ENERGY AND WATER SAVINGS IN MULTIFAMILY AFFORDABLE HOUSING

ASSESSMENT OF THE PENNSYLVANIA HOUSING FINANCE AGENCY'S ARRA-FUNDED WEATHERIZATION PROGRAM, PRESERVATION THROUGH SMART REHAB

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EXECUTIVE SUMMARY

When the American Reinvestment and Recovery Act of 2009 (ARRA) allocated $5 billion in stimulus dollars for Weatherization Assistance Programs (WAP), Pennsylvania was one of four states — Colorado, New Jersey, Kansas and Pennsylvania—that had a well-established staff and infrastructure in a state-wide agency to deliver and administer funds to multifamily housing (Glatter 2009). The Pennsylvania Housing Finance Agency (PHFA), through its *Preservation through Smart Rehab* program, received $22.5 million of the ARRA monies. The program itself predates ARRA and is designed to preserve multifamily affordable rental units in the state. Beginning in February 2010, PHFA allocated ARRA funds to upgrade 8,288 units in 109 properties. The first property was completed in December 2010; the last was completed August 2012.

This report is the initial analysis of the results of that program based on one year of pre-retrofit and one year of post-retrofit utility bills. Of the 109 funded properties, all implemented energy upgrades and 91 had sufficient pre-retrofit and post-retrofit energy data to be included in the study. Seventy-seven properties implemented water upgrades and all of them had sufficient pre-retrofit and post-retrofit water data to be included.

Key findings from this analysis are:

- The 91 properties included in the energy analysis provide 7,439 units of affordable housing with 9,435 bedrooms in 6,228,297 square feet of space, including common areas.

- The properties in this dataset are predominantly wood frame (38%) or concrete masonry unit (21%) structures.

- The average reduction in energy use intensity (EUI) in the first post-retrofit year was 8.21 kBTU/ft2 per year. For the 91 properties, this represents a total annual energy savings of 51.1 billion BTUs and a reduction in carbon dioxide equivalent emissions of 10,332 metric tons. That is the equivalent of eliminating greenhouse gas emissions from 2,175 cars per year. The average percent savings in EUI was 12.34%. The highest percent savings in EUI in an individual property was 45%; the lowest was a 14% EUI increase.

- Properties that installed or upgraded heat pumps had an average EUI savings of 17% and their monthly percent savings in electricity use was greater than that for all other properties in eleven of the twelve post-retrofit months.

- Properties that upgraded lighting in both the housing units and common areas had an average percent savings in EUI of 14% and realized electricity savings in every post-retrofit month.

- Properties that upgraded heating boilers achieved a greater percent reduction in fossil fuel consumption than all other properties in ten of the twelve post-retrofit months.

- A positive correlation was found between EUI savings and retrofit hard cost for heat pumps and for building envelope insulation, suggesting that total energy savings for properties that implemented these upgrades are well correlated with the cost of those upgrades.

- For 71 properties included in the detailed water analysis, the average savings in water consumption was 55.5 gallons per bedroom per day, or a 16% savings. For these properties, this represents a total annual water savings of approximately 135 million gallons of water per year.

- No correlation was found between water savings and the hard cost of water retrofits, but properties that upgraded only the faucets (aerators) or faucets + showerheads (low-flow showerheads) seemed to achieve the greatest water savings for the lowest retrofit hard cost.

- Accurate tabulation of energy data was the single most challenging aspect of this project. Electronic retrieval of utility bill data was not a smooth process during the study period. In addition, data privacy requirements, utility mergers/buyouts, utility company switching due to deregulation and tenant turnover added substantial complexity to the summary of pre- and post-retrofit energy consumption for most properties.

- Improvements in metering and sub-metering would vastly improve assessment of weatherization investments. In this dataset, there were 7.7 energy-related upgrades per property on average. Changes in the monthly pattern of electricity and/or fossil fuel consumption pre- and post-retrofit were the only means available to try to evaluate the impact of individual upgrade measures.

- A new approach to weather normalization was used for this analysis, a machine learning model that includes humidity and solar radiation as well as temperature changes between the pre-and post-retrofit year. Further development of this approach might be used in the future to identify properties in which energy use is strongly influenced by weather differences from year to year. This, in turn, can help guide the selection of building upgrades.

- The average pre-retrofit and post-retrofit EUI for these properties are lower than those in similar datasets. However, there is a remarkable lack of data nationally about energy consumption in multifamily affordable housing so comparisons can be difficult. The PHFA Preservation through Smart Rehab program is valuable for its support of multifamily affordable housing and its accomplishments with the ARRA funding. The dataset is valuable for its contribution to our national understanding of this type of housing.

1 INTRODUCTION

PA County	# of Units	Percent of Total Units
Allegheny	692	8.35%
Beaver	139	1.68%
Berks	37	0.45%
Bucks	202	2.44%
Centre	122	1.47%
Chester	70	0.84%
Dauphin	504	6.08%
Elk	36	0.43%
Erie	40	0.48%
Fayette	126	1.52%
Jefferson	101	1.22%
Lackawanna	64	0.77%
Lancaster	339	4.09%
Lehigh	300	3.62%
Luzerne	504	6.08%
Mercer	151	1.82%
Mifflin	44	0.53%
Monroe	41	0.49%
Montgomery	980	11.82%
Northampton	150	1.81%
Northumberland	47	0.57%
Perry	50	0.60%
Philadelphia	2201	26.56%
Potter	42	0.51%
Schuylkill	72	0.87%
Snyder	24	0.29%
Somerset	28	0.34%
Venango	128	1.54%
Warren	44	0.53%
Washington	312	3.76%
Wayne	88	1.06%
Westmoreland	229	2.76%
York	381	4.60%
Total	**8288**	**100%**

It is a remarkable fact that the energy performance of multifamily housing is poorly understood even though 30% of the US population lives in multifamily dwellings (Trehubenko 2012). Consider the variation in potential benchmarks. The most well-established national database of residential energy consumption, the Department of Energy (DOE) Energy Information Administration's Residential Energy Consumption Survey (RECS), bases its energy use projections for multifamily housing on survey results of fewer than 1,000 individual units within multifamily properties nationwide. The average site energy use intensity (EUI) for US multifamily housing in the 2009 RECS survey is 69.2 kBTU/ft2 per year in smaller properties (2-4 units) and 54.5 kBTU/ft2 per year in larger properties (5+ units).

By contrast, the new (June 2013) DOE Buildings Performance Database that uses only metered properties shows a national median site EUI of 23 kBTU/ft2 per year in multifamily and residential mixed-use properties throughout the US.[1] A site EUI of 23 kBTU/ft2 is not much higher than the energy intensity of recent single-family homes designed to be net zero energy.[2]

DOE Commercial Reference Building Models for midrise and high rise apartments have an average site EUI across climate zones of 43 to 45 kBTU/ft2 and a median of 39 to 43 kBTU/ft2. For these building models, high rise buildings are slightly more energy intense than midrise buildings. (Deru 2011). By comparison, the trend in RECS data cited above shows a *lower* EUI for larger properties.

There are many possible reasons for disparities in the numbers, including but not limited to differences in property age, size and climate zone; in common area size and services; and in building area calculation and the inclusion or exclusion of unconditioned spaces such as parking lots. With so much variation, however, comparisons to national or regional EUI benchmarks are difficult and metered performance is hard to

[1] Average EUI is not shown; median is based on approximately 143,000 properties, including many in New York and Pennsylvania.
[2] Renewable energy contribution excluded, EUI range in metered net zero housing is typically 7-18 kBTU/ft2.

assess. This underscores the value of PHFA's multifamily focus as well as its multifamily dataset.

When the American Reinvestment and Recovery Act of 2009 (ARRA) allocated $5 billion in stimulus dollars for Weatherization Assistance Programs (WAP), Pennsylvania was one of only four states—Colorado, New Jersey, Kansas and Pennsylvania—that had a well-established staff and infrastructure in a state-wide agency to deliver and administer funds to multifamily housing (Glatter 2009). PHFA, through its *Preservation through Smart Rehab* program, received $22.5 million of the ARRA monies. The program itself, which predates ARRA, is designed to preserve multifamily affordable rental units in the state and in the post-2008 economy, its mission is critical. In Allegheny County alone,[3] 70% of the housing units with rent below $700 per month have disappeared in the last ten months, replaced with far more expensive rentals, although median income in the county has not changed. One long-established affordable housing organization in the county, ACTION Housing, reports that they have a waiting list of 2,000 people and a total of 1,500 affordable rental units in the county, most of which are already occupied.[4] Pennsylvania and most other states in the US are experiencing a similar demand for affordable multifamily units and an important aspect of their affordability is manageable utility bills.

Beginning in February 2010, PHFA allocated ARRA funds to upgrade 8,288 units in 109 properties. Each property that received funding was assessed by an auditor trained and certified by the Building Performance Institute (BPI) Certified Multifamily Analyst program. Auditors were required to enter the details of each property into one of three approved energy modeling software packages[5], to reconcile the model with the prior year's utility bills, and to provide an audit report with property description and the audit analysis results and recommendations. The PHFA program funded upgrades that offered a savings-to-investment ratio (SIR) >1 and payback within ten years. Selected upgrades were summarized for each property and include the description of each measure, the cost, anticipated savings, and SIR.

Properties applying to the program agreed to provide twelve months' of pre-upgrade utility data and five years' of post-upgrade data. The first property was completed in December 2010 and the last was completed August 2012. Carnegie Mellon University (CMU) was aware of PHFA's program through *pro bono* participation as a technical consultant to the Energy Conservation Collaborative, a group of multifamily owners and developers of multifamily affordable housing in western Pennsylvania. As the Preservation through Smart Rehab program drew to a close, CMU applied for and received funds from DOE's Energy Efficient Buildings Hub, now the Consortium for Building Energy Innovation, to analyze the first-year results. This report is the initial analysis of the results of that program based on one year of pre-retrofit and one year of post-retrofit utility bills.

[3] Allegheny County, PA, located in Western Pennsylvania and encompassing Pittsburgh.
[4] Personal conversation with Linda Metropulos, Housing Development Director, ACTION Housing Inc.
[5] TREAT and EA-QUIP are approved by DOE for modeling multifamily housing and were accepted by PHFA. REM/Rate was accepted for modeling buildings with 25 or fewer units if each unit had its own conditioning system.

2 METHODOLOGY

The fundamental approach in this analysis was to build a database of property characteristics, of energy and water upgrades, and utility bill data for the pre-retrofit and post-retrofit year and to evaluate the impact of the upgrades on energy and water consumption in these properties. The data provided by PHFA included:

- an audit report for each property;
- a property spreadsheet file with utility bill details for each account associated with the property;
- a separate property report of the implemented upgrades, the predicted savings to investment ratio (SIR) and lifecycle savings, and the actual upgrade costs.

This information was input into a database created for the study. CMU also requested and received a small sample (3) of the energy simulation files prepared by the auditors.

2.1 USE OF AUDIT REPORTS

The audit reports describe each property and the auditors' recommended upgrades. Reports varied in length from approximately 12 to 90 pages. The CMU team reviewed each report and used the property description in it to populate the database with pre-retrofit property characteristics: building age, size, construction details, and types of mechanical systems, lighting, ventilation and appliances. While all of the reports provided building detail and justification for the upgrades, they varied substantially in the amount of additional detail they provided, and in the way information was organized and presented. For example, some audit reports contained extensive descriptions of the building(s) and existing conditions regardless of whether those conditions were related to the recommended upgrades. Other reports focused on upgrades only and the property conditions related to those upgrades. These variations did not hamper the analysis but they did result in disparities in level of detail available to characterize the property.

When developing a database structure to capture property characteristics, CMU originally created a nested database structure that captured detail at the dwelling unit level (apartment or townhouse) and then by building and by property. Given the variability in the level of detail available for each property, however, a modified data structure was used for this analysis. Where properties had multiple buildings that could be of different types (both apartments and townhouses), different ages, construction materials and equipment, CMU characterized the entire property by the predominant type of building and construction material. The construction date most representative of the property was used. Common areas and living areas were characterized separately with respect to equipment and lighting. For lighting, many audit reports provided substantial detail about the number and type of fixtures and these varied substantially. To make data entry manageable within the scope of this analysis, CMU identified the predominant type(s) of lighting by number of fixtures. The results of this characterization are provided in Section 3.

2.2 Processing of Utility Bill Data

Utility bill data was provided in a single spreadsheet file for each property. These files contained the monthly quantity of energy or water for owner-paid accounts and for tenant-paid accounts for which tenants authorized PHFA access.[6] Properties that received funding through the Preservation through Smart Rehab program agreed to provide utility bill data for a minimum of 50% of tenant-paid housing units. In reality, this is difficult, for reasons described below. To support data analysis, PHFA attempted to gather utility data for at least 20% of the tenant-paid units in each property and in some properties, utility bills for 40%-60% of the tenant-paid accounts were provided.

Acquiring "complete" account data was the single most challenging aspect of the project. PHFA accepted 250 days of utility data as a full year. DOE requested that CMU use a full year (365 days) of utility information for the pre- and post-retrofit years, but this was possible for very few properties, for reasons discussed below. As a compromise, CMU defined a full year of data as a minimum of 360 days of utility data per year that had to include at least two of the peak winter months (December through February) and at least one peak summer month (July or August). CMU required a full year of utility data for a minimum of 10% of separately metered dwelling units per property and attempted to obtain bills for at least 10% of each *size* dwelling unit (based on number of bedrooms) at each property. PHFA tried to provide additional data as requested, although they were not always available. In properties where upgrades where finished early in the program cycle (2010), PHFA indicated that some pre-retrofit year data (2009) had been deleted by the utility. Of the original 109 properties in the dataset, PHFA was able to provide sufficient utility data for 91 properties by the end of December 2013. CMU summed the data for all "complete" accounts and projected total property energy consumption based on the percent of housing unit data provided.

The transition between the pre- and post-retrofit period was determined by a single "implementation date" that separates the 12-month pre-retrofit and 12-month post-retrofit period. This was the date on which inspectors verified that the authorized upgrades were installed or completed as described. PHFA stated that property upgrades typically required one month or less, so there would have been little overlap between the pre- and post-retrofit years.

Some of the additional challenges that affected data acquisition and processing were:

- Long interruptions in data "scraping": Data scraping is the automatic electronic collection of data from utility company servers. Property owners and tenants could authorize PHFA to scrape data from their accounts. During the post-retrofit year, there were extended periods during which data could not be scraped from utility servers. According to PHFA, when utilities upgrade server security, connection with non-utility servers for automatic data scraping is interrupted and the connection needs to be re-set by the utility. Some utilities took up to six months to re-establish the connection. During these periods, PHFA had to enter data manually into spreadsheets. Manual entry of monthly utility data for each apartment and each common area account was time-intensive. PHFA hired additional staff

[6] Most, but not all, bills had monthly frequency. Some water bills were quarterly, and the frequency of propane and oil bills varied for each property that used these fuels.

to make this possible, but data collection and delivery to CMU was delayed from February 2013 to the end of the year. Manual entry also resulted in some errors in the unit quantities associated with accounts and those needed to be clarified and corrected.

- Manual data entry for tenant accounts where the tenant already had an online utility account: PHFA indicated that utilities allowed only one online account per customer, so if a tenant already had an online account, PHFA could not acquire a second for data scraping and had to manually enter the data.

- Re-establishing authorization for data acquisition with new utility companies: The account switching possible with de-regulation in Pennsylvania, coupled with data privacy laws, resulted in the need to obtain tenant release forms more than once for several properties.

- Maintaining a sufficient number of tenant-paid accounts: Data privacy laws and tenant turnover in some properties required ongoing efforts by property managers to "recruit" sufficient tenants to meet their data collection obligation under this program. Tenant turnover also resulted in the creation of multiple incomplete data files that CMU needed to omit from the energy use calculations.

- Maintaining data continuity after utility company buyouts/mergers: Utility company buyouts and mergers during the program period resulted in data overlaps/double counting in some accounts that needed to be manually reconciled. Double-counting of fuel or electricity on separate bills for the commodity and for its transmission also had to be resolved when data were summarized.

- Bulk purchase of propane and oil: Purchases of oil and propane occurred intermittently in bulk quantities and monthly consumption was not metered. For properties that used propane or oil, bulk quantities were allocated evenly across the months between fuel purchases even though fuel use by month undoubtedly varied.

Due to a variety of data anomalies in the utility spreadsheet files, CMU was not able to write a script that automatically and accurately captured the required utility information. As a result, the utility data for each property were manually tabulated. Energy use data were then weather normalized, a process described in Section 4, and the resulting monthly weather normalized pre-retrofit energy consumption and actual monthly post-retrofit energy consumption were entered into the database. Water data were summarized and allocated evenly by month if bills represented multiple months and entered into the database.

2.3 UPGRADES AND THEIR CLASSIFICATION

PHFA's Preservation through Smart Rehab program was created to help maintain Pennsylvania's stock of affordable apartments. For the ARRA-funded upgrades, auditors were not limited to a specific menu of upgrades. Rather, they were free to recommend any health and safety upgrade, and any energy- or water-efficiency upgrades for which the simulation software showed that the total savings to investment ratio (SIR) $\geq$ 1 and the average overall payback period was ten years or less. PHFA evaluated audit recommendations and approved 714 energy-related upgrades for the 91 properties in this dataset. There was a median of 7 and an average of 7.8 upgrades per property including health and safety upgrades.

To evaluate the impact of these upgrades, CMU explored multiple strategies for their categorization based on existing practice and the implemented measures. Initially, upgrade measures were grouped by the load they would affect: heating, cooling, lighting, DHW, appliances, water, and non-energy measures (health & safety). Measures that would affect both heating and cooling, such as a heat pump installation, were placed in both load categories. The intention here was to link upgrades to an anticipated seasonal pattern of energy consumption and to assign them to either the base load (lighting, DHW, appliances, and water) or to heating or cooling. Table 2-1shows the results of that classification, with the number of properties that implemented measures related to each load, the number of upgrades associated with that load and the median anticipated payback of those measures in years as estimated by the auditors' software models. Measures that affect both heating and cooling, e.g., insulation, air-sealing and heat pump installation, are double-counted with this approach. Health and safety measures are excluded here and throughout this analysis since they were not implemented for energy and water efficiency.

*Table 2-1: Energy and Water Upgrades Categorized by Building Load**

Load	Number of Properties	Total Number of Related Upgrades	Median Simple Payback in Years
Heating	86	250	5.8
Cooling	83	167	5.9
Lighting	79	189	5.8
DHW	49	58	5.4
Appliances	51	67	5.7
Water	77	96	1.9

*Upgrades such as insulation, air sealing or heat pumps that affect both heating and cooling are counted in both categories

Because of double-counting in the load-based categories, the upgrades were then regrouped by the nature of the upgrade. The strategy was to group as many upgrades into a category as possible to facilitate analysis while maintaining the ability to isolate and analyze specific types of measures. For example, one potential category would have been "heating equipment," but because of the number of heat pump and boiler upgrades, heat pumps and boilers were assigned their own categories. Other heating equipment upgrades, fewer in number, were grouped together. Building envelope insulation is a customary weatherization upgrade and was used as a single category for this analysis. However, the specific building insulation measures in this category include an activity as small as insulating an attic hatch and as large as furring-out and adding R-23 insulation to interior walls of an old masonry high rise. A similarly large range in the scope of activities represented in a single category also exists within the Building Air Sealing and Ventilation categories. The complete list of upgrade categories and the number of properties and number of units implementing them is shown below in Table 2-2.

