hr^{-1} and 0.52, respectively. The ACH_{50} is a widely used measure of envelope leakage, although NL_4 is a better indicator of air infiltration rates. In B1, air sealing was not performed to avoid the combustion appliance backdrafting risk, while in B2A1 the contractor was not able to perform air sealing due to the wishes of the resident. The mean post-retrofit ACH_{50} for the apartments that received air sealing was 7.7 hr^{-1}, providing a mean reduction of 20%. The lowest post-retrofit ACH_{50} was 5.9 hr^{-1}, in B2A3. The largest ACH_{50} improvement (42%) occurred in B2A6 which had a broken window replaced by the building manager. For the apartments that received air sealing in B2 and B3, average air leakage reductions were 26% and 15%, respectively. In the B3 apartments with a bedroom window replacement and no ERV installation (B3A1, B3A5, B3A6), the reduction was 21%, substantially greater than the 8% reduction in the other three apartments that received ERVs and no window replacement. The values for NL_4 follow similar trends. The mean post-retrofit NL_4 for the apartments that received air sealing was 0.37, with a mean reduction of 27%.

Figure 2 presents the pre- and post-retrofit airflows for bathroom exhaust fans. None of the pre-retrofit fans had flow rates meeting the 24 L s^{-1} (50 cfm) specification of ASHRAE Standard 62.2 [18]. The bathroom fans in B1 did not have any flow, probably due to obstructed ducts. Even with the new fans and ducting, the measured airflows were below 24 L s^{-1}. In B2 and B3, the pre-retrofit airflow rates were approximately 9.4 L s^{-1} (20 cfm) while flow rates for all but one of the newly installed fans (main bathroom of B3A5), met the recommendation with the mean airflow exceeding 33 L s^{-1} (70 cfm). The lower post-retrofit flow rates in B1 may be a consequence of the use of a different fan for B1 than in B2 and B3. The new bathroom fans were much quieter than the original fans, a change that may promote fan use and reduce discomfort. The bathroom exhaust fans were operated, or operated above their baseline speed for continuously operating devices, 7% of the time in B1 after the retrofits (no pre-retrofit data available), 9% and 15% of the time in B2 before and after the retrofits, respectively, and 2% and 11% of the time in B3 before and after the retrofits, respectively. The increased use of the bath fans is likely due to the quietness of the new units and the sensors that turn on fans when occupants are sensed or humidity is high.

Figure 3 shows the airflow rates of kitchen range hoods for the low and high fan-speed settings, measured before and after the retrofits. The pre-retrofit kitchen range hoods in B1 were not vented to outdoors, providing no exhaust airflow. During the retrofits, new hoods and ducts venting outdoors were installed. The mean post-retrofit airflows in B1 for the low and high settings were 43 L s^{-1} (91 cfm) and 111 L s^{-1} (235 cfm). In B2 and B3, only the range hoods (but not the ductwork) were replaced. The same make and model of kitchen range hood was installed in B1 and B2. The lower airflows observed for the high setting in B2 (mean of 81 L s^{-1} or 171 cfm) compared to B1 are assumed to result from greater airflow resistance in the ducting. At the low fan speed, only one of the installed range hoods reached the 42 L s^{-1} (100 cfm) airflow required by ASHRAE to correspond to the 3-sone sound limit. Airflow performance at low speed is also relevant because it is the most likely operating condition owing to its quietness relative to other settings. At the high fan speeds, five of 17 range hoods had post-retrofit flow rates meeting the 118 L s^{-1} (250 cfm) recommendation of the Home Ventilating Institute (HVI). The effectiveness of kitchen range hoods in removing cooking-produced pollutants increases with flow rate, and is also influenced by the geometry of the hood with respect to the burners [27, 28].

Averaged across apartments, the kitchen range hoods were used 6% of the time in B1 after the retrofits (no pre-retrofit data available), for 10% of the time in B2 both before and after the retrofits, and for 5% and 2% of the time in B3 before and after the retrofits, respectively. These data indicate that installation of newer quieter range hood did not increase use. Estimation of operation times of range hoods from pressure sensor data required considerable judgment, and the reported operation times have a high level of uncertainty. We did not monitor use of the cooking ranges to assess the fraction of cooking events for which range hoods were operated. In our post retrofit survey, the majority (14/16) of households reported “always” using their kitchen fans while cooking, although this behavior may be over-reported.