Table 2-2: All Upgrades in 91-Property Dataset

Upgrade Category	Description	# of Units in Properties Using the Upgrade	Corresponding # of Properties Using the Upgrade
Appliance: Dehumidifier	Replacement of existing dehumidifier(s)	48	1
Appliance: Dishwasher	Replacement of existing dishwashers with energy efficient dishwashers	22	2
Appliance: Elevator	Elevator-related upgrade measures	88	1
Appliance: Other	Tune gas ranges in apartments and community rooms	101	1
Appliance: Refrigerator	Replace some or all refrigerators	2786	35
Appliance: Vending Miser	Install vending miser	1192	14
Appliance: Washing Machine	Replacement of washing machine(s) with energy efficient washing machine(s)	332	3
Building Envelope Air Seal	Reducing air leakage through building envelope by sealing the air gaps	3770	59
Building Envelope Air Seal Openings	Sealing openings (doors, attic hatches, windows) to reduce air leakage	1210	12
Building Envelope Entry Door Sensor	Installing a sensor for the entry door	75	1
Building Envelope Insulation	Adding or upgrading building envelope insulation - either wall, roof, or floor, or any of them in combination	2053	26
Building Envelope Repair	Repairing attic or exterior brick	244	2
Building Envelope Windows	Replacing windows	332	2
Cooling Upgrade	Replace cooling units with higher efficiency cooling units	829	7
Domestic Hot Water Control	Controlling domestic hot water system and supply temperatures	1775	22
Domestic Hot Water Insulation	Insulating the domestic hot water system piping	1226	15
Domestic Hot Water Upgrade	Replacing domestic hot water equipment	1041	18
Health & Safety	Various upgrades to protect occupant health & safety	1794	19
Heating Boiler	Replacing existing boilers with higher efficiency boilers or installing new boilers	1474	14
Heating Controls	Changing the schedule of operation or adjust setpoint or setback temperatures	1423	11
Heating Furnace	Replace existing furnace with high efficiency furnace	512	7

Upgrade Category	Description	# of Units in Properties Using the Upgrade	Corresponding # of Properties Using the Upgrade
Heating Hydronic	Install hydronic heating system	6	1
Heating Insulation	Insulating heating ductwork and/or pipes	655	8
Heating Upgrade	Installing isolation dampers or electric thermal storage heaters	129	2
Heating & Cooling Controls	Adjusting or installing on/off controls of the heating and/or cooling system	348	2
Heat Pump	Installing new or upgrading existing heat pumps	1670	20
Lighting Control/Sensor	Installing occupancy sensor or timers for lighting	2167	28
Lighting Upgrade Whole Building	Replacing the existing lighting in whole building (property) with higher efficiency lighting	2330	25
Lighting Upgrade Common	Replacing the existing lighting in common areas with higher efficiency lighting	4238	47
Lighting Upgrade Exterior	Replacing the existing exterior lighting with higher efficiency lighting	978	10
Lighting Upgrade In-Unit	Replacing the existing lighting in housing units with higher efficiency lighting	3293	40
Master Meter[7]	Replace individual apartment meters with single meter for whole property (either electricity or gas)	351	2
Thermostat	Upgrading or replacing the thermostat	2357	35
Ventilation	Exhaust fan controls, replacement of exhaust fans, bath fan flow regulators, upgrading building fresh air ventilation system, garage ventilation system replacement	2722	30
Variable Frequency Drive	Installing variable frequency drives on heating, cooling, or ventilation systems	1081	6
Upgrade Category	**Description**	**# of Bedrooms in Properties Using the Upgrade**	**Corresponding # of Properties Using the Upgrade**
Water-Faucet	Installing aerators on bathroom and/or kitchen faucets	616	8
Water-Faucet + Shower	Installing aerators on bathroom and/or kitchen faucets and installing low flow showerheads	4716	48
Water-Faucet + Shower + Toilet	Installing aerators on bathroom and/or kitchen faucets, installing low flow showerheads, and replacing older toilet with low GPF toilets	581	7

[7] Replacing individual apartment meters with master meters provides no energy savings, only cost savings. An owner is charged less for gas or electricity when the property has a single master meter. Important detail and feedback information is lost, however, when apartment meters are removed and CMU regards this strategy as a disincentive to energy savings. CMU lists this as a separate category to highlight it.

Upgrade Category	Description	# of Units in Properties Using the Upgrade	Corresponding # of Properties Using the Upgrade
Water-Shower	Installing low flow showerheads	122	3
Water-Toilet	Replacing older toilet with low GPF toilets	599	4

The categories above were then linked in the database to the upgrade measures, characteristics and energy or water consumption data for each property.

2.4 Data Analysis

The analysis of energy-related upgrades and findings from that analysis are described in Section 5; the analysis of water upgrades and the findings from that analysis are described in Section 6.

2.5 Process Evaluation

In order to understand the building audit process and the audit software output, CMU interviewed one of the regional audit program managers and reviewed three software energy models provided by PHFA. Information gathered from these activities is integrated into the report summary and recommendations.

3 Property Characteristics

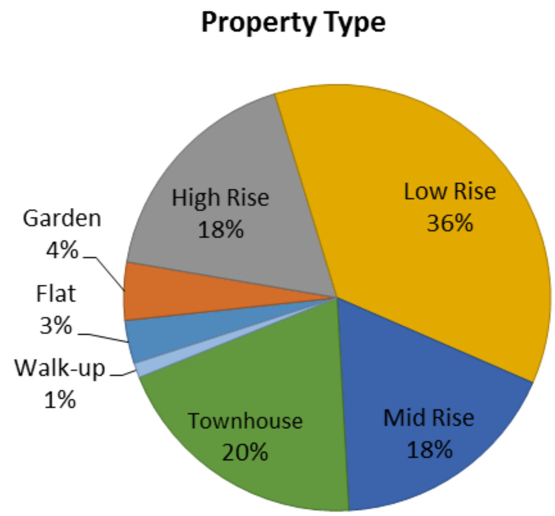

Figure 3-1: Properties by Type

Beginning in February 2010, PHFA allocated ARRA funds to upgrade 8,288 affordable housing units in 109 properties. By December 2013, 91 of the original 109 properties had sufficient pre- and post-retrofit utility bill data to be included in this analysis. A discussion of sufficient utility bill data is provided in the Section 2.

The 91 properties with sufficient utility bill data represent **6,228,296 square feet of affordable housing**, with 7,439 units of housing and 9,435 bedrooms. More than one-third of these properties (36%) are low-rise buildings, 20% are townhouses, 18% are mid-rise and 18% are high-rises, and the remaining properties are garden apartments and flats. See Figure 3-1.

Twenty-two (22) of these properties are family occupancy with 1,308 housing units (17.5% of total units) and 2,990 bedrooms. Fifty-four (54) properties are senior occupancy with 5,163 housing units (69.4%) and 5,437 bedrooms. The remaining 15 properties provide housing for disabled individual or provide single room occupancy (SRO). These properties represent 968 units (13%) and 1,008 bedrooms.

The PHFA dataset does not provide occupancy data, but CMU conservatively assumed one person per bedroom because of the high percentage of senior housing. As a result, these properties are estimated to **serve at least 9,435 low income individuals**. The comparative size of these properties and their distribution across the Commonwealth is shown in Figure 3-2.

The age of the properties included in the PHFA weatherization program is shown in Figure 3-3 and compared to the vintage of US Northeast housing stock as reported in in DOE's Energy Information Administration 2009 Residential Energy Consumption Survey (RECS). Since RECS provides information for individual dwelling units only (see Section 5), the chart shows the PHFA housing units as a percent of the total dataset (7,439 units). In the US, the Northeast region (which includes Mid-Atlantic) has the oldest housing, but properties in the PHFA dataset are more recent. The PHFA dataset has far fewer pre-1940 housing units and far more units built since 1970 than the Northeast region overall.

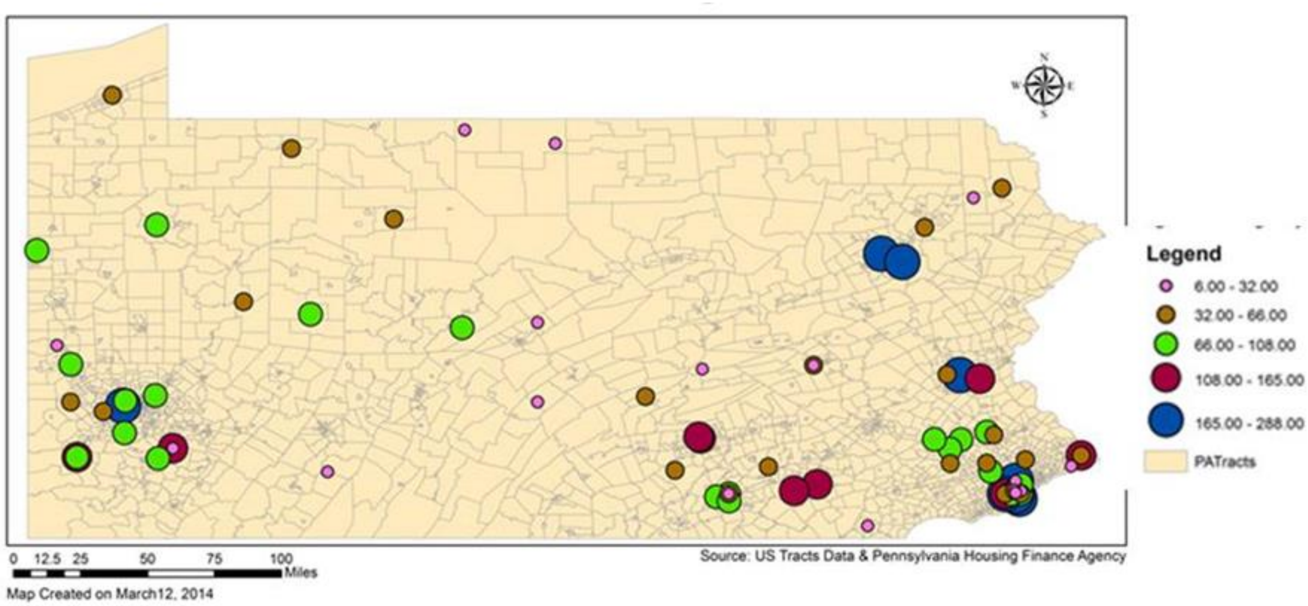

Figure 3-2: PHFA Participating Properties by Number of Units

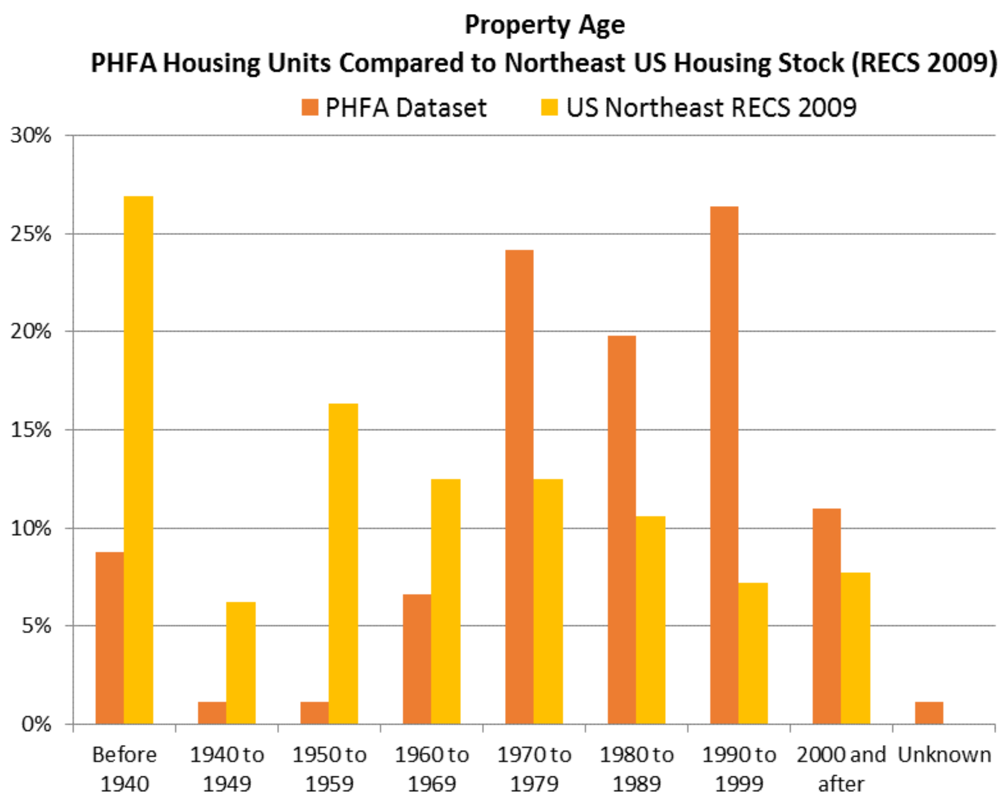

Figure 3-3: Vintage of PHFA Properties Compared to Housing in Northeast US

3.1 Building Structure

Based on the building audit reports, the buildings in the PHFA dataset are predominantly wood-framed or concrete masonry unit (CMU) structures. The breakdown of structural materials is shown in Figure 3-4. The roof construction is also predominantly wood-framed (49%) or concrete, as shown in Figure 3-5. The foundations are mostly slab-on-grade or basements for properties where that information was provided. In several cases, the audit reports did not include foundation details as seen in Figure 3-6.

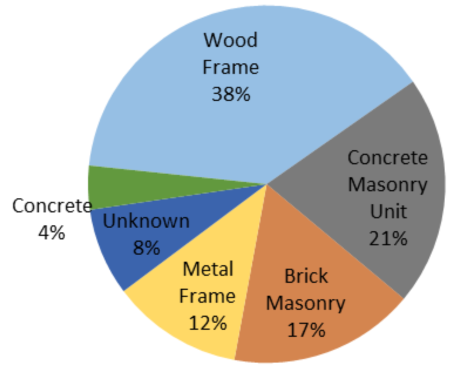

Figure 3-4: Wall Structure

3.2 Windows

Residential windows have a significant impact on energy consumption and occupant comfort, particularly in heating-dominated climates like those in Pennsylvania. Although window replacement is generally not done during weatherization because of per-unit cost limits, 82% of the properties in the PHFA dataset currently have double-pane windows as the primary window type. Properties with single pane windows often have storm windows. Window frames are aluminum in 52% of the properties; the remainder is fairly evenly divided between vinyl and wood frames. Few window replacements were recommended during pre-retrofit audits.

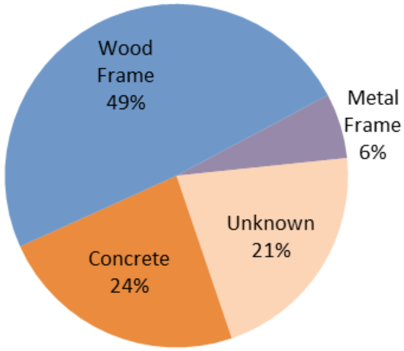

Figure 3-5: Roof Construction

3.3 Lighting

Most audit reports provided detailed descriptions of lighting in both the housing units and the common areas, and most properties have multiple types of lighting. For this analysis, lighting is categorized as either living area lighting (apartments, SROs or townhouses) or common area lighting (hallways, laundry rooms, etc.) and was recorded from the audit reports as the predominant type of lighting based on number of fixtures.

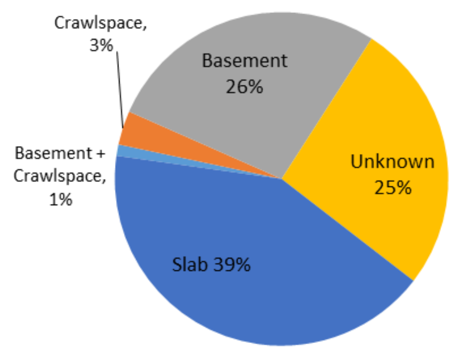

Figure 3-6: Foundation Type

In the living areas, incandescent lighting was the predominant type of lighting in almost half of the properties (47%) prior to the retrofit. After the upgrades, CFLs were the predominant type of lighting in the living areas in 54% of the properties (show in Figure 3-7and Figure 3-8).

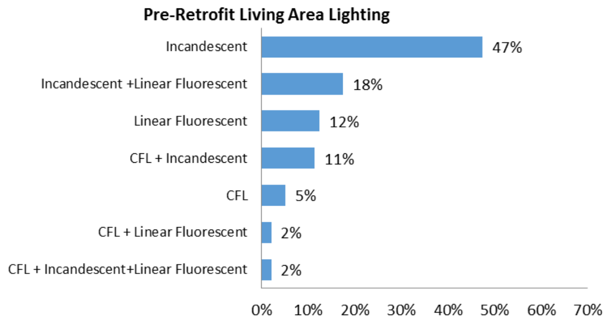

Figure 3-7: Pre-Retrofit Living Area Lighting

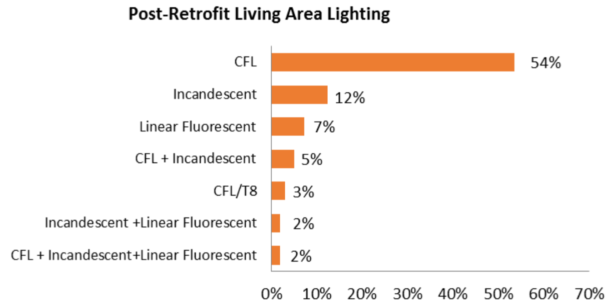

Figure 3-8: Post-Retrofit Living Area Lighting

In the common areas of the buildings, linear fluorescents were the primary type of lighting in 60% of the properties prior to the retrofits. After the retrofits, linear fluorescents predominate in only 31% of the properties. CFLs are now the primary type of common area lighting in 26% of the properties and a combination of CFLs and linear fluorescents account for an additional 25%. These three types or combinations are found in 82% of the properties. See Figure 3-9 and Figure 3-10.

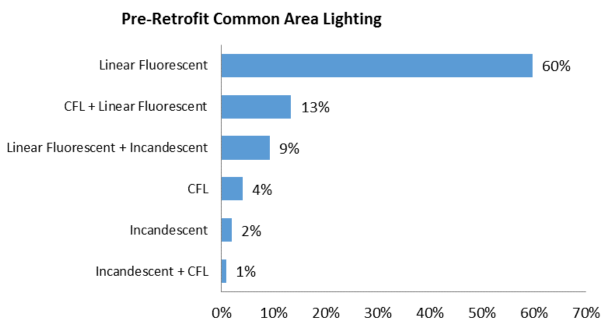

Figure 3-9: Pre-Retrofit Common Area Lighting

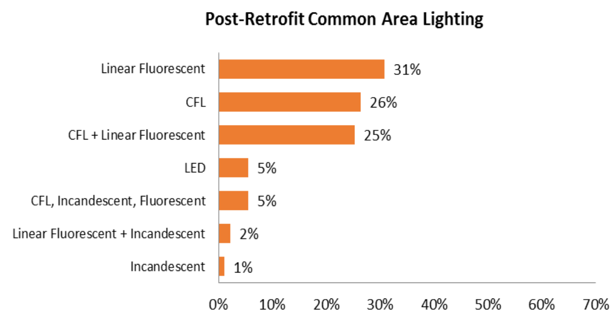

Figure 3-10: Pre-Retrofit Common Area Lighting

3.4 Heating And Cooling Systems

3.4.1 Heating

Similar to the classification of lighting, heating and cooling systems are categorized as systems used in living areas (apartments, SROs or townhouses) and those used in common areas. Since Pennsylvania climate zones are all heating dominated, a building's heating system will have a substantial impact on its energy consumption. Prior to the retrofits, three types of heating equipment were used in the living areas in 74% of the properties. A central boiler was used to heat the living areas in 30 properties with 3,434 housing units. Surface-mounted electric resistance heaters—most commonly baseboard heaters, but also ceiling mounted and wall-mounted units—were used to heat living areas in 19 properties with 1,468 housing units. Gas furnaces were used to heat living areas in 16 properties with 739 housing units. See Figure 3-11.

Because ARRA funding allowed more money to be spent per housing unit, heating systems could be replaced and as a result, several properties upgraded their heating systems.

Central boilers are still the most common type of heating for living areas in these properties, but 13% of the properties with 1,176 housing units now have higher efficiency boilers. Gas furnaces are still the living area heating system in 739 housing units, but 192 of those units now have higher efficiency gas furnaces. Prior to the upgrades, none of the properties used mini-split heat pumps for living areas and now, mini-splits are the living area heating system in 12 properties with 750 housing units. An additional 5% of the properties with 381 housing units upgraded to higher efficiency air source heat pumps, packaged terminal heat pumps and water heaters (as heating systems); and rooftop units were installed in 3% of the properties. Surface-mounted electric resistance heating is now used in only 10% of the properties. See Figure 3-12.