Figure 4 illustrates the return and supply duct leakage for the study apartments. The mean pre-retrofit return and supply leakages in B1 apartments were 26 L s^{-1} (55 cfm) and 28 L s^{-1} (58 cfm), respectively. Since the ductwork was not modified in B1, the post retrofit duct leakage was not measured. B2A1 did not have any ductwork since it had a wall heater, while the other five units in B2 had central air handler units (AHUs) in internal closets with ductwork in the attics; in these five units the return plenums were sealed and all accessible ductwork was replaced. In B2A6, the post-retrofit duct leakage could not be measured because the HVAC system was not functioning both times we visited the apartment. The mean return and supply duct leakages before the retrofits in B2 were 88 L s^{-1} (185 cfm) and 50 L s^{-1} (105 cfm), respectively, indicating great losses on the return sides partially due to noticeable gaps in the return plenums. The mean return and supply duct leakages for B2 apartments after the retrofits were 35 L s^{-1} (73 cfm) and 21 L s^{-1} (43 cfm), respectively corresponding to reductions of 60% and 38%.

Considerable reductions in leakage were observed for A2 (82% return and 79% supply) and A3 (76% return and 92% supply) – in these cases the initial leakage rates were high suggesting that larger holes, that are more likely to be found, may have been present. In B3, only apartments A2, A4 and A6 received duct replacement since A1 and A5 had the majority of the ductwork inside the wall cavities, while A3 had much lower initial leakage. The mean pre-retrofit return and supply duct leakages in all B3 apartments were 47 L s^{-1} (99 cfm) and 33 L s^{-1} (69 cfm). The mean return and supply duct leakage reductions for the three apartments that received duct replacement and return plenum sealing were 53% and 40%. In the remaining three apartments, there was an increase in duct leakage, partially explainable by the uncertainty of the delta Q test (1% of CFM_{50}). Additionally, the pressure changes resulting from the replacement of low efficiency filters with high efficiency filters might have increased duct leakage rates.

3.4 Occupant satisfaction

All families (17) completed at least one enrollment survey per household, and most completed at least one pre-retrofit (16/17) and one post-retrofit (16/17) survey per household. While the sample size limits the quantitative conclusions that can be drawn from these data, some trends are worth noting. At baseline, only one household rated their air quality over the past month as "very acceptable" (on a four-level scale which included "somewhat acceptable", "barely acceptable" and "not acceptable"), as compared to eleven households giving this rating post-retrofit. All families reported being either "very satisfied" (15/16) or "generally satisfied" (1/16) with the retrofit work in general (on a four-level scale which also included "generally dissatisfied" and "very dissatisfied"). Similar results were found when household members were asked about satisfaction with individual retrofit components (e.g., fans, range hoods, lighting, etc.), with the majority reporting being "very satisfied." While few households reported any dissatisfaction, two of the three households who received continuously vented bath fans reported some dissatisfaction with the associated noise level.

4. DISCUSSION

This paper presents a unique protocol for selecting energy and IEQ retrofits, and documents the use of this protocol. As illustrated in Table 1, many of the retrofit measures are expected to simultaneously save energy and improve some aspect of IEQ. The potential for retrofit packages to simultaneously improve both energy and IEQ appears high; however, the actual impacts have not yet been quantified for the apartments in this study.

The retrofit selection protocol has several strengths and some limitations. It provides a rational and repeatable method for evaluating candidate retrofits based on energy savings, IEQ benefits, and costs, addressed in an integrated manner. The protocol uses a simple summary metric (cost-normalized benefit score) to compare retrofit options and provides a relatively simple process for calculating these scores. Compared to pre-existing protocols that consider only energy and measure costs, this new protocol provides a better means of maximizing total benefit per unit expenditure. However, there are limitations in methods for quantifying some of the benefits and converting benefits into scores. The protocol would benefit from an accounting for the life expectancy of pre-existing devices (e.g., furnace systems) and the expected life of the retrofits considered. A user-friendly web-based interface would make the protocol more accessible and enable use of a finer-scaled scoring system without imposing burdensome calculations (the current system has only 3 levels, 1, 2, or 3). Additionally, there is substantial subjectivity inherent in the benefit evaluations and in the establishment of the brackets for assigning scores. Ideally, this subjectivity would be reduced; however, to maximize protocol utility, there must be a compromise between accuracy of impact quantification and time and expertise requirements. We believe that the presented retrofit selection protocol is a first step in the correct direction.

During the retrofit implementation, the challenging nature of the retrofit work became evident. Available retrofit options are limited and sometimes non-ideal or prohibitively expensive. Conditions identified during the early stages of retrofit implementation may make it necessary to modify plans, and increase retrofit costs. A particular challenge for this project, and possibly for projects in other apartment buildings, is the number of participants. The sometimes divergent motivations and priorities of the various stakeholders – including the building owner, building manager, contractors, energy raters, tenants, and commissioning agents (in this case, the study team) – makes the process challenging and calls for extensive communication between the different parties. It is particularly important for contractors to anticipate potential challenges and to communicate with the customer about unforeseen challenges that arise. Likewise, it is important for a qualified party to inspect and evaluate the retrofit work to ensure that specifications were met. In this study, despite use of BPI-accredited contractors, some measures were not initially implemented as specified.

The diagnostic measurements summarized in this document indicate significant improvements in apartment performance. Occupant self-reports of satisfaction with the retrofits were also encouraging. Substantial variations were observed in the level of improvement depending mainly on the initial conditions and on the quality of the retrofit implementation.

5. CONCLUSIONS

There are opportunities to simultaneously save energy and improve IEQ when apartments are retrofit; however, IEQ is normally not considered at the time of retrofit selection. This paper provides a protocol for selecting retrofits based on predicted energy and IEQ benefits, retrofit cost, and initial apartment conditions. Examples of retrofits selected via this protocol include air sealing coupled with application of energy efficient ventilation equipment, replacement of gas ranges with pilot lights, addition of thermal insulation, upgrading of filtration systems, and replacement of single pane windows with more efficient windows. The projected energy savings for the three buildings ranged from 17 to 27%, with simultaneous substantial predicted improvements in thermal comfort and indoor air pollutant levels (measured energy savings and IEQ changes will be provided in subsequent papers). Diagnostic measurements identified, in this set of apartments, frequent low air flow rates in existing bathroom fans and kitchen range hoods, as well as bathroom fans and range hoods with no exhausts to outdoors or obstructed exhaust ducts. A challenge identified with retrofits that incorporate exhaust ventilation was the risk of causing backdrafting of natural-draft combustion appliances, together with the limited availability of quiet forced-combustion water heaters. Relative to current practices, the protocol described in this document has the potential to better maximize the total societal benefits of building retrofits, consequently, the protocol should be of interest to building owners, retrofit contractors, utilities, and governmental organizations involved with building retrofits.