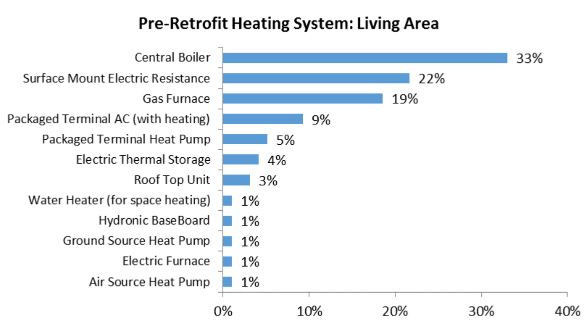

Figure 3-11: Pre-Retrofit Living Area Heating

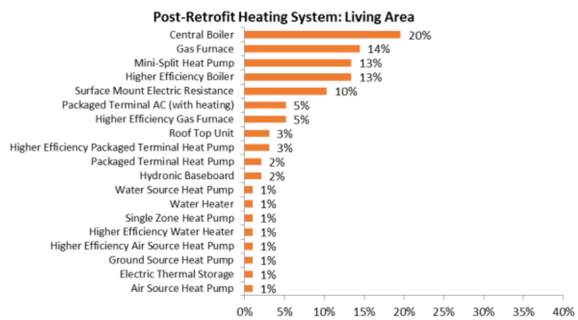

Figure 3-12: Post-Retrofit Living Area Heating

In common areas of these properties, four types of heating equipment were used in 74% of the properties. Central boilers were the most common type of heating system prior to the upgrades, used in 27 properties. Surface-mounted electric resistance heaters were used in 25 properties. Gas furnaces were used in 11 properties and rooftop units (RTUs) were used in 9 properties. Heat pumps, PTACs with heating coils, electric thermal storage systems and water heaters were used in the remaining properties except for four properties that have no common area heating. See Figure 3-13. Sixteen (16) properties upgraded common area heating systems. Nine properties upgraded common area boilers, and the remaining seven properties upgraded PTACs, gas furnaces and surface mounted electric resistance heaters. See Figure 3-14.

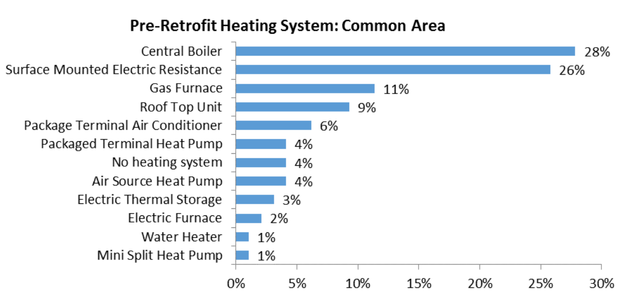

Figure 3-13: Pre-Retrofit Common Area Heating

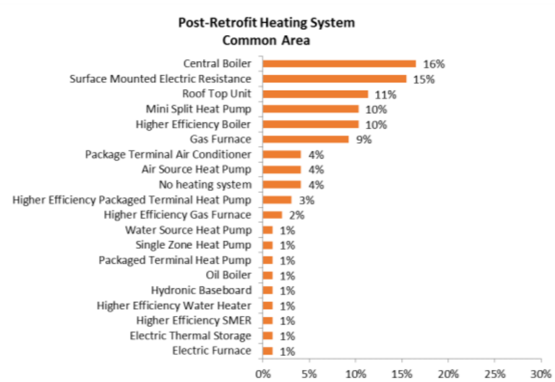

Figure 3-14: Post-Retrofit Common Area Heating

3.4.2 Cooling

Three types of cooling equipment were used in the living areas of 75% of the properties prior to the retrofits. Window air conditioners were used in 29 of the properties and 1,817 housing units. Packaged terminal air conditioners (PTACs) were used in 25 properties and 2,041 housing units. Central chillers were used in 14 properties for 2,223 housing units. Split system air conditioners accounted for an additional 11% of the properties, and the remainder of the properties used heat pumps of various kinds and RTUs. One property with 78 housing units had no cooling system and did not install one during the upgrades. See Figure 3-15.

Few properties upgraded living area cooling systems. The predominant types of cooling systems for living areas in 73% of the properties are still window air conditioners, PTACs, and central chillers. Higher efficiency split system air conditioners, PTACs and mini-splits were installed in five properties with 337 housing units. See Figure 3-16.

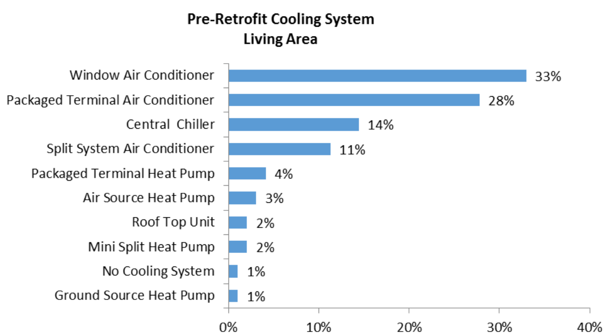

Figure 3-15: Pre-Retrofit Living Area Cooling

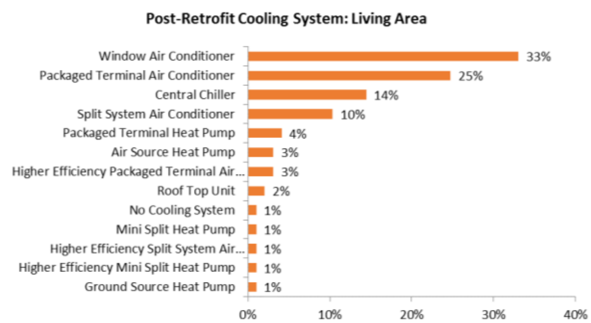

Figure 3-16: Post-Retrofit Living Area Cooling

Cooling systems in common areas were also largely unchanged during the upgrades. The most frequently used type of common area cooling equipment before and after the upgrades is PTACs, found in 20% of the properties prior to the upgrades and 18% of the properties afterwards. The other four most frequently used common area cooling systems, both pre- and post-retrofit, were split system air conditioners, rooftop units, window air conditioners, and chillers. Four properties upgraded the common area cooling equipment. Nineteen percent (19%) of the properties have no common area cooling system; most of these are townhouse properties. See Figure 3-17and Figure 3-18.

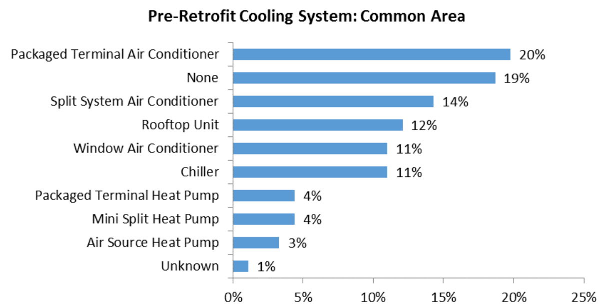

Figure 3-17: Pre-Retrofit Common Area Cooling

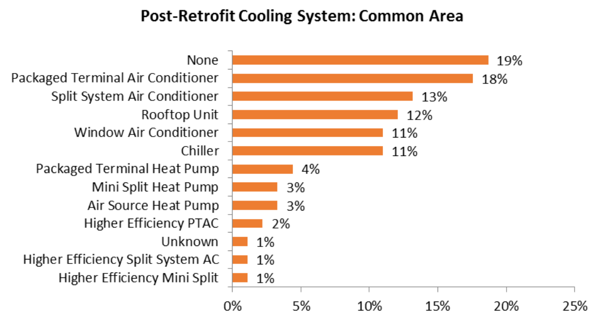

Figure 3-18: Post-Retrofit Common Area Cooling

3.5 Domestic Hot Water

Almost half of the properties in the dataset used central gas DHW systems for common areas and for living areas. Where separate systems are used for living areas and common areas, electric equipment is typically used. In-unit electric storage equipment was used in 29 properties with 2,014 housing units and in-unit gas storage equipment was used in nine properties with 433 housing units. There is no common area DHW in 18% of the properties (townhouses have no common system). The DHW system was not addressed in the audit reports of 7 properties. See Figure 3-19 and Figure 3-20 for additional details.

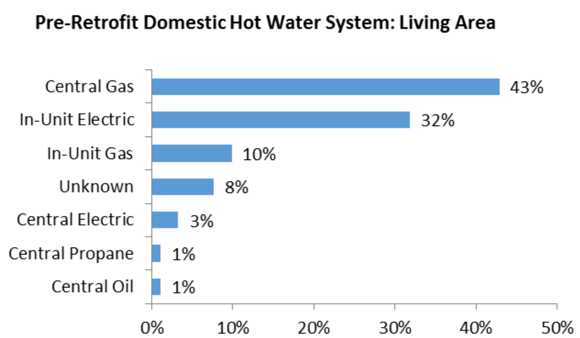

Figure 3-19: Pre-Retrofit Living Area Domestic Hot Water

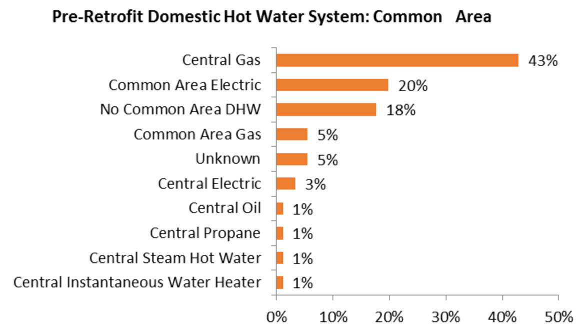

Figure 3-20: Post-Retrofit Living Area Domestic Hot Water

3.6 Fuel Types

Cooling and plug loads use electricity, so the differences in fuel use among these properties are the fuels for heating and DHW.

3.6.1 Heating Fuels

Thirty-three properties with 2,320 units heat with electricity. Thirty-nine properties with 3,232 units heat with natural gas. Eighteen properties with 1,628 units

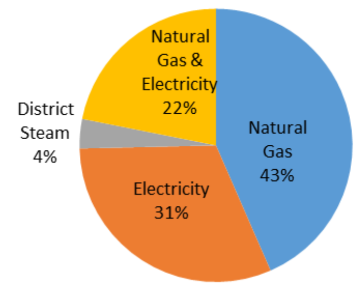

Figure 3-21: Heating Fuel Type

heat with a combination of natural gas and electricity in the common areas and apartments. One property with 259 units heats with a combination of steam from a district system and electricity. See Figure 3-21.

3.6.2 DHW Fuel

From a source energy perspective, natural gas is preferable to electricity and more than half of the properties and units in the PHFA dataset heat water with natural gas. See Figure 3-22 and Figure 3-23.

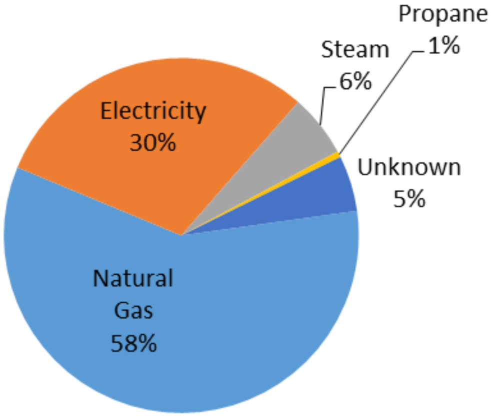

Figure 3-22: DHW Fuel in Common Areas

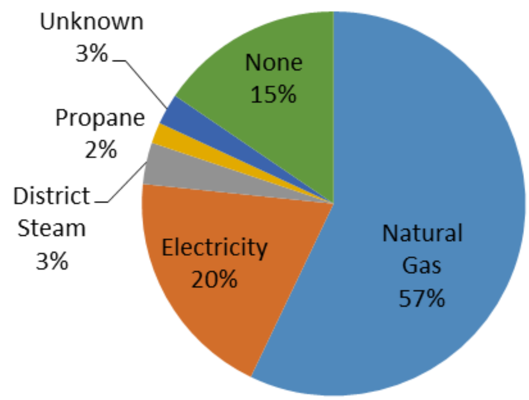

Figure 3-23: DHW Fuel in Living Areas

3.7 Who Pays The Bills?

The owner pays all utility bills, including apartment plug loads, in 49 of these properties, encompassing 5,041 housing units or 68% of the total units. For 36 properties and 2,004 housing units (27%), the tenants pay all the utilities. For the remaining six properties, the owner pays only heating and DHW in four properties with 258 units (3%) and the owner pays only DHW in two properties and 136 units (2%). See Figure 3-24.

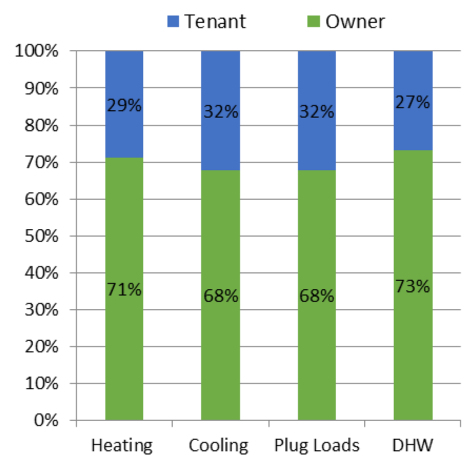

Figure 3-24: Who Pays the Bills

4 WEATHER NORMALIZATION

A building's annual energy consumption can be affected by changes in weather from year to year. Weather affects each building differently, depending on characteristics of the building envelope, equipment and internal loads. As a result, the impact of weather normalization varies from building to building. In general, lightweight and/or heavily glazed buildings experience more weather-related energy impacts than do heavier and/or less glazed buildings, unless internal loads dominate energy consumption.

To quantify the energy impact of retrofit measures, weather-induced changes in energy consumption need to be isolated and removed from the calculation of retrofit-based energy savings. Weather normalization does this by statistical methods. One common approach is to use utility bills and actual weather data to model post-retrofit energy use as a function of weather and a property's operating conditions and equipment. Then a post-retrofit model can be used to predict how much energy the un-retrofit property would consume in post-retrofit weather. The difference between the predicted energy consumption and the actual post-retrofit utility bills is the calculated energy impact of the weatherization upgrades.

4.1 WEATHER NORMALIZATION MODELS EVALUATED FOR THIS ANALYSIS

For the PHFA analysis, the CMU team explored three approaches to weather normalization: change point models and two non-linear regression approaches, general regression neural network (GRNN), and support vector machine (SVM). Ultimately, CMU chose to use an SVM model, a machine learning method, based on comparative accuracy. This section describes CMU's weather normalization work and the basis for choosing the SVM model to calculate retrofit-based energy savings.

The first weatherization method CMU used is currently the most widely used approach, temperature change point models. This method was developed by Kissock in the late 1990s and emerged from his earlier work with degree day models in PRISM, the Princeton Scorekeeping Method. PRISM regresses building energy use against degree-days. Change point models use temperature rather than degree-days and can include additional independent variables such as occupancy. A change point model comprises one or more connected line segments. Change points occur at the transition point from one line segment to the next. When temperature is the independent variable, a change point is similar to a building *balance point* temperature, an outdoor temperature at which building energy use begins to rise with the rise or fall of outdoor temperature.

Kissock's change point models are named by their number of change points or regression coefficients in the model: 2P, 3PC, 3PH, 4P and 5P. Of these, CMU tested the 3PC, 3PH and 5P models.

A 2P model is used when energy use is linearly correlated with a single independent variable like temperature. The model is a simple linear regression in the form:

$$Y = \beta_1 + \beta_2 X_1$$

Y is the dependent variable (energy use), β_1 and β_2 are regression coefficients and X_1 is the independent variable (temperature).

A 3P model is used when energy use is linearly correlated over part of the temperature range and is uncorrelated over the rest of the range. For example, natural gas consumption for heating and DHW would be linearly correlated with temperature below the change point and uncorrelated with temperature above that point, when it is used only for heating DHW. A 3P model is in the form:

$$Y = \beta_1 + \beta_2 (X_1 - \beta_3)$$

β_1 is the y- coordinate of the change point, β_2 is the slope term, and β_3 is the x-coordinate of the change point. Kissock uses the term *3PC* for a model that evaluates cooling energy consumption, and *3PH* for a model that evaluates heating energy consumption. This type of model is suitable for most buildings, where there is baseline consumption of electricity for plug loads or natural gas for DHW that is uncorrelated with temperature, and temperature-dependent consumption of those fuels for heating or cooling.

A 5P model could be used for a building with heat pumps. A 5P model consists of two sloped line segments (heating and cooling electricity) connected by a flat linear segment (baseline electricity). The line segments are joined at two change points, forming a basic U-shape. The change points identify temperatures at which electricity use rises with increasing temperature (cooling) and where it rises with falling temperature (heating). A 5P model has the form:

$$Y = \beta_1 + \beta_2(X_1 - \beta_4)^- + \beta_3 (X_1 - \beta_5)$$

β_1 is the y-coordinate of the change points, β_2 is the left slope, β_3 is the right slope, β_4 is the x-coordinate of the left change point, and β_5 is the x-coordinate of the right change point. Figure 4-1 shows the form of these models.

For weather normalization with change point models, CMU used Kissock's Energy Explorer™ software. Energy Explorer can generate the formula for regression lines and estimate the energy consumption of the pre-retrofit building in post-retrofit weather using outdoor temperature as the independent variable. For outdoor temperature, Energy Explorer uses average daily temperature rather than hourly data. To provide average daily temperature for the pre- and post-retrofit year, CMU used Global Summary of the Day (GSOD) files from NOAA's National Climatic Data Center[8] for the six Pennsylvania weather stations and assigned each PHFA property to the closest GSOD station. By inputting each property's monthly electricity and/or gas consumption data into Energy Explorer, CMU was able to generate 3P and 5P models that compared weather normalized, estimated pre-retrofit energy consumption with actual energy use in the post-retrofit period and to

[8] http://www.ncdc.noaa.gov/

calculate the retrofit-based savings. A description of the software routine for each model is provided in Appendix A[9]

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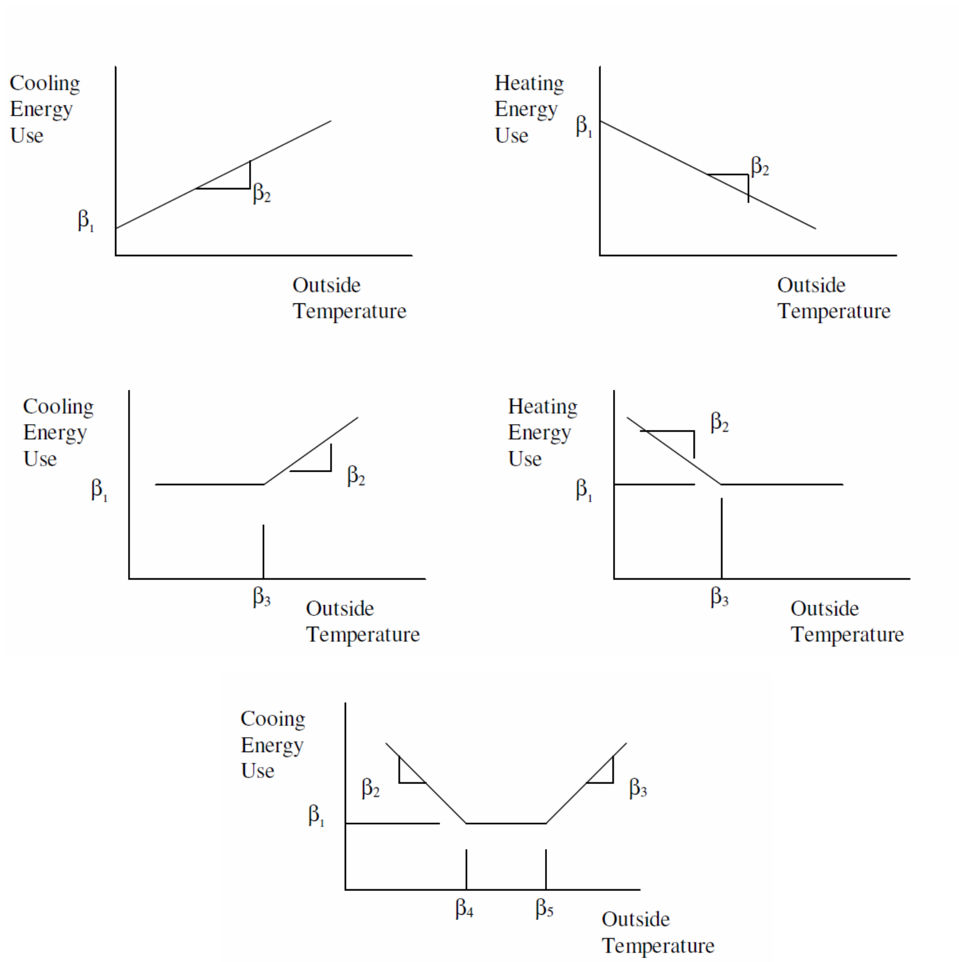


Figure 4-1: Change Point Models for Weather Normalization

Energy Explorer's graphical user interface (GUI) models actual energy consumption, weather normalized consumption, and functional form of the original and weather normalized energy models, allowing the baselines, change points, and slopes to be compared. For example, Figure 4-4-2 shows the graphic output of an Energy Explorer 3PH model representing a property's natural gas consumption in the pre- and post-retrofit years. The blue line represents pre-retrofit gas consumption and the red line represents post-retrofit consumption. The flat line segments show baseline use (for DHW). At the change point temperature, the line become sloped, showing gas consumption rising as temperature falls.