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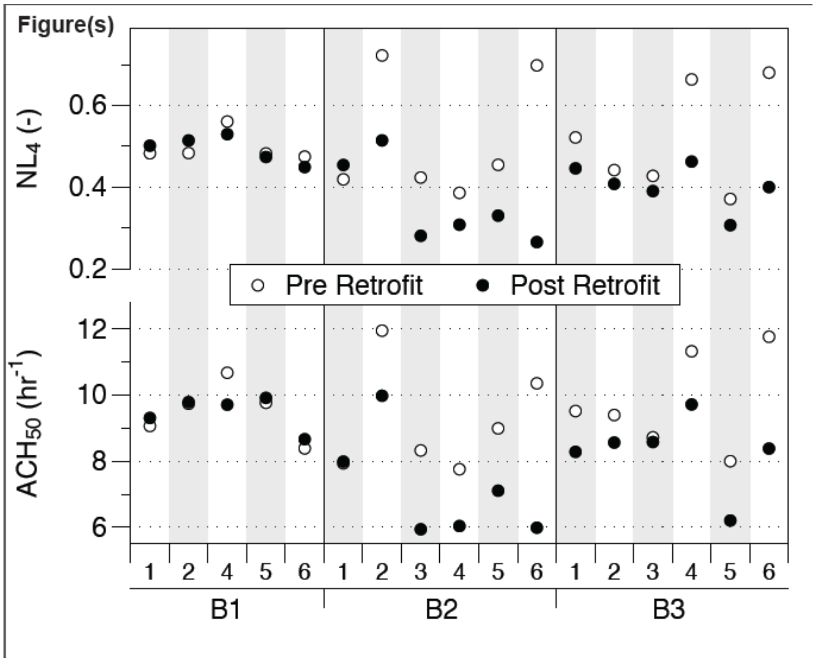

Figure 1. Air changes per hour at 50 Pa (ACH50) and normalized leakage at 4 Pa (NL4) measured before and after retrofits. No work was done to improve envelope airtightness in B1 and B2A1.

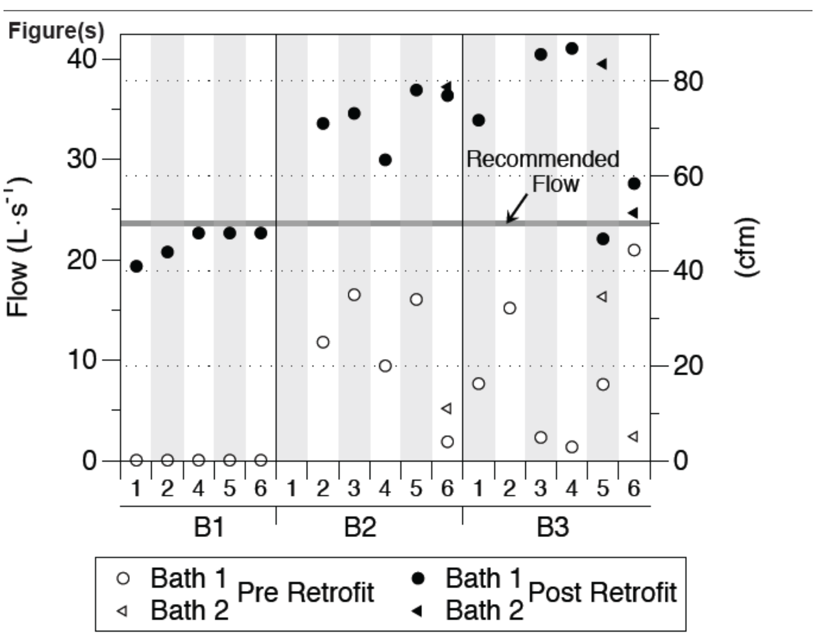

Figure 2. Bathroom exhaust fan airflows measured before and after the retrofit implementation.