[9] EPA's Energy Star Portfolio Manager uses a very similar approach to weather normalization that includes Energy Tracker™, another Kissock change point modeling software, and the GSOD weather files.

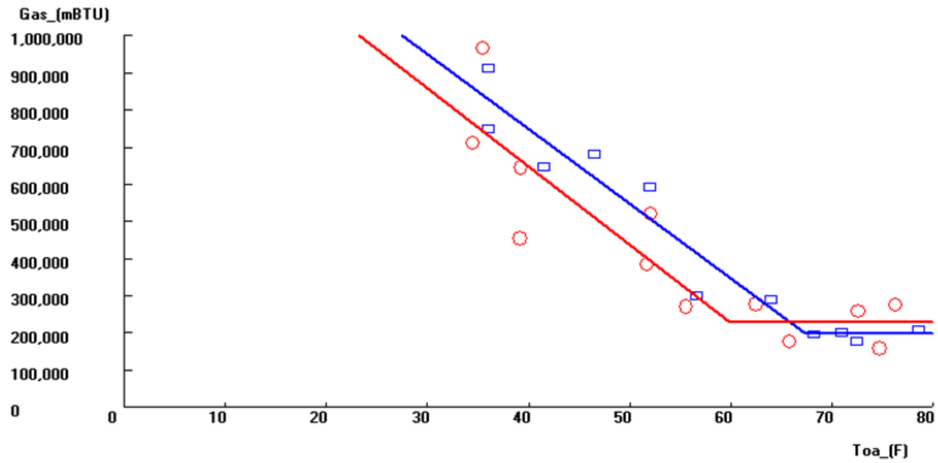


Figure 4-4-2: Energy Explorer 3P Graphed Output of Pre- and Post Retrofit Gas Use

In this example, the model indicates that the retrofit lowered the change point temperature so that the heating system begins to operate at a lower outdoor temperature. Insulation and air sealing may have produced this kind of improvement. Baseline consumption is slightly higher, however, and the sloped segment steeper. This suggests that after the retrofit, the heating energy consumption increased slightly more rapidly with falling temperatures and that slightly more gas was consumed for baseline energy (DHW). This may indicate the need for tuning equipment setpoints or controls.

The CMU graduate student who generated the Energy Explorer models, Danyang Li[10], was simultaneously doing thesis research on new models for predicting building energy consumption based on prior consumption and weather data. In contrast to linear regression methods like change point models, Li focused on computational learning models such as artificial neural networks (ANN) and Support Vector Machines (SVM). Both of these are machine learning approaches that use nonlinear regression. ANN approximates the predicted data by generating nonlinear combinations of the previous input and output data. The ANN can produce accurate output in a relatively short time by "learning" from previous data. The challenge in using ANN is that the algorithm remembers valid data as well as noise, so modeling parameters must be chosen carefully to limit potential noise.

Support vector machines are a relatively new modeling approach developed by Vapnik and his coworkers in 1995. These models analyze data in multidimensional space (hyperplanes) and recognize patterns that are used for data classification and regression analysis. Given "training" data such as post-retrofit weather and energy consumption, SVM creates a training algorithm that

[10] Ms. Li graduated with her Master's in Building Performance & Diagnostics in December 2013.

allows new data to be analyzed. SVM has been successfully applied to forecast and classify complex data in many fields including load prediction of the electricity grid, battery models for vehicles and financial prediction, but has not been extensively used for predictive building energy performance. SVM adopts the structural risk minimization (SRM) principle, while ANN employs empirical risk minimization (ERM). SVM has been shown to reduce modeling error because ERM only minimizes the training error, while SRM minimizes the sum of training error and confidence level. However, SVM usually requires more computation time than conventional ANN, and both of these approaches are generally more time-consuming than linear regression models.

Li's research involved finding appropriate ANN and SVM models that could be applied to building energy prediction, understanding the mathematical algorithm in each of the model, constructing models using software, testing and finding ways to improve the performance of the models, and testing the models with a variety of inputs. During her work to test and improve the models, Li examined the components of weather data that seemed most effective in predicting consumption. An important finding in her work is that adding **relative humidity and solar radiation data to temperature data improved modeling accuracy.**

The two models chosen by Li are General Regression Neural Network (GRNN) and SVM. A GRNN model evaluates the 'distance' or difference between the pre-retrofit weather data and the post-retrofit data in multidimensional space using a basic function, and uses the pre-retrofit energy data points to represent, or predict, the energy corresponding to the post-retrofit weather. With this approach, the predicted energy consumption will be a weighted combination of the pre-retrofit energy data. The closer the pre-retrofit data points to the post-retrofit data, the more representative it will be in the prediction, which means it will be given more weight.

The SVM model takes all the pre-retrofit data points and maps them into hyperplanes by a selected kernel function and conducts a linear regression in that space. By introducing the parameter Epsilon (ε), the model gives a confidence level that can be adjusted by user. As can been seen in Figure , if the predicted output is within the cylindrical area determined by ε there will be no loss, or the loss would be the magnitude of the difference between the predicted output and the radius ε of the cylinder. Another parameter, "C," controls the trade-off between the accuracy and complexity of the model. These two parameters should be carefully determined by evaluating the pre-retrofit data so that the model can achieve its best performance in prediction. When the regression curve is established, it is used with post-retrofit weather data to determine the pre-retrofit energy consumption.

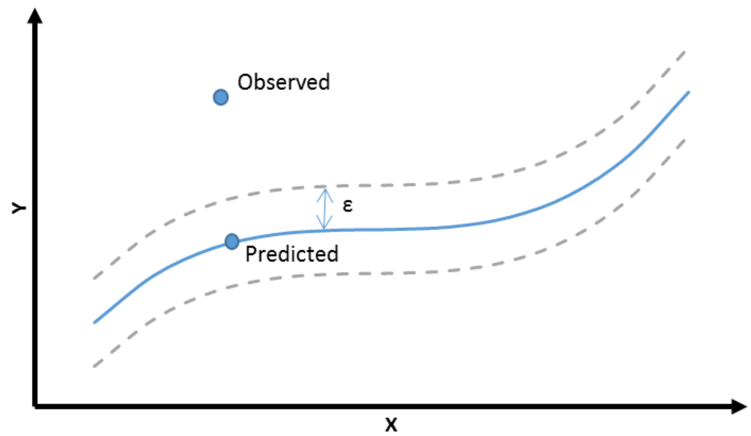


Figure 4-3: SVM Regression in High Dimension Space

4.2 Test of Weather Normalization Models

As an experiment, Li tested her models (General Regression Neural Network [GRNN]) and SVM using three PHFA properties. For hourly weather data, Actual Meteorological Year (AMY) files from Weather Analytics LLC[11] were used. These AMY files provide the same weather parameters in the same format as the TMY2 and TMY3 weather files used for building energy simulation.

The types of upgrades in each of the three properties are shown in Table 4-1.

Table 4-1: Weatherization Upgrades in Three Properties Used for Modeling Tests

	Property 1	Property 2	Property 3
Building Enclosure	Seal exterior doors Re-caulk around windows	Weather-strip exterior doors Air seal chase Sensor repair	Air sealing
Heating	Replace electric boiler with gas boiler Replace pump motor Install isolation damper	Upgrade boiler Modify set-point and flow of boiler Install twist timers on Lounge heaters	Insulate hot water pipe Adjust set-point and heating level Upgrade thermostat
Cooling	-	Disable auto switchover	-
Hot Water	Install recirculation control Kitchen hot water control	Upgrade boiler Modify set-point Install temperature/time sensors	-
Lighting		Install occupancy sensors	LED upgrade

Monthly energy consumption data from twelve months of pre-retrofit and post-retrofit utility bills were used for each model. This provided 12 energy bill data points in the pre-retrofit period that

[11] http://www.weatheranalytics.com/

were used to build the model and 12 energy bill data points in the post-retrofit period to make the comparison with the predicted result in order to determine the savings. AMY files from the Weather Analytics station closest to each property and for the actual pre- and post-retrofit time period were used. Instead of using only temperature data, relative humidity and solar radiation data were also included.

To test the performance of her GRNN and SVM models, Li used a 12-fold cross validation, which means in every run, data from one month was tested and the remaining 11 data points were used to build the model. In this way, the test produced 12 root mean square error (RMSE) values in total. The RMSE is the distance, on average, of a data point from the fitted line, measured along a vertical line. It is a measurement of goodness of fit. By minimizing the average RMSE value of each run, Li was able to optimize parameter(s) for the model. The smaller the RMSE value, the more accurately the model can predict the energy consumption based on the weather data.

The RMSE produced by each model for the pre-retrofit period and the calculated Co-Efficient of Variation of the Root Mean Square Error (CV-RMSE) are displayed in the Table 4-2.

Table 4-2: Comparative Modeling Results

Units: MBTUs		Energy Explorer		GRNN		SVM	
		RMSE	CV-RMSE	RMSE	CV-RMSE	RMSE	CV-RMSE
Property 1	Electricity	19,837	28.9%	16,697	24.3%	9,557	13.9%
	Gas	25,500	52.4%	16,000	32.9%	9,600	19.7%
Property 2	Electricity	26,109	18.5%	16,657	11.8%	10,485	7.4%
	Gas	80,860	35.7%	81,600	36.0%	43,900	19.4%
Property 3	Electricity	9,449	17.1%	6,697	12.1%	4,624	8.4%
	Gas	34,228	69.2%	19,356	39.14%	6,204	12.5%

From the table, it can be seen that the RMSE and CV-RMSE are lowest for the SVM model and highest in almost all instances for Energy Explorer. The one exception is the gas consumption prediction for Property 2, where the CV-RMSE of GRNN is slightly higher than Energy Explorer by 0.3%. This suggests both the GRNN and SVM models have better performance in predicting building energy consumption than the Energy Explorer software as it was used here. If hourly weather data could be used in Energy Explorer and if humidity and solar radiation were added as independent variables, it is possible that the results would be better, except for buildings where energy consumption is not affected by those weather parameters.

The energy consumption curves drawn by the models for Property 3 are compared below in Figure 4- (annual gas) and Figure 4-5(annual electricity). The weather normalized pre-retrofit predicted curve is a dashed line for Energy Explorer and a blue line for the GRNN and SVM models. The actual post-retrofit consumption is the solid red line in Energy Explorer and the green line in GRNN and SVM.

For gas consumption, we see that the shape of each predicted curve is similar in all three models. However, for electricity consumption, the Energy Explorer curve looks quite different and not really reasonable, a more gradual rise in electricity consumption with increasing temperature and gradual fall in consumption with decreasing temperature, would be expected.

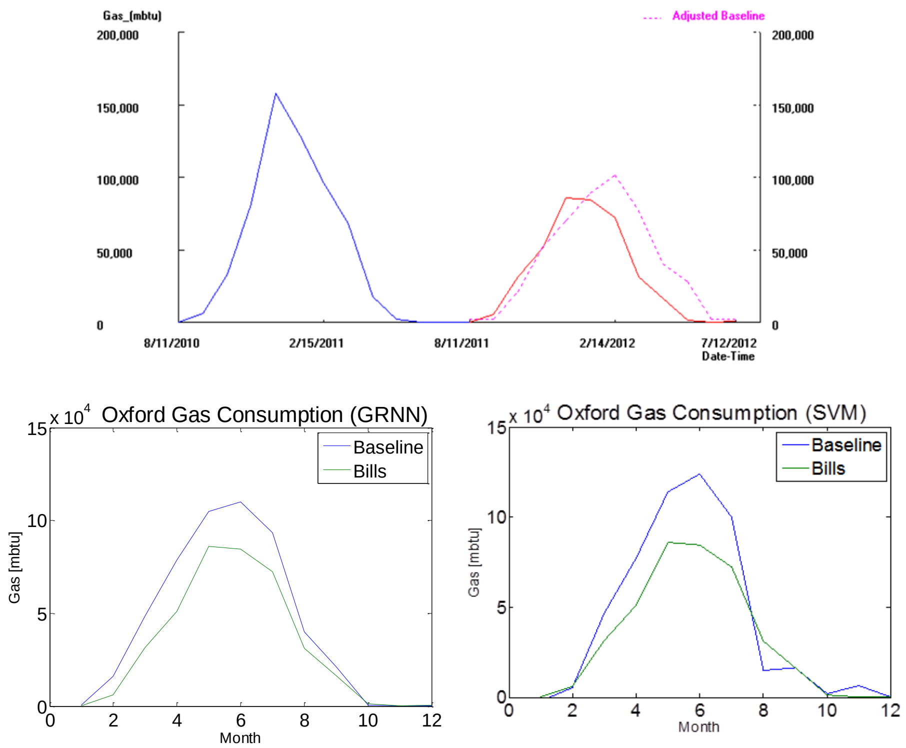


Figure 4-4: Comparative Weather Normalized Gas Consumption Curves

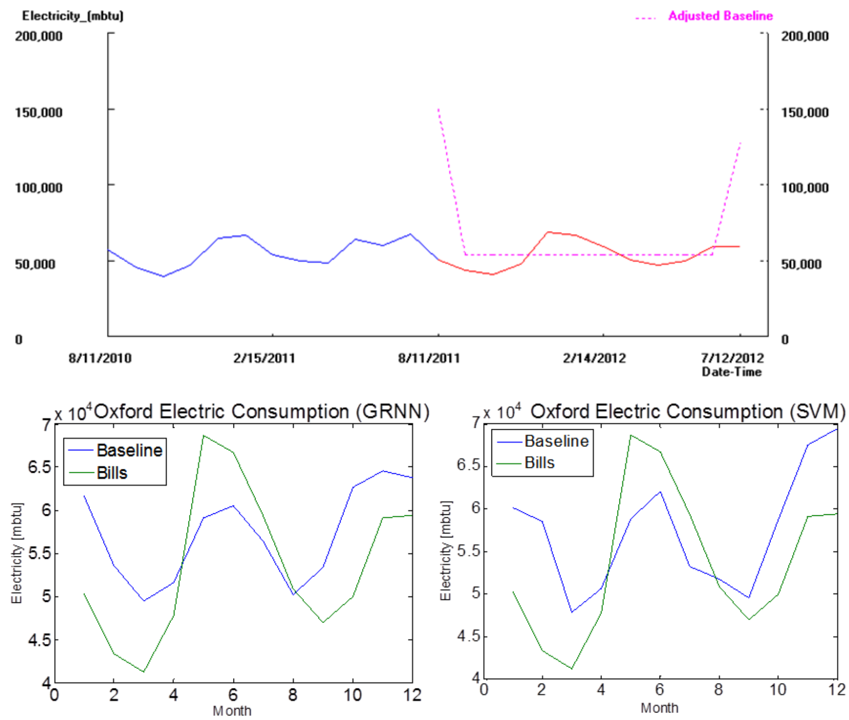


Figure 4-5: Comparative Weather Normalized Electricity Consumption Curves

The findings from this experiment were consistent with Li's overall thesis findings that GRNN and SVM models perform better in predicting building energy consumption than linear regression models. *Because Li's GRNN and SVM models appear to offer a promising new approach to weather normalization, the CMU team decided to include them in their analysis and <u>to use the energy savings calculated with the SVM model as the basis for their analysis.</u>*

Li generated GRNN and SVM weather normalization models for the 91 PHFA properties for which sufficient billing data existed. The absolute and percent difference between the modeled pre-retrofit Energy Use Intensity (EUI) and post-retrofit EUI were calculated for each property. It should be noted that although SVM models appear to be the most accurate of the models compared in this study, producing the best goodness of fit as evidenced by smaller RMSE and CV-RMSE, SVM models require more time and effort. In the future, it may be possible to create a software tool like Kissock's Energy Explorer™ that streamlines SVM model generation.

4.3 The Impact of Weather Normalization

As stated above, CMU chose to use the SVM model as the weather normalization approach for this analysis. The table below shows the non-weather normalized and weather normalized pre-retrofit EUI, the post-retrofit EUI, and the difference between them for each property, in kBTU/ft2 and as a percent difference. The greatest percent difference between weather-normalized and non-normalized data is 27%. This is slightly higher (by 2%) than an example Kissock cites in the Energy Explorer User's Guide (p. 50) of the potential variation in natural gas consumption between average and extreme weather years (Kissock 2010). CMU will continue to evaluate the SVM approach.