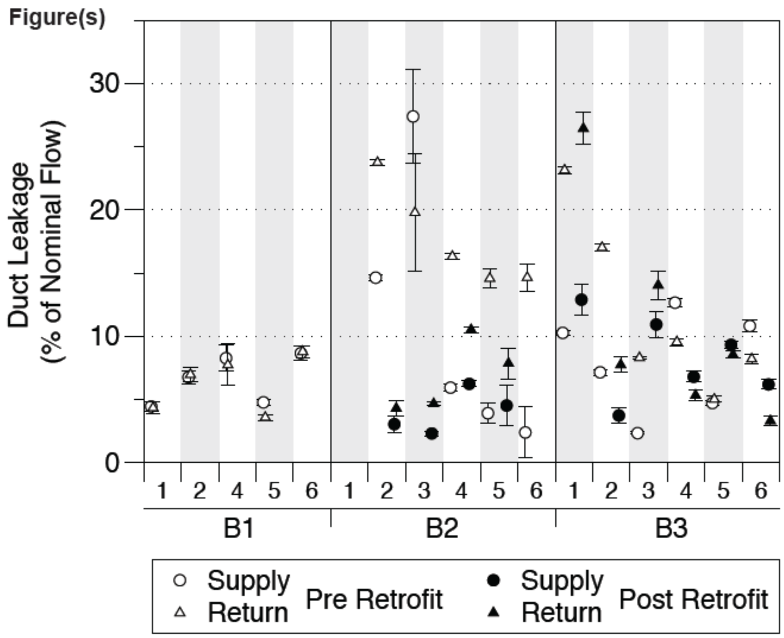

Figure 3. Kitchen range hood airflows at low and high fan speeds, measured before and after the retrofit implementation.

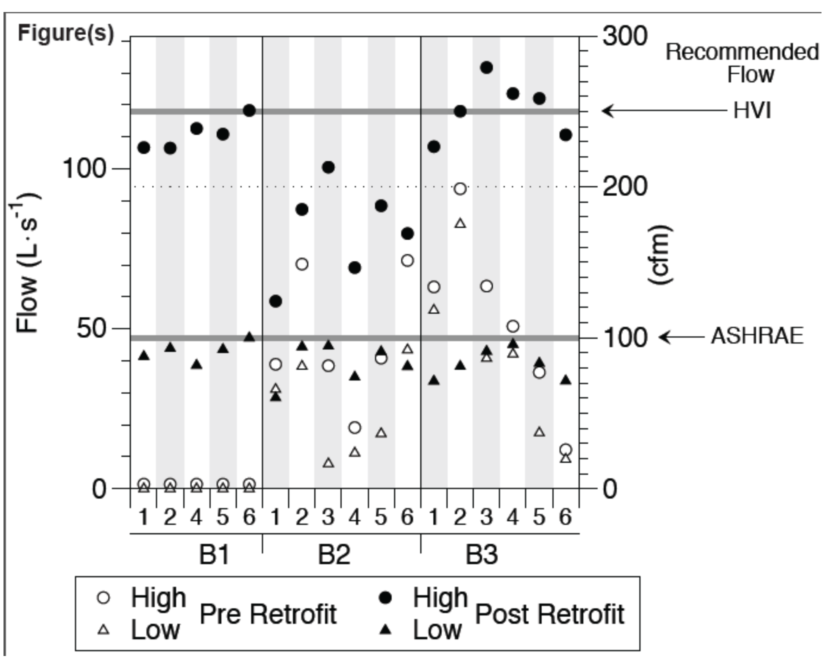

Figure 4. Fig. 4. Pre- and post-retrofit duct leakages expressed as percentage of HVAC system nominal flow.

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Table 1. Expected energy and IEQ (IAQ and comfort) impacts of retrofits.

Retrofit	Energy impacts	IEQ impacts
Air seal envelope	• Reduces heating and cooling	• Reduces pollutant entry from other apartments and common areas • Reduces outdoor air ventilation-potentially worsening IAQ
Replace bath fan	• More efficient motor decreases electricity use • Potentially more use, increases heating and cooling demand	• Reduces fan noise • Improves moisture and indoor pollutant removal
Replace range hood	• More efficient motor decreases electricity use • Potentially more use, increasing heating and cooling demand	• Reduces fan noise • Improves removal of cooking pollutants and moisture (if system is used)
Replace natural draft water heater with forced combustion water heater	• Reduces water heater energy use	• Reduces risk of combustion pollutant spillage to indoors
Provide portable fan	• Reduces cooling demand in air-conditioned apartments	• Improves thermal comfort
Replace gas cook stove with standing pilot with electronic ignition stove	• Reduces natural gas use • Reduces cooling demand, increases heating demand	• Eliminates indoor pollutants from pilot light
Replace HVAC ductwork & seal return plenum	• Reduces heating and cooling demand	• Reduces drawing of pollutants from other apartments, attics, etc. • May improve thermal comfort
Replace single-pane sliding glass doors and windows	• Reduces heating and cooling demand	• Reduces cold drafts and radiant heat losses, improving comfort
Add insulation	• Reduces heating and cooling demand	• Improves thermal comfort and noise transmission
Install HEPA filter	• Increases electricity consumption	• Reduces indoor particle levels

Table 2. Summary of building and apartment characteristics.