Pre- and Post-Retrofit EUIs for Properties in Analysis

Prop ID	Gross Sq Feet	Non-Normalized Pre-Retrofit EUI	Normalized Pre-Retrofit EUI	kBTU/ft2 Difference in Non- and Weather Normalized EUI	% Difference in Non- and Weather Normalized EUI	Post-Retrofit EUI from Bills	Weather Normalized EUI % Difference
1	20,210	43.41	51.62	-8	-19%	41.73	-19.15%
2	4,862	37.16	38.81	-2	-4%	38.00	-2.10%
3	4,652	45.40	45.44	0	0%	35.00	-22.99%
4	16,426	26.75	28.24	-1	-6%	20.94	-25.86%
5	30,000	27.69	27.63	0	0%	21.85	-20.93%
7	50,564	26.69	29.00	-2	-9%	23.53	-18.86%
8	38,562	30.76	34.02	-3	-11%	26.32	-22.63%
9	50,000	51.74	52.00	0	-1%	53.00	1.92%
10	78,214	100.10	96.58	4	4%	101.40	5.00%
11	19,392	38.43	28.02	10	27%	27.20	-2.91%
12	71,172	36.24	35.04	1	3%	36.55	4.30%
13	61,668	38.26	35.82	2	6%	37.50	4.70%
14	72,002	38.86	38.51	0	1%	31.37	-18.55%
15	33,394	39.81	35.13	5	12%	30.93	-11.94%
16	75,602	30.57	29.10	1	5%	26.84	-7.76%
17	25,314	61.99	58.52	3	6%	53.42	-8.71%
18	92,204	37.46	33.99	3	9%	31.23	-8.14%
19	25,783	38.21	31.87	6	17%	26.00	-18.42%
20	17,514	39.34	34.40	5	13%	37.05	7.70%
21	21,000	47.87	47.02	1	2%	38.00	-19.18%
23	82,140	43.21	42.52	1	2%	38.15	-10.28%
24	36,658	44.35	39.85	5	10%	42.85	7.53%

Prop ID	Gross Sq Feet	Non-Normalized Pre-Retrofit EUI	Normalized Pre-Retrofit EUI	kBTU/ft2 Difference in Non- and Weather Normalized EUI	% Difference in Non- and Weather Normalized EUI	Post-Retrofit EUI from Bills	Weather Normalized EUI % Difference
25	61,080	51.00	48.75	2	4%	46.00	-5.65%
26	26,167	48.11	44.03	4	8%	39.18	-11.00%
27	64,523	45.76	50.68	-5	-11%	42.42	-16.31%
28	13,800	88.39	84.89	4	4%	82.00	-3.40%
29	95,122	38.46	36.44	2	5%	33.80	-7.24%
31	84,454	52.48	49.83	3	5%	44.85	-9.99%
32	92,155	49.47	43.91	6	11%	43.89	-0.04%
34	65,423	45.64	41.93	4	8%	48.00	14.48%
35	27,488	59.92	51.20	9	15%	46.59	-9.01%
36	80,624	53.14	55.18	-2	-4%	57.00	3.29%
37	27,218	59.61	56.19	3	6%	58.50	4.11%
38	77,454	63.85	70.78	-7	-11%	50.00	-29.36%
39	45,600	63.38	63.63	0	0%	54.00	-15.13%
40	90,211	51.91	58.43	-7	-13%	55.18	-5.56%
41	49,600	61.86	60.68	1	2%	54.80	-9.69%
42	97,000	64.63	64.23	0	1%	52.35	-18.49%
43	54,426	63.02	61.18	2	3%	57.74	-5.62%
44	103,656	66.37	67.63	-1	-2%	61.61	-8.90%
45	97,000	67.41	72.53	-5	-8%	66.71	-8.02%
46	38,760	66.47	72.89	-6	-10%	63.98	-12.22%
47	40,778	70.85	67.11	4	5%	61.08	-8.99%
48	102,880	84.84	68.32	17	19%	71.32	4.38%
49	74,200	56.84	52.18	5	8%	46.16	-11.53%
50	118,990	75.09	78.42	-3	-4%	77.98	-0.56%

Prop ID	Gross Sq Feet	Non-Normalized Pre-Retrofit EUI	Normalized Pre-Retrofit EUI	kBTU/ft2 Difference in Non- and Weather Normalized EUI	% Difference in Non- and Weather Normalized EUI	Post-Retrofit EUI from Bills	Weather Normalized EUI % Difference
51	95,179	75.69	76.96	-1	-2%	57.00	-25.93%
52	247,367	66.92	71.51	-5	-7%	68.83	-3.75%
53	10,940	94.47	98.59	-4	-4%	67.52	-31.51%
54	68,382	66.26	78.53	-12	-19%	60.30	-23.22%
55	81,340	46.24	50.39	-4	-9%	40.00	-20.63%
56	38,532	80.26	76.67	4	4%	69.70	-9.09%
57	108,405	76.36	78.41	-2	-3%	74.33	-5.21%
58	191,391	83.68	91.29	-8	-9%	84.00	-7.99%
59	72,157	109.20	124.22	-15	-14%	82.00	-33.99%
61	84,100	88.81	92.72	-4	-4%	89.31	-3.68%
62	137,400	77.89	98.54	-21	-27%	67.36	-31.64%
63	4,680	88.34	96.53	-8	-9%	89.00	-7.80%
64	49,876	86.52	92.87	-6	-7%	78.00	-16.01%
65	40,572	62.86	59.37	3	6%	49.71	-16.27%
67	19,620	82.53	70.74	12	14%	82.74	16.97%
68	167,957	37.31	37.80	0	-1%	33.68	-10.90%
69	233,372	122.88	116.21	7	5%	113.19	-2.60%
70	182,384	15.18	16.00	-1	-5%	11.00	-31.25%
74	41,981	30.26	25.11	5	17%	27.76	10.57%
75	40,956	59.02	58.67	0	1%	57.64	-1.77%
79	63,540	47.31	51.71	-4	-9%	40.72	-21.25%
81	28,674	46.60	47.48	-1	-2%	38.28	-19.39%
82	22,242	28.72	28.71	0	0%	27.55	-4.04%
83	24,980	75.66	72.38	3	4%	57.09	-21.13%

Prop ID	Gross Sq Feet	Non-Normalized Pre-Retrofit EUI	Normalized Pre-Retrofit EUI	kBTU/ft2 Difference in Non- and Weather Normalized EUI	% Difference in Non- and Weather Normalized EUI	Post-Retrofit EUI from Bills	Weather Normalized EUI % Difference
84	28,000	25.69	27.53	-2	-7%	21.48	-21.96%
85	28,496	78.84	78.79	0	0%	69.97	-11.20%
86	42,252	36.21	35.54	1	2%	29.33	-17.48%
89	22,313	31.76	34.46	-3	-9%	28.00	-18.75%
91	97,632	90.08	98.21	-8	-9%	78.73	-19.84%
92	70,876	88.52	90.58	-2	-2%	75.56	-16.58%
94	70,000	52.94	56.00	-3	-6%	40.00	-28.57%
95	62,653	68.15	70.48	-2	-3%	60.94	-13.55%
96	54,777	86.36	92.74	-6	-7%	73.91	-20.31%
97	50,700	101.76	106.11	-4	-4%	86.88	-18.12%
98	53,683	106.17	118.27	-12	-11%	87.80	-25.76%
101	126,882	64.67	62.22	2	4%	63.96	2.80%
106	104,616	99.59	91.51	8	8%	85.03	-7.08%
107	99,696	41.41	41.77	0	-1%	37.29	-10.72%
108	176,000	47.56	50.54	-3	-6%	48.60	-3.85%
109	70,000	52.94	56.00	-3	-6%	40.00	-28.57%
110	102,061	116.71	127.85	-11	-10%	124.34	-2.75%
112	30,500	20.10	20.40	0	-1%	16.75	-17.87%
113	181,000	51.95	61.31	-9	-18%	55.08	-10.16%
116	4,366	63.52	73.64	-10	-16%	40.64	-44.81%

5 ENERGY UPGRADE ANALYSIS

5.1 ENERGY USE METRICS IN MULTIFAMILY HOUSING

The metric widely used to indicate energy performance is energy use intensity or EUI, expressed as energy consumption per unit area per year. In the US, the units are typically kBTU/ft2. Site energy, what is measured at the meter, is specific and often reported, but source energy is frequently estimated to account for the source-to-site conversion losses in electricity generation and the full fuel impact of building energy use.

The most well-established database of US residential energy consumption, the DOE's Energy Information Administration (EIA) Residential Energy Consumption Survey (RECS), reports site EUI. Figure 5-1 shows a comparison between site energy use intensity in PHFA properties by vintage and national RECS results (2009). It's important to note that RECS data represent energy consumption for *individual dwelling units only,* primarily single family homes. For dwelling units in multifamily housing, RECS excludes energy use in common areas (e.g., hallway lighting, elevators, and laundry rooms) and energy used by central equipment (e.g. domestic hot water is typically provided by central boilers).[12] Nevertheless, the properties in the PHFA dataset, particularly those built since 1970, compare favorably with the RECS results.

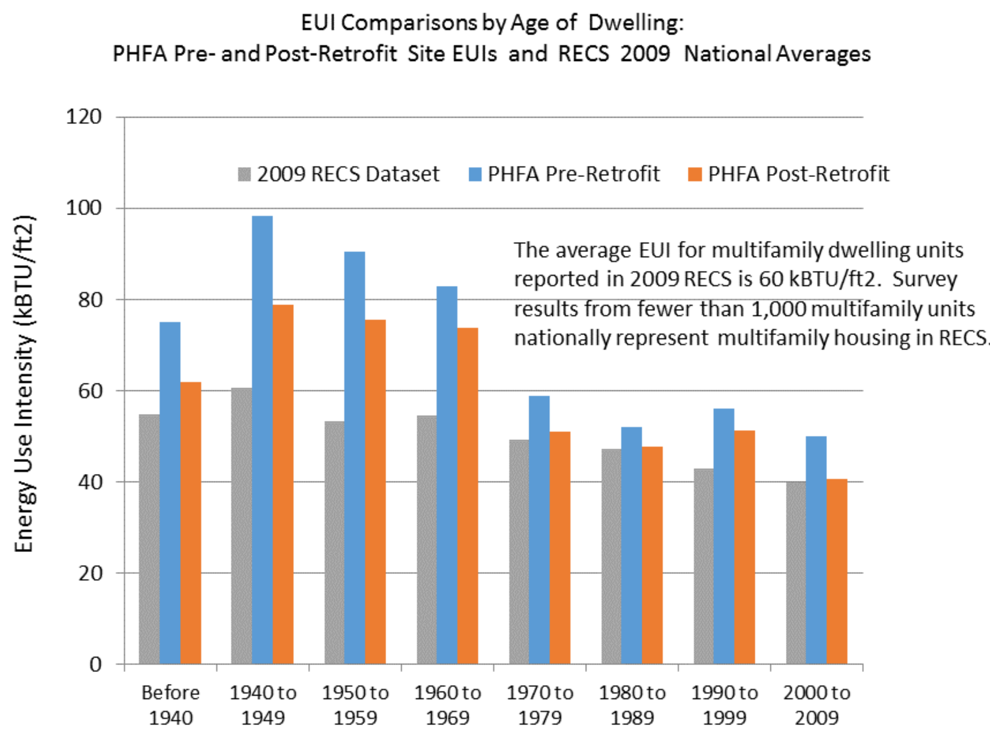


Figure 5-1: PHFA Pre- and Post-Retrofit EUIs Compared to National RECS 2009 Dataset

[12] Personal conversation with James (Chip) Berry, Residential Survey Manager, US Energy Information Administration, March 27, 2013.

5.2 EUIs in PHFA Dataset and Similar Housing

Across the PHFA dataset, the median weather normalized pre-retrofit site EUI is 56 kBTU/ft2 per year and the average is 59.85 kBTU/ft2. **In the first post-retrofit year, the median EUI was 49.71 kBTU/ft2 per year and the average was 52.66 kBTU/ft2.** Although multifamily dwellings are substantially under-represented in the RECS dataset and do not reflect whole-building energy consumption, the available RECS comparisons are 69.2 kBTU/ft2 for multifamily units in properties with 2-4 housing units and 54.5 kBTU/ft2 for properties with five or more housing units. This suggests that the post-retrofit PHFA properties may perform better than the RECS 2009 national multifamily average, and that the PHFA pre-retrofit buildings performed better than average for smaller buildings.

A better source of comparative EUI data may be the 2010 study of energy retrofits in 231 buildings with 21,000 housing units in New York City; 96% of these were affordable housing units. The study was funded by the Deutsche Bank Americas Foundation and Living Cities (DB/LC), and prepared by Steven Winter Associates and HR&A Advisors (Steven Winter Associates, HR&A Advisors January 2012). In the study report, separate site EUIs are graphed (not stated) for electricity and fuel. The scatter plot for fuel EUIs shows that most pre-retrofit fuel EUIs exceeded 60 kBTU/ft2 per year. The addition of electricity boosts the EUIs at least 10 kBTU/ft2 to a total of roughly 70 kBTU/ft2. Based on these data, the properties in the PHFA dataset perform better on average, both pre- and post-retrofit, than the NYC affordable housing in the DB/LC study.

Another large and recent dataset of metered multifamily housing energy performance is the New York City Local Law 84 benchmarking data. NYC requires single buildings larger than 50,000 GSF and multiple buildings on the same lot with more than 100,000 GSF to report their energy and water consumption. Many multifamily buildings are included. The data are summarized in a report, (PlaNYC 2013), the most recent of which is dated September 2013. The report provides EUIs based on source energy rather than site energy and assigns grades to buildings based on their weather normalized source EUIs.

In order to compare the PHFA dataset to the NYC benchmarking data, the PHFA site EUIs were roughly converted to source EUIs[13] assuming an average of either 30% or 40% of site energy is electricity. This is consistent with the percentages of electricity in the fuel mix for the NYC buildings. Table 5-1 shows the results of that conversion and the NYC benchmarking grades. Similar to the Deutsche Bank study results, the PHFA properties perform well based on pre- and post-retrofit EUIs. If the NYC Mayor were grading these buildings, most would receive an A, even prior to the retrofits.

[13] IECC 2012 site to source multiplier of 3.16 for electricity was used.

Table 5-1: Approximate Source EUIs for PHFA Dataset and Comparison with NYC EUI Grades

kBTU/ft2	PHFA Pre-Retrofit Median	PHFA Pre-Retrofit Average	PHFA Post-Retrofit Median	PHFA Post-Retrofit Average
Site EUI	56.00	59.85	49.71	52.66
Calculated Source EUI (30% electricity)	96.20	102.82	85.39	90.47
Calculated Source EUI (40% electricity)	104.38	111.75	93.02	97.96
NYC Grades for Source EUIs (kBTU/ft2/yr)				
EUI < 109 **A**	109 < EUI $\leq$ 132 **B**	132 $\leq$ EUI $\leq$ 160 **C**	EUI > 160 **D**	

One possible reason for the comparative energy effectiveness of the Pennsylvania multifamily affordable housing building stock is the long-standing efforts of PHFA to focus on this sector. In a 2010 paper by Glattner and Engel, *Use of Weatherization Program Funds to Benefit Residents of Multifamily Housing*, Pennsylvania was recognized for excellent statewide weatherization programs and for its multifamily expertise. Another possible reason may be that the property owners who pursued PHFA's Preservation through Smart Rehab funding have a greater level of awareness about the benefits of improved energy performance. They may actively seek weatherization funding and may manage their properties accordingly. It is also possible that the dearth of national and regional data about multifamily housing means that meaningful comparative data are not available. The PHFA dataset helps to addresses a critical gap in our understanding of multifamily energy consumption. The map showing the distribution of properties participating in the program (see Figure 5-2) indicates concentrations of program participants in major cities, but ample area across the state may benefit from similar efforts.

5.3 Energy Savings Achieved in PHFA-Funded Multifamily Properties

For the 91-property PHFA dataset of 7,439 housing units, the average reduction in energy use intensity in the first post-retrofit year was 8.21 kBTU/ft^2 per year. This represents a total annual energy savings of **51.1 billion BTUs per year** for the 6,228,296 ft2 represented in this dataset. The carbon dioxide equivalent emissions avoided by this savings are 10,332 metric tons per year. This is the equivalent of eliminating the greenhouse gas emissions from 2,175 cars per year.[14]

Because the focus of PHFA's program is affordable housing, a socially-focused mission, each property's EUI savings was weighted by the number of housing units served using an arithmetic

[14] EPA Greenhouse Gas Equivalencies Calculator, http://www.epa.gov/cleanenergy/energy-resources/calculator.html

weighted average. **The unit-weighted average EUI savings for the 91-property dataset was 12.34% per year**. For individual properties, the highest percent savings in the first post-retrofit year was 45%; the lowest "savings" was a 14% increase in energy consumption. Properties with the highest weather-normalized pre-retrofit EUIs (>100 kBTU/ft2) achieved the greatest percent savings, an average of 17%. Eleven properties with 1,182 total housing unit achieved more than 25% energy savings in the first post-retrofit year. Figure 5-2 shows the distribution of energy savings by property in the first post-retrofit year. *Table 5-7* at the end of this section lists the EUI % savings for each property, total upgrade costs per property, the costs per unit and the costs per square foot.

In the detailed energy upgrade analysis below, CMU reports EUI percent savings as well as EUI reduction, but does not focus on specific EUI values beyond the dataset average and median. This is because at least 10-15% of the property EUIs seem too low. Given the average site EUIs from RECS 2009 (54 to 69 kBTU/ft2 per year for multifamily dwellings) and the Principal Investigator's own dataset of metered EUIs for net zero housing (~7-18 kBTU/ft2 per year)[15], EUIs in this dataset that are lower than 30 kBTUs/ft2 per year were considered suspect. An EUI of 30 kBTU/ft2 suggests that a multifamily property performs 45% better than the average US multifamily property with 5+ units and 34% better than the average US single family home. Eleven pre-retrofit properties in the PHFA dataset and 14 post-retrofit properties met that criterion, with EUIs ranging from 2.62 kBTU/ft2 to 29.33 kBTU/ft2. In the future, it may be possible to review these EUI data with individual property managers, but within the scope of this study, CMU focuses on the *change* in EUI rather than its absolute value to avoid potentially misleading comparisons.

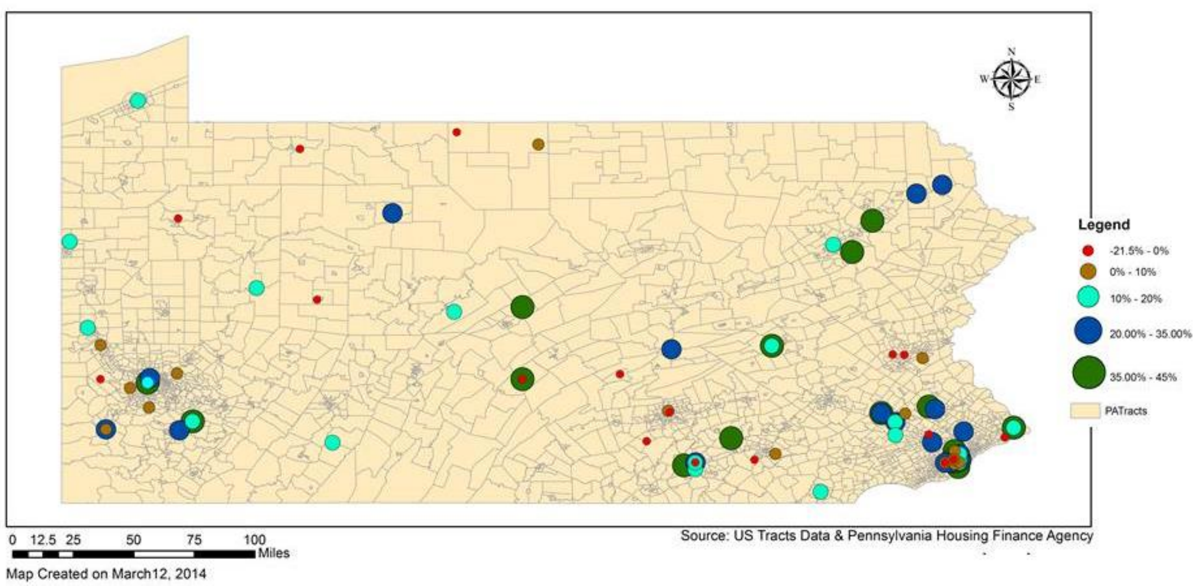


Figure 5-2: Distribution of Percent EUI Savings in PHFA-funded Properties

[15] This number excludes renewable energy production.

5.4 ASSESSING THE IMPACT OF SPECIFIC UPGRADE MEASURES

5.4.1 Classifying Energy-Related Upgrade Measures

A total of 611 energy-related upgrades were implemented in the 91 properties in this analysis. The CMU team categorized these initially by building load to assist in the weather normalization analysis, and then grouped them by the nature of the upgrade, e.g., an equipment repair, an equipment replacement, a control adjustment, a control installation. Table 5-1 lists and describes the categories of energy-related upgrades used for this analysis.

5.4.2 Which Energy-Related Retrofits Were Used Most Often?

From Figure 5-3 it can be observed the most frequently implemented upgrade, based on the number of housing units affected by the upgrade, was an improvement in common area lighting. This was implemented in 47 properties with a total of 4,238 housing units. The second most frequently implemented measure was building envelope air sealing in 59 properties with 3,770 total units. The least common upgrades were the installation of a hydronic heating system in a 6-unit property (using DHW heaters for both heating and water heating), and upgrading dishwashers in two properties with 22 total units. Table 5-1also lists the number of properties and number of housing units affected by each category of upgrade.

Total number of units: 7439

Total number of properties: 91

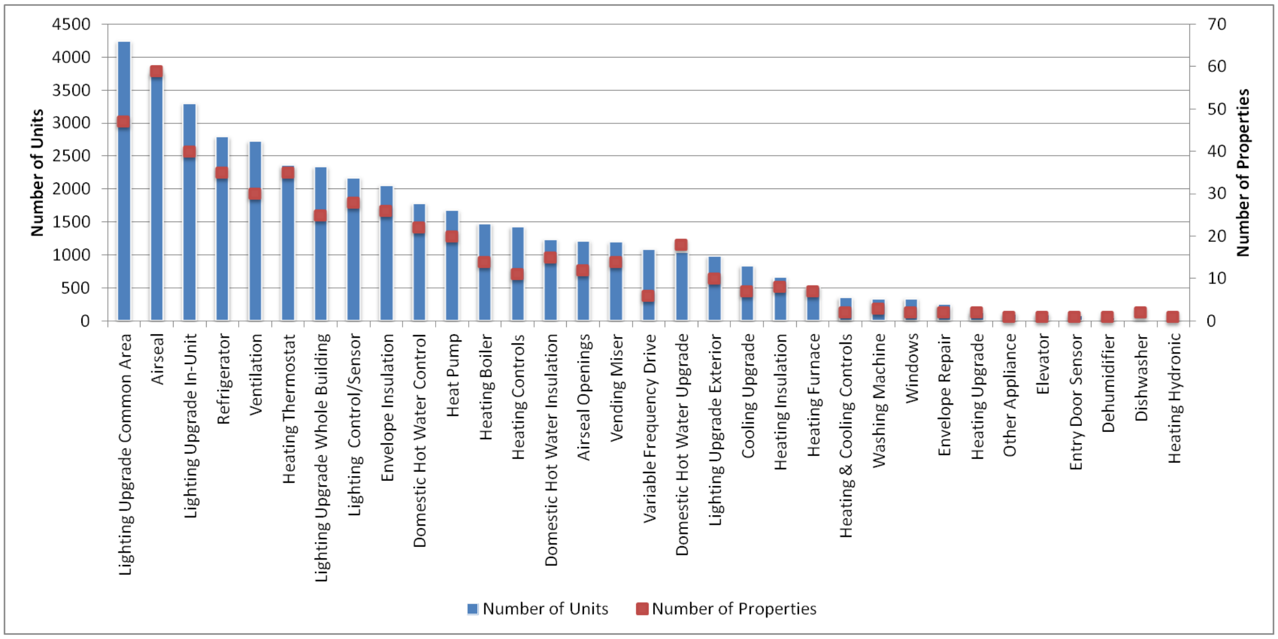


Figure 5-3: Popularity of Energy-Related Retrofit Measures

Table 5-2 Energy-Related Upgrades in PHFA Dataset

Upgrade Category	Description	# of Units in Properties Using the Upgrade	Corresponding # of Properties Using the Upgrade
Appliance: Dehumidifier	Replacement of existing dehumidifier(s)	48	1
Appliance: Dishwasher	Replacement of existing dishwashers with energy efficient dishwashers	22	2
Appliance: Elevator	Elevator-related upgrade measures	88	1
Appliance: Other	Tune gas ranges in apartments and community rooms	101	1
Appliance: Refrigerator	Replace some or all refrigerators	2786	35
Appliance: Vending Miser	Install vending miser	1192	14
Appliance: Washing Machine	Replacement of washing machine(s) with energy efficient washing machine(s)	332	3
Building Envelope Air Seal	Reducing air leakage through building envelope by sealing the air gaps	3770	59
Building Envelope Air Seal Openings	Sealing openings (doors, attic hatches, windows) to reduce air leakage	1210	12
Building Envelope Entry Door Sensor	Installing a sensor for the entry door	75	1
Building Envelope Insulation	Adding or upgrading building envelope insulation - either wall, roof, or floor, or any of them in combination	2053	26
Building Envelope Repair	Repairing attic or exterior brick	244	2
Building Envelope Windows	Replacing windows	332	2
Cooling Upgrade	Replace cooling units with higher efficiency cooling units	829	7
Domestic Hot Water Control	Controlling domestic hot water system and supply temperatures	1775	22
Domestic Hot Water Insulation	Insulating the domestic hot water system piping	1226	15
Domestic Hot Water Upgrade	Replacing domestic hot water equipment	1041	18
Heating Boiler	Replacing existing boilers with higher efficiency boilers or installing new boilers	1474	14
Heating Controls	Changing the schedule of operation or adjust setpoint or setback temperatures	1423	11
Heating Furnace	Replace existing furnace with high efficiency furnace	512	7
Heating Hydronic	Install hydronic heating system	6	1
Heating Insulation	Insulating heating ductwork and/or pipes	655	8

Upgrade Category	Description	# of Units in Properties Using the Upgrade	Corresponding # of Properties Using the Upgrade
Heating Upgrade	Installing isolation dampers or electric thermal storage heaters	129	2
Heating & Cooling Controls	Adjusting or installing on/off controls of the heating and/or cooling system	348	2
Heat Pump	Installing new or upgrading existing heat pumps	1670	20
Lighting Control/Sensor	Installing occupancy sensor or timers for lighting	2167	28
Lighting Upgrade Whole Building	Replacing the existing lighting in whole building (property) with higher efficiency lighting	2330	25
Lighting Upgrade Common	Replacing the existing lighting in common areas with higher efficiency lighting	4238	47
Lighting Upgrade Exterior	Replacing the existing exterior lighting with higher efficiency lighting	978	10
Lighting Upgrade In-Unit	Replacing the existing lighting in housing units with higher efficiency lighting	3293	40
Thermostat	Upgrading or replacing the thermostat	2357	35
Ventilation	Exhaust fan controls, replacement of exhaust fans, bath fan flow regulators, upgrading building fresh air ventilation system, garage ventilation system replacement	2722	30
Variable Frequency Drive	Installing variable frequency drives on heating, cooling, or ventilation systems	1081	6

5.4.3 EUI Savings Associated with Each Upgrade

The 34 categories of energy-related upgrades in Table 5-2 are defined as unconfounded upgrades in the analysis that follows. This means that each upgrade occurred at the unit or property level and was present in some properties, not present in other properties, and its presence or absence did not always occur in the presence or absence of other upgrades.

The average EUI savings in properties that implemented each type of upgrade was examined. Figure 5-4 displays that information. The X axis displays the upgrade, the primary Y axis shows the property's average EUI % savings, and the secondary Y axis shows the number of units in properties where the upgrade was used. The average EUI savings of 12% for the entire dataset is shown for comparison.

The EUI % savings for each upgrade category reflects the impact of all upgrades implemented in the properties. The median number of energy upgrades per property was 7 and the average was 7.7. The EUI % savings calculated for each upgrade reflects the combined impact of the upgrade of interest and the impact of other upgrades in those properties. This can potentially skew the results, as demonstrated by the Entry Door Sensor upgrade (see the 2nd column from in the left in Figure 5-4). This measure was implemented in only one property and the associated EUI savings is 21%, almost double the dataset average. This particular property (ID 55) implemented 19 upgrades, including air sealing and replacement of the heating boiler, in-unit lighting and refrigerators. The 21% EUI savings is undoubtedly associated with the suite of measures applied, not with the installation of an entry door sensor.

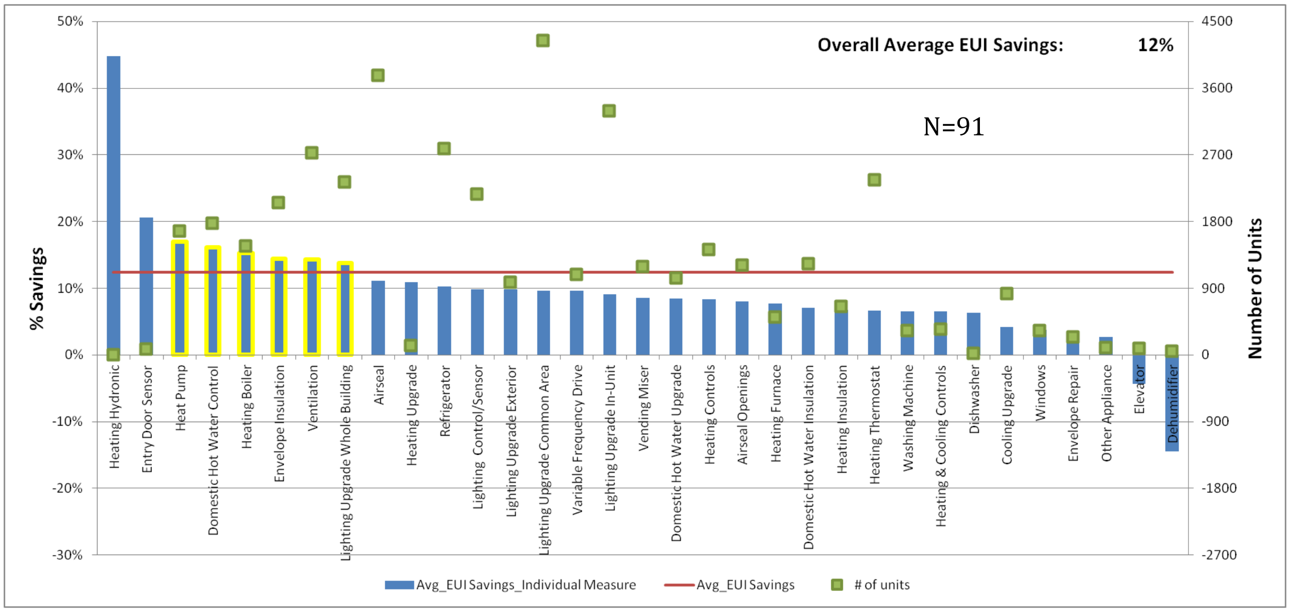


Figure 5-4: EUI savings in properties that included retrofit measure

Despite the limitations of this approach, since monthly utility bills were the only means available to analyze the impact of multiple upgrades, it does provide a method to attempt to distinguish the impact of different upgrades. To increase the likelihood that above-average % savings for a specific upgrade is robust, CMU focused on upgrades with EUI savings above the dataset average that affected 1000 housing units or more. The bars highlighted in yellow in Figure 5-4 meet these criteria and include:

> ***Heat Pump*****:** The Heat Pump upgrade involved the replacement of other types of conditioning equipment with heat pumps or the replacement of existing heat pumps with more efficient models. It was used in properties with 1,670 total units. The average unit-weighted EUI savings in properties that implemented heat pump upgrades is 17%.
>
> ***Domestic Hot Water (DHW) Control***: Domestic Hot Water (DHW) Control upgrades involved controlling DHW system and supply temperatures. It was implemented in properties with 1,775 total units. The average unit-weighted EUI savings in properties that implemented DHW control is 16%.
>
> ***Heating Boiler***: The Heating Boiler measure involved replacing existing boilers with higher efficiency boilers or installing new boilers. It was used in 1,474 units. The average unit-weighted EUI savings in properties that implemented heating boiler upgrades is 15%.
>
> ***Building Envelope Insulation***: Building Envelope Insulation involved adding or upgrading building envelope insulation: wall, roof, or floor, or any of them in combination. Building

Envelope Insulation was used in properties with 2,053 total units. The average unit-weighted EUI savings in properties that implemented building envelope insulation is 14%.

Ventilation: Ventilation upgrades involved a variety of measures including exhaust fan controls, replacement of exhaust fans, bath fan flow regulators, upgrading building fresh air ventilation system, or garage ventilation system replacement. These upgrades affected 2,722 units and properties that included them achieved an average EUI savings of 14%.

Lighting Upgrade Whole Building: Whole Building Lighting upgrades involved replacing the existing lighting in whole building (property) with higher efficiency lighting. This measure was implemented in properties with 2,330 total units and properties that included this measure achieved an average EUI savings of 14%.

The upgrades associated with above-average EUI savings are shown in Table 5-3. The highlighted categories are those implemented in at least 1000 housing units.

Table 5-3: Retrofit Measures Associated with Above-Average EUI Savings

Upgrade Category	% Savings	# of units	# of properties
Heating Hydronic	45%	6	1
Entry Door Sensor	21%	75	1
Heat Pump	17%	1670	20
DHW Control	16%	1775	22
Heating Boiler	15%	1474	14
Building Envelope Insulation	14%	2053	26
Ventilation	14%	2722	30
Lighting Upgrade Whole Building	14%	2330	25

5.4.4 Patterns of Energy Savings by Upgrade

To evaluate the impact of these six upgrades more closely, CMU examined the monthly energy savings and EUI in properties that implemented these measures and compared them with monthly EUI and energy savings in all other properties.

Heat Pumps: The pre- and post-retrofit average monthly EUI for electricity use in the 20 properties that implemented heat pump upgrades is plotted in Figure 5-5. The graph makes visible the electricity savings that resulted from this measure and the monthly pattern associated with those savings. Figure 5-6 shows the heat pump data together with the pre- and post-retrofit average monthly EUI for electricity use in all other properties. Because many properties do not use electricity to heat, one would expect the wintertime electricity EUIs for all other properties to be lower than those for heat pump properties. This is, in fact, what the graph shows for winter months. However, the efficiency of heat pumps for cooling is apparent in summer months. Here, the monthly EUI for electricity use for heat pump properties is substantially lower than the monthly EUI for all other properties.

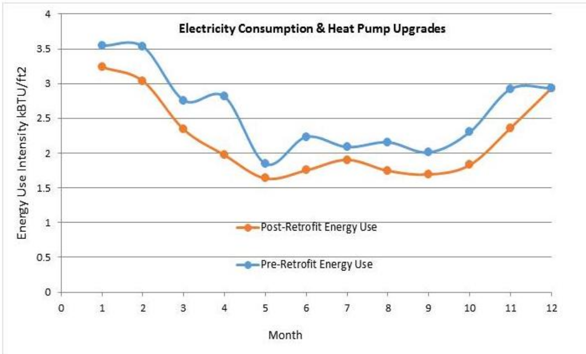


Figure 5-5: Monthly Average Electricity Consumption in Properties with Heat Pump Upgrades (n-20)

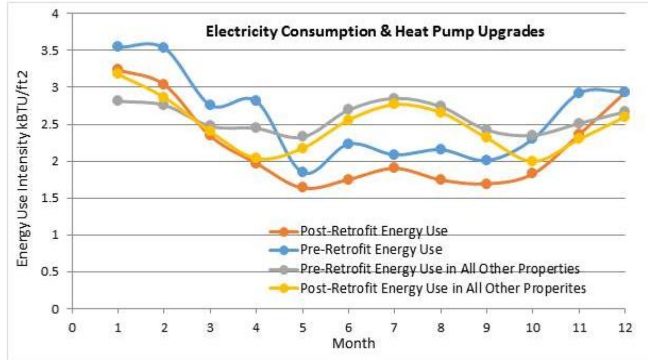


Figure 5-6: Monthly Average Electricity Consumption in Properties with and without Heat Pump Upgrades

Figure 5-7 plots the monthly EUI **%** electricity savings in properties that implemented heat pump upgrades and in all other properties. Here again, the benefits of heat pumps are apparent. In all months except December, the monthly EUI % electricity savings in properties that implemented heat pump upgrades exceeded the EUI % electricity savings for all other properties.

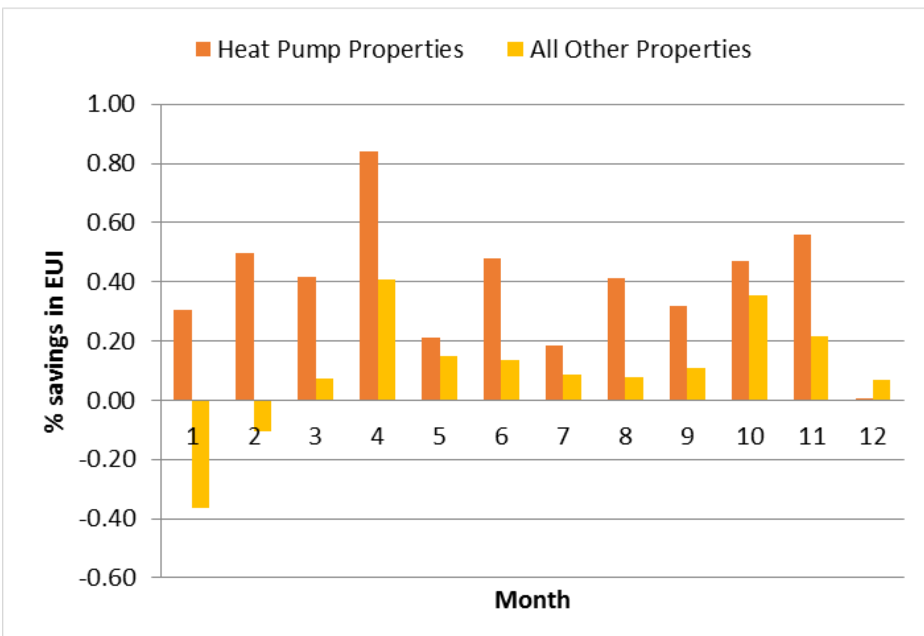


Figure 5-7: Monthly Percent EUI Savings in Electricity for Heat Pumps Properties Compared to All Other Properties

DHW Control: A similar analysis was done for properties that implemented DHW Control. For this upgrade, the results are less clear. Of the 22 properties that implemented this upgrade, 18 of them heat DHW with natural gas. When pre- and post-retrofit monthly fossil fuel EUI is plotted for all properties implementing this measure, the plot in Figure 5-8 shows that monthly fossil fuel EUI is reduced throughout the year and most appreciably during September through January. However, the average monthly fossil fuel EUI for these properties is higher than the monthly fossil fuel EUI for properties that did *not* implement this upgrade (see Figure 5-9).

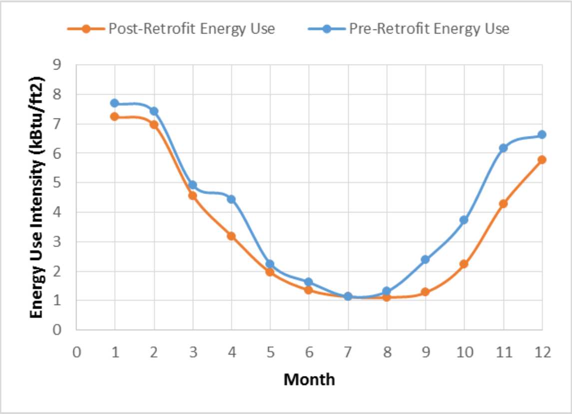


Figure 5-8: Monthly Average Fossil Fuel Consumption in Properties with DHW Control Upgrades (n=22)

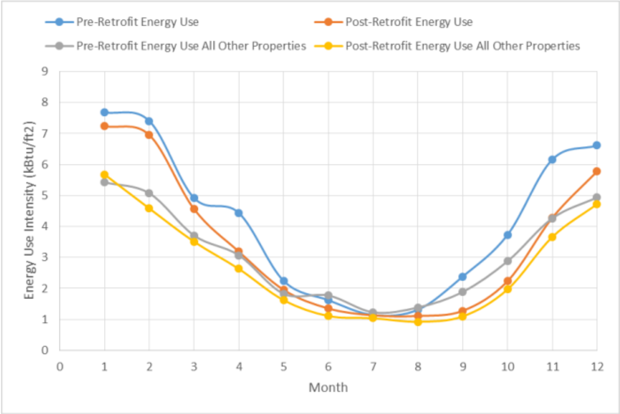


Figure 5-9: Monthly Average Fossil Fuel Consumption in Properties with and without DHW Control Upgrades

To examine the inter-relationships among upgrades and how other upgrades may affect overall savings, CMU created diagrams of these relationships for the six upgrades associated with above-average EUI % savings. The DHW Control diagram was the most complex and is shown here to illustrate the point. Figure 5-10 shows the properties that implemented DHW control in combination with other measures. The second tier of the diagram identifies properties for which the addition of a second upgrade measure produced even greater average EUI % savings than DHW Control (>16%). The third tier of the diagram proceeds in a similar fashion, identifying properties in which the addition of a third upgrade measure resulted in average EUI % savings that exceeded 17%. In this diagram, blocks of the same color represent the same properties. The number of properties and associated dwelling units are shown on each block.