	B1	B2	B3
Location	Sacramento, CA	Richmond, CA	Fresno, CA
HDD; CDD	2750; 1240	3020; 150	2560; 1970
Year built	1967	1973	1975
Housing Program, Subsidy Type	Project-based section 8[3]	Project-based section 8[3]	Project-based section 236[4]
Number of apartments	144	172	72
Apartment size [1]	2BR: 70 m^2; 3BR: 85 m^2; 4BR: 92 m^2	1BR: 67 m^2; 2BR: 76 m^2; 3BR: 125 m^2; 4BR: 139 m^2	2BR: 80 m^2 3BR: 98 m^2
Heating and air conditioning	2BR: heat pump; 3BR & 4BR: gas rooftop packaged units	1BR: gas wall heater; 2BR, 3BR, 4BR: gas forced air furnace in internal closet; No air conditioning	Gas rooftop packaged units
Water heater system	Individual gas in internal closet	Individual gas for 3BR (indoor closet) and 4BR (outdoor closet); shared for others.	Individual gas in outdoor closet
Cooking appliance	Gas with pilot light	Gas with electronic ignition	Electric
Windows pane[2]	D	D windows; S sliding doors	S
Insulation	Few cm of fiberglass in walls and ceilings	Few cm of fiberglass in most walls and attics	Few cm fiberglass in walls and attic

[1]BR= bedroom [2]Single: S; Double: D [3]rental subsidy applicable to apartment complex, not to a housing agency, and paid to private landlord [4]rent subsidy applied in the form of interest reduction, through which multifamily housing unit is produced

Table 3. Number of retrofit measures implemented in each building and actual installed costs. Parenthetical values following numbers of installations of non a-priori retrofits are mean cost-normalized benefit scores.

Retrofit	B1	B2[1]	B3	Mean unit cost (range)
Air sealing	-[2]	5	6	$667 (650-684)
Install energy recovery ventilator (ERV)	5	-	3	$1,610 (1,440-1,780)
Replace intermittent bath exhaust fan	5	-	3	$880 (720-1,080)
Add continuous bath exhaust fan	-	6	3	$880 (720-1,080)
Replace intermittent kitchen range hood	5	6	6	$1,160 (1,100-1,280)
Upgrade HVAC system filter	5	5	6	$30
Add water heater jacket and insulation	-	3	-	$100
Replace natural draft water heater with forced combustion condensing water heater	5 (0.9)	-	-	$3,280
Weatherstrip water heater closet door	-	2 (NA)	-	$120
Provide portable fan	5 (20)	6 (20)	6 (20)	$50
Install carbon monoxide (CO) detector	5 (20)	5 (20)	-	$50 (included-$50)
Clean minor mold damage in bathroom	3 (5)	-	-	$200
Replace incandescent light bulbs with compact fluorescent lights	5 (20)	6 (40)	6 (40)	$7/bulb
Replace gas cookstove with standing pilot with electronic ignition stove	5 (4.4)	-	-	$680
Replace refrigerator with energy-efficient refrigerator	5 (1.4)	6 (1.2)	6 (1.2)	$813 (740-850)
Replace heating and cooling rooftop packaged unit with a more efficient unit	5 (1.0)	-	-	$4,060
Add attic insulation (cellulose R-38)	-	4 (3.0)	4 (2.1)	$1,223 (984-1,463)
Replace HVAC ductwork & seal return plenum	-	5 (0.9)	3 (1.0)	$2,200 (2,160-2,240)
Install stand-alone wall-mounted HEPA filter	-	6 (2.7)	6 (2.3)	$813 (750-875)
Replace single pane sliding door with double pane door	-	2 (0.8)	-	$2,450
Replace single pane window with double pane window	-	-	3 (1.1)	$850 each

[1] Some recommended measured not implemented in one apartment to accommodate tenant preferences
[2] Entry doors were weather-stripped