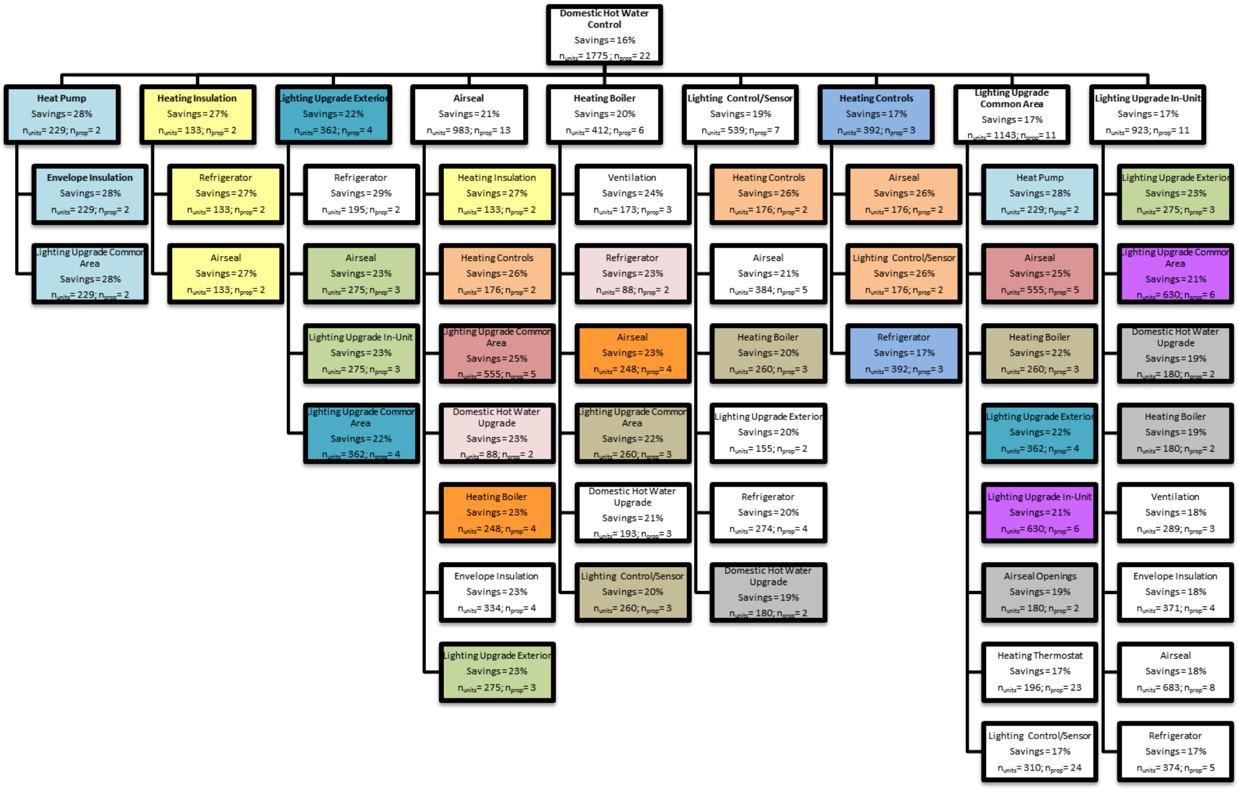


Figure 5-10: Diagram of Properties that Achieved Above-Average EUI % Savings by Implementing DHW Control and Other Measures

The diagram shows that DHW control was implemented with several other upgrades per property. In fact, as will be discussed in the cost analysis section below, DHW control is one of the least expensive upgrades, costing an average of $40 per housing unit, and it was frequently implemented with several other measures. This produces a pattern of overlaps in which the EUI % savings achieved by certain properties will repeatedly impact the overall results. On close examination, the DHW control diagram shows that a heating boiler or heat pump upgrade is often included in these combinations and the impact of those measures may be driving the percent savings. However, because sub-metered data for building equipment like heat pumps, boilers, DHW heaters, lighting and ventilation are not available, it is difficult to isolate the impact of specific measures.

Heating Boiler: In the 14 properties that implemented heating boiler upgrades, all the boilers use natural gas. In these properties, fossil fuel EUI savings were realized in most months (see Figure 5-11), with the greatest savings in September through December. A closer look at those monthly savings is provided in Figure 5-12, which graphs the fossil fuel EUI % savings for properties that implemented heating boiler upgrades compared to fossil fuel EUI % savings in all other properties. The graph shows that properties that upgraded their heating boilers realized a greater percent reduction in fossil fuel EUI between the pre- and post-retrofit year than all other properties in every month except July and August. However, the fossil fuel EUI for winter months is higher in properties that implemented heating boiler upgrades than in properties that did not (see Figure 5-13). This may be related to the characteristics of multifamily properties that use boilers or may reflect the impact of other property upgrades, or both. Furthermore, the winter fossil fuel EUI for these properties (7-9 kBTU/ft2) is substantially higher than it is for properties that implemented heat pump upgrades based on site energy consumption (see Figure 5-6, 3.2-3.5 kBTU/ft2). If source energy were calculated, this difference would disappear.

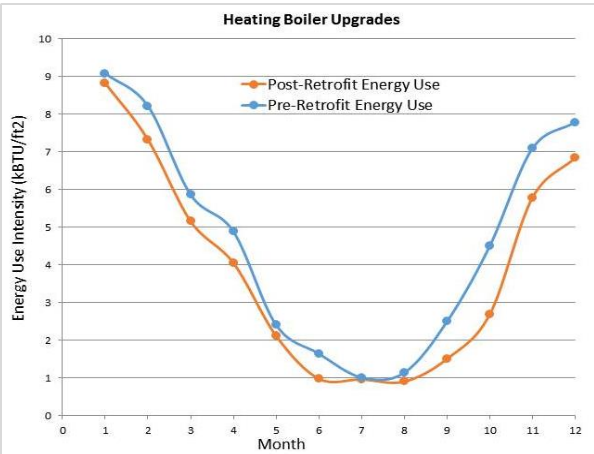


Figure 5-11: Monthly Average Fossil Fuel Consumption in Properties with Heating Boiler(n=22)

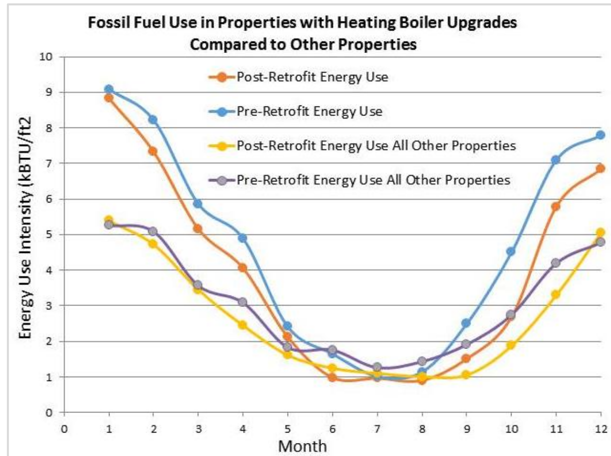


Figure 5-12: Monthly Average Fossil Fuel Consumption in Properties with and without Heating Boiler

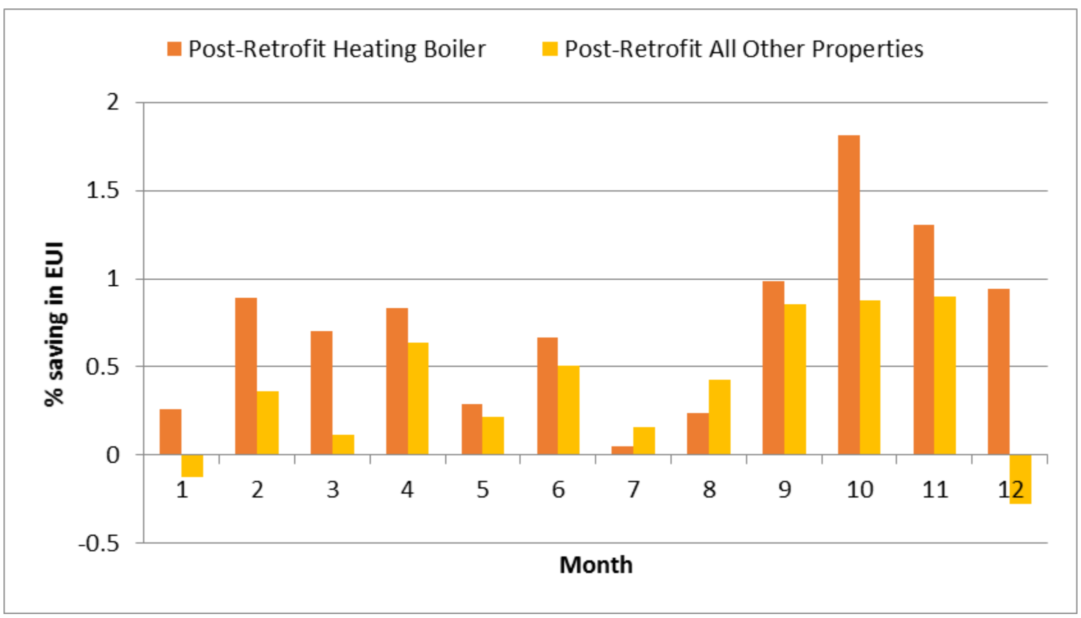


Figure 5-13: Monthly Fossil Fuel Percent EUI Savings for Heating Boiler Properties Compared to All Other Properties

Building Envelope Insulation: Insulation has long been a relatively low-cost and reliable weatherization strategy for reducing energy consumption and improving occupant comfort. Twenty-eight (28) properties added building insulation. With this measure, it is important to realize how varied the work was, ranging from insulating an attic hatch to furring out and insulating all exterior walls. Table 5-4provides a description of the work and its cost.

Table 5-4: Building Envelope Insulation Projects in PHFA Dataset

Property ID	Description of Insulation Work	Upgrade Hard Cost
4	Added 6" attic insulation, hatch gaskets	$9,328
7	Air seal and attic insulation	$9,812
8	Add R30 blown cellulose to all ceilings via attic area	$20,150
11	Add 6" blown cellulose to ceilings in attic all units	$9,006
14	Flat roof ceiling work - install missing insulation	$1,815
14	Insulate attic hatch	$148
17	Insulate basement utility equipment room ceiling & seal penetrations	$1,548
17	Repair insulation & seal 4th floor attic space	$567
18	Wall insulation	$16,935
18	Attic floor insulation	$21,618
19	Insulate over recessed lighting in attic	$816
19	Add cellulose to attic	$6,698
21	Air Seal and Insulate Attic	$9,458
27	Insulate and seal top of elevator shaft	$1,910
32	Add 10.5" insulation to Bldg. 'A' attic	$12,500
40	Cottage wall insulation to R13	$3,648
40	Increase cottage attic insulation to R49	$16,058
53	Attic sloped ceiling cavities - insulate	$4,800
56	Kitchen wall foam insulation	$3,500
56	Add attic insulation	$22,000
59	Furr walls - Provide R-23 Foam insulation	$429,804
69	Improve attic/crawlspace insulation	$51,202
70	Attic insulation repair	$58,925
75	Fiberglas blown-in insulation 6,500 ft2	$12,428
77	Add 9" cellulose insulation	$15,822
77	Insulate and weather strip attic hatch	$3,550
81	Install new cellulose insulation and baffles in truss space	$57,493
82	Install additional insulation in truss space	$8,539
91	Increase attic insulation common building, laundry to R39	$22,018
92	Increase attic insulation to 12" R40/ reduce uncontrolled air leakage	$31,204
106	Air seal and insulate attic	$92,198
108	Attic air seal and insulation	$53,123
110	Attic seal/R49 insulation for Common spaces	$7,040
110	Attic seal/R49 insulation/hatch/duct insulation for apartment spaces	$90,154

For the properties that added insulation, fossil fuel EUI was reduced in every month (Figure 5-14). Electricity EUI was also reduced by a lesser amount, primarily in the spring and fall (Figure 5-15). In addition, properties that implemented an insulation upgrade had lower pre-retrofit and post-retrofit electricity EUIs than properties that did not implement this measure (Figure 5-16). One possibility is that properties that were insulated may lend themselves to this type of upgrade (e.g., frame construction as opposed to solid masonry), but further analysis would be required to understand this pattern.

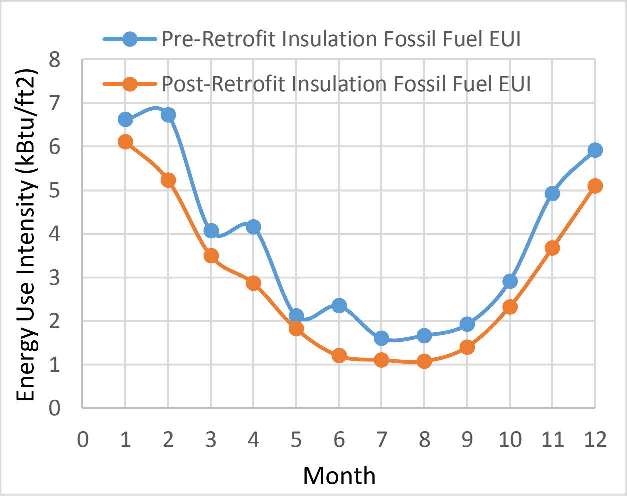


Figure 5-14: Monthly Average Fossil Fuel Consumption in Properties with Building Envelope Insulation (n=22)

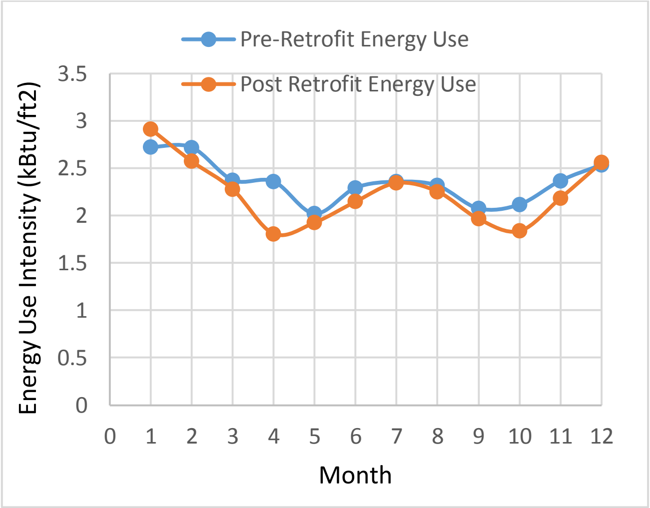


Figure 5-15: Monthly Average Electricity Consumption in Properties with Building Envelope Insulation(n=22)

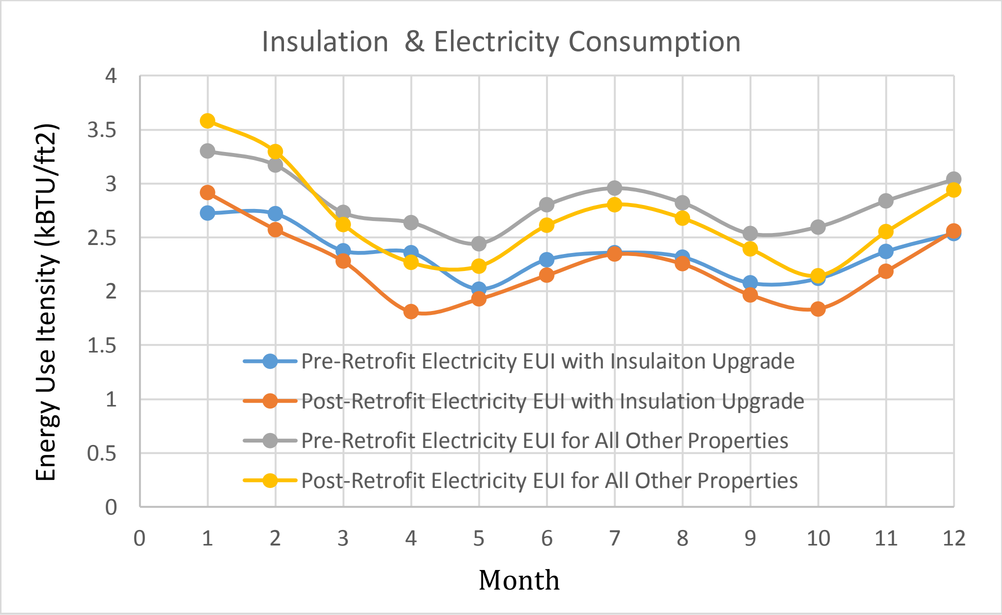


Figure 5-16: Monthly Average Electricity Consumption in Properties with and without Building Envelope Insulation

Ventilation: Thirty (30) properties implemented a ventilation upgrade. The specific adjustments to ventilation are so varied that it is surprising to find this upgrade among those associated with above-average EUI % savings. Some properties increased upgraded bathroom fans to Energy Star models, but others increased air flow in halls, bathroom, or laundries and therefore potentially increased energy consumption (Ueno 2012). Nevertheless, among properties that implemented a ventilation upgrade, both fossil fuel and electricity EUIs were reduced. See Figure 5-17 and Figure 5-18. Closer study indicates that the two measures that may be driving the savings are boiler and heat pump upgrades that were also implemented in these properties. See the diagram in Figure 5-19 that illustrates the relationships among properties that implemented ventilation upgrades in combination with other measures for above-average EUI % savings.

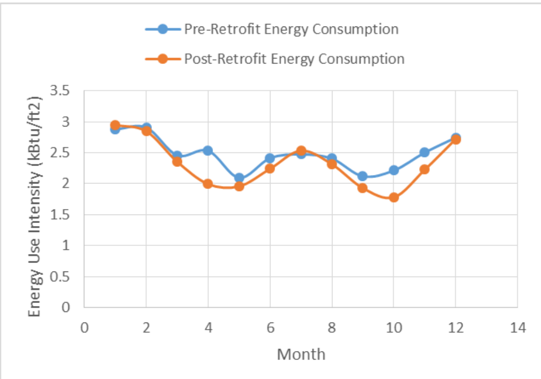


Figure 5-17: Monthly Average Electricity Consumption in Properties with Ventilation Upgrades (n=30)

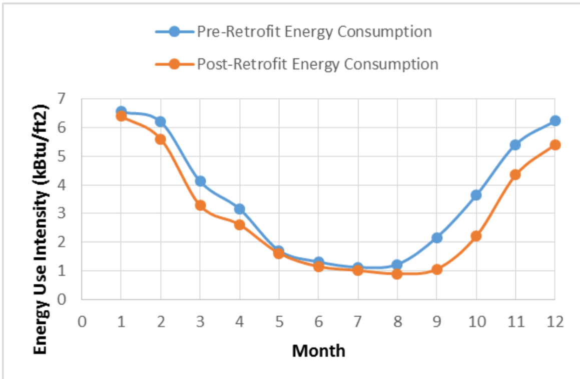


Figure 5-18: Monthly Average Fossil Fuel Consumption in Properties with Ventilation Upgrades (n=30)

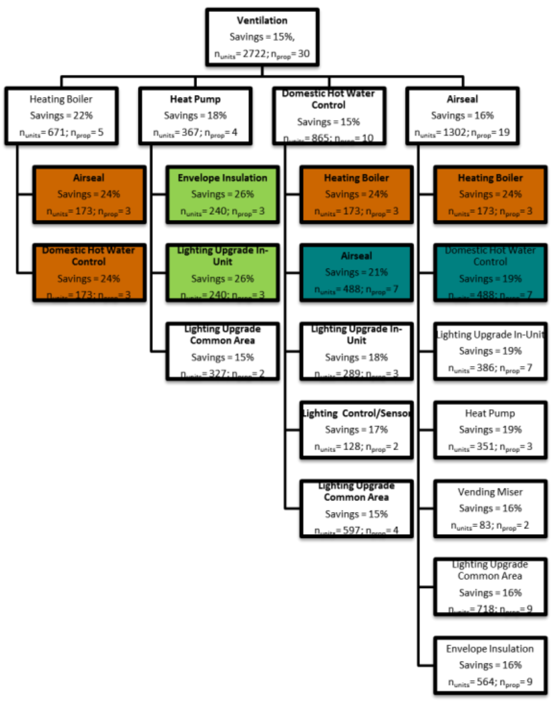


Figure 5-19: Diagram of Properties that Achieved Above-Average EUI % Savings by Implementing Ventilation Upgrades and Other Measures

There is also substantial similarity in the shapes of the electricity EUI curves for ventilation and for insulation, and similar to properties that implemented insulation upgrades, properties that implemented ventilation upgrades have lower pre-retrofit and post-retrofit electricity EUIs in most months than properties that did not implement this measure (see Figure 5-20). Further analysis would be needed to understand these patterns more clearly.

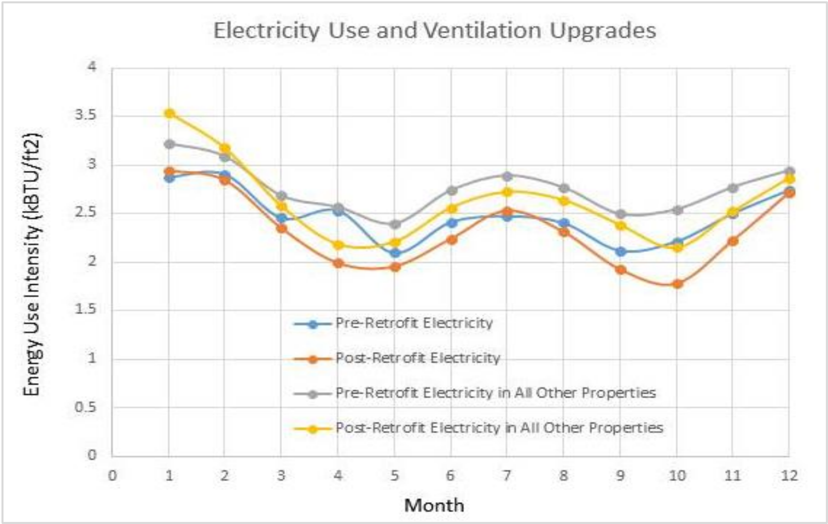


Figure 5-20: Monthly Average Electricity Consumption in Properties with and without Ventilation Upgrade

Lighting Upgrade Whole Building: Building lighting upgrades are usually low-hanging fruit among building retrofits: a cost-effective means to reduce electricity consumption. Among the 25 properties in the PHFA dataset that implemented whole building lighting upgrades, however, the results were also not equivocal. These properties realized EUI electricity reductions during most of the year except January and February, but the electricity EUI in these properties was *higher* than it was in properties that did not implement this upgrade. These results are shown in Figure 5-21.

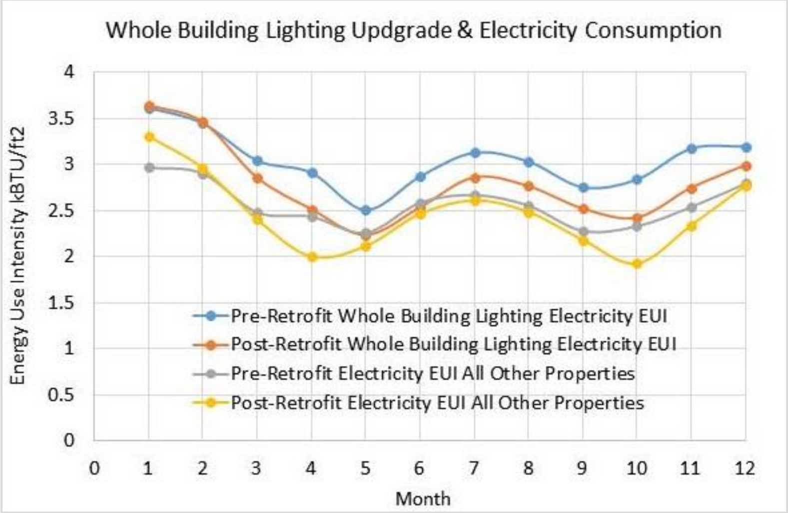


Figure 5-21: Monthly Average Electricity Consumption in Properties with (25) and without Whole Building Lighting Upgrade

The patterns of energy savings described above are complex. For each upgrade, the EUI savings presented are cumulative savings of all the upgrades implemented in each property. There is a wide range in the property characteristics and a range in the suite of upgrades implemented in each property. In addition, different contractors performed the upgrades and their work would not be identical. Nevertheless, a few trends are apparent:

- Properties that implemented whole building lighting upgrades realized electricity savings in every post-retrofit month.

- Properties that implemented heat pump upgrades realized good EUI savings and their EUI % savings in electricity is better than the EUI % savings in electricity for all other properties for every month in the post-retrofit year. In addition, their electricity consumption in summer months, as indicated by EUI, is substantially lower than that of all other properties.

- Properties that implemented boiler upgrades appear to achieve good fossil fuel savings and realized more fossil fuel EUI % savings that all other properties during every month in the post-retrofit year.

- For properties that implemented insulation upgrades, there appears to be a good trend of savings for both fossil fuel and electricity, but the pattern is less clear. Additional analysis would be needed.

5.4.5 Cost-Effectiveness of Energy-Related Upgrades

One of the distinct aspects of the ARRA-funded Weatherization Assistance Program was that the allowable cost per housing unit was boosted from $3,000 to $6,500 (Eisenberg 2010). This was done to allow more extensive upgrades that might produce greater energy savings. Within the PHFA Renovation for Smart Rehab Program, no specific per-unit cost limits were set. Rather, PHFA used the estimated SIRs as the means to identify effective upgrades for each property. PHFA also made additional funds available (e.g., a MacArthur Foundation grant) and properties could add their own money to cover project costs. With this approach, the total funding[16] made available for upgrades to the 91 properties and 7,439 housing units was $23,016,763 or $3,094 per housing unit. **The total ARRA weatherization funding** used for these properties was $16,279,106 or **$2,188 per unit**, with a minimum of $16 per unit and a maximum of $6,729 per unit.

For this analysis, CMU was provided with hard cost detail for property upgrades, regardless of funding source (ARRA or other funds). CMU evaluated the hard cost of the energy-related upgrades[17] for each property and compared the cost per unit to the change in EUI. **The average cost per unit for energy-related upgrades was $2,548.** Figure 5-22 shows the geographic

[16] Total funding includes the hard costs for energy, water, and health & safety upgrades as well as soft costs such as the property energy audit, the audit software license fee and A&E fees.

[17] Energy-related upgrades were considered to be all upgrades *except* for those categorized as Health & Safety or Water upgrades.

distribution of energy-related upgrade costs per property. Because hard cost per unit varied considerably, unit costs were grouped into ranges, as shown below in Table 5-5. The cost of energy-related upgrades varies from $20 per unit to almost $20,000 per unit. As a reminder, multiple sources of funding were used for these upgrades, including a property's own monies.

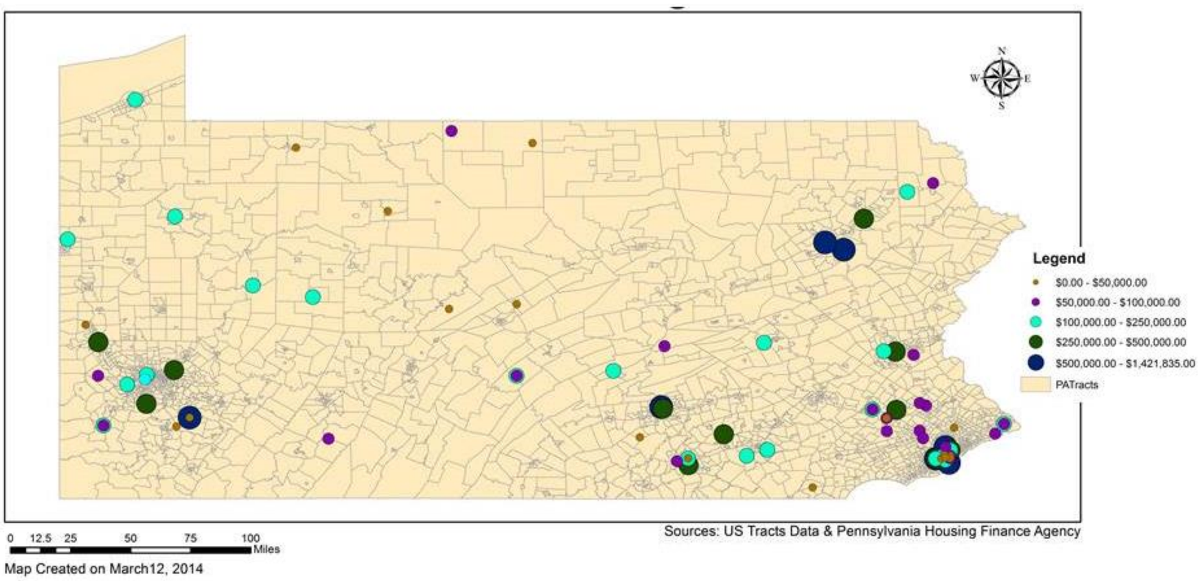


Figure 5-22: Distribution of Upgrade Costs per Property across PHFA Dataset

Table 5-5: Upgrade Hard Cost per Unit and EUI % Change

Hard Cost Per Unit ($)	Average Weighted EUI % Change	Total Units	# of Properties Represented	Post-Retrofit EUI or EUI Range[kbu/ft²]
$0- $20	13.55	85	1	61
$100- $200	18.12	40	1	87
$300- $399	(2.16)	114	2	64, 83
$400- $499	10.69	124	2	28 , 76
$500- $599	19.48	180	2	31, 79
$600- $699	(1.17)	196	2	43, 49
$700- $799	18.21	249	4	21 – 53
$800- $899	4.02	558	3	67 – 78
$900- $999	20.93	121	2	26, 74
$1,000- $1,999	12.58	1508	22	24 – 89
$2,000- $2,999	10.08	1959	20	16 – 124
$3,000- $3999	6.24	806	10	22 – 74
$4,000- $4,999	12.64	817	7	34 – 113
$5,000- $5,999	19.09	419	6	11 – 70
$6,000- $6,999	11.50	178	4	21 – 101
$9,000- $9,999	(21.46)	15	1	3
$11,000- $11,999	44.81	6	1	41
$19,000- $19,999	21.25	64	1	41

The rows highlighted in blue show the cost ranges for the greatest number of housing units, $1,000-$3,000, with an average EUI % savings of 10.08% to 12.58%. This can be compared to the overall dataset average EUI % savings of 12.34%.

The rows highlighted in light orange indicate cost ranges in which above-average EUI % savings were achieved for relatively low cost. Some of these units realized EUI savings above 18%, yet spent less than $800 per unit. For example, Property 95, an 85-unit property, achieved 13.55% EUI savings and spent $16.39/unit by upgrading building lighting to CFLs and installing DHW recirculation control. Property 91, a 100-unit property, achieved 19.48% EUI savings and spent $574.25/unit by air sealing and weather stripping, increasing attic insulation, upgrading the building lighting system to CFLs, and adding lighting controls and sensors outdoors and in common areas.

Figure 5-23 graphs the information in Table 5-6. Many properties and housing units (yellow line) realized above-average EUI % change (blue columns) for less than the average cost of $2,548 per unit.

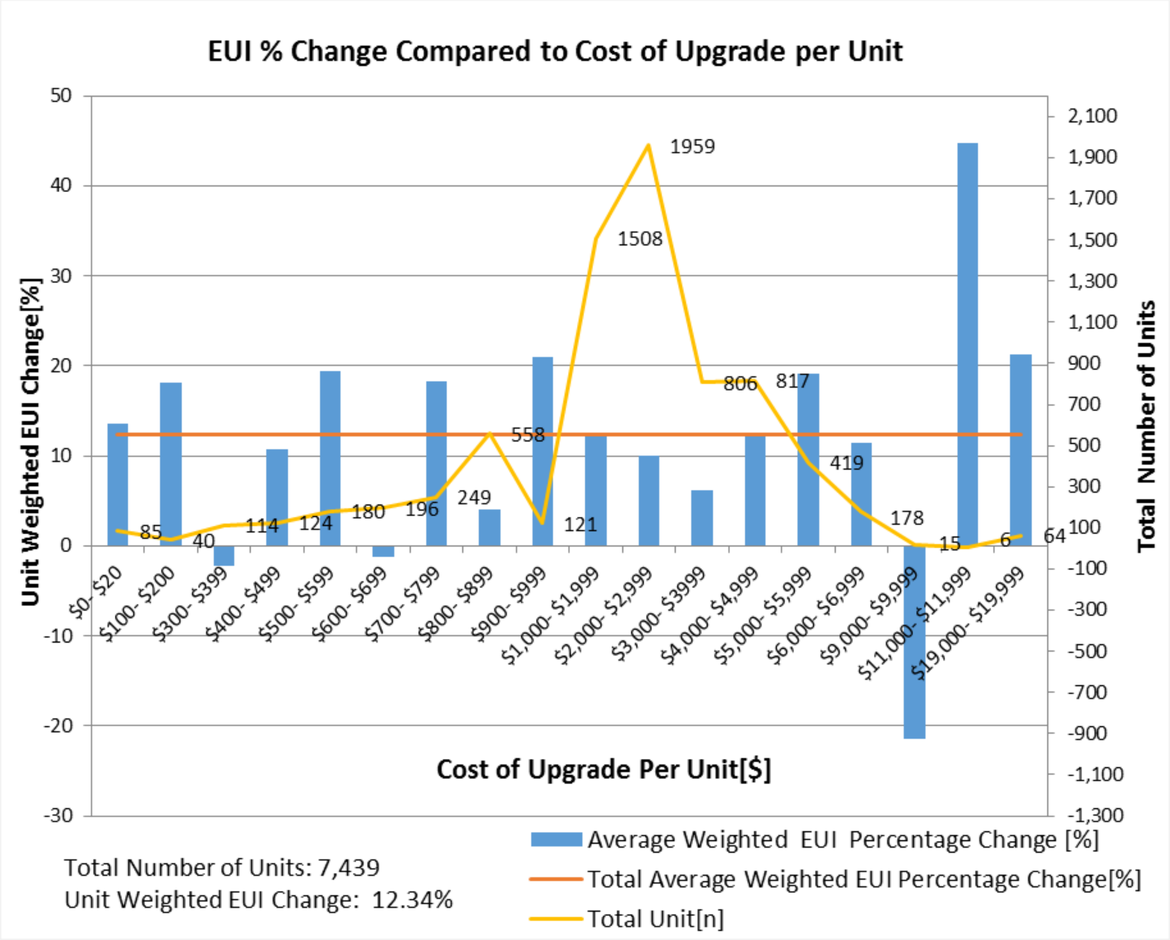


Figure 5-23: Percentage Change in EUI & Hard Cost of Upgrades per Housing Unit

The bottom two rows on Table 5-6and the corresponding last two columns in Figure 5-23 show the greatest amount spent per unit on energy-related upgrades. There are only two properties and 70 housing units (<1% percent of the dataset) in these ranges and they are skewed by these single properties. For the 64-unit property where hard costs exceeded $19,000 per unit, the original estimate was $6,500 per unit. Mini-split heat pumps were installed here for $933,000, twice the original estimate. Whole-building lighting upgrades were estimated at $45,000 and cost $174,000, almost 4X the estimate. The estimated annual percent energy savings for these two measures was 32%; the EUI % savings realized in the first year was 21%.

The 6-unit property that achieved a unit-weighted 44.81% EUI reduction implemented three upgrades for approximately $72,000, approximately 2.5X the estimated cost. The most significant of these involved upgrading the domestic hot water heaters that are used for both heating and DHW in each apartment. In addition, programmable thermostats were installed and air sealing/caulking was performed. The HVAC upgrades were not proposed in the original audit report, so the predicted and achieved percent savings cannot be compared. The audit report recommendations anticipated a 10% EUI savings for this building; the realized 45% savings was far greater. This is an all-electric building in which tenants pay their utilities. The high level of savings is a substantial benefit to the tenants as well as to the environment.

CMU also evaluated the absolute reduction in kBTUs/ft2 within the cost ranges established above. The results are graphed in Figure 5-24.

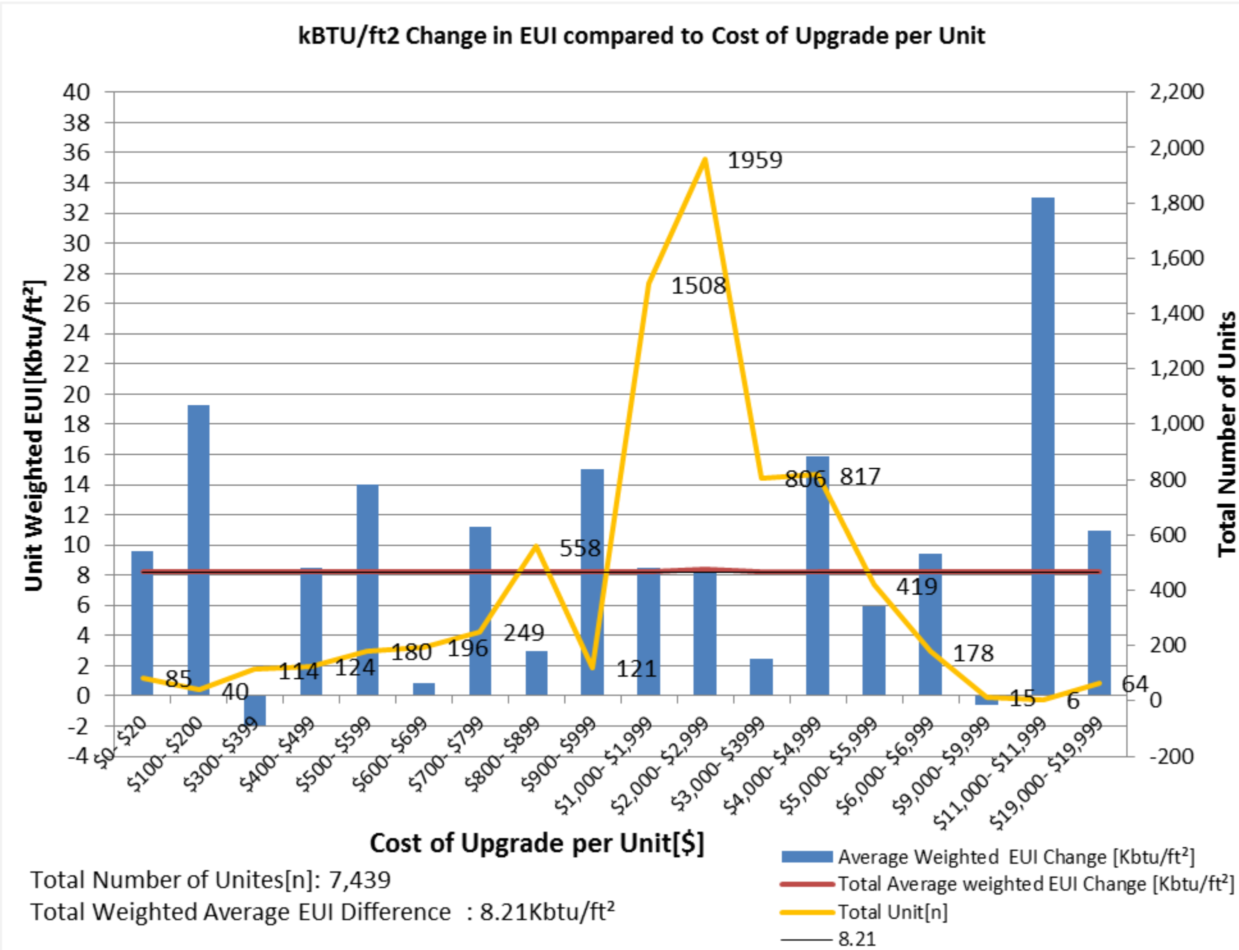


Figure 5-24: Absolute Change in EUI & Hard Cost of Upgrades per Housing Unit

The blue columns in Figure 5-24 underscore the potential to realize good energy benefits at a low cost. For 678 housing units, or 9% of the dataset, above-average energy reductions were achieved by spending less than $1000 per housing unit. One property (ID 97) achieved a reduction of 19.23 kBTU/ft2 per year and spent less than $200 per unit. In this property, the upgrades included air sealing and upgrading the lighting system by installing occupancy sensors.

PHFA confirmed that upgrade costs were not standardized for this program, so the costs may simply reflect varying costs in varying markets across the state. However, one thing that becomes apparent from this analysis is that above-average savings can be achieved for a modest cost per unit. A table of all upgrade hard costs for each property (energy, water, and health/safety) and the corresponding cost per unit and cost per square foot is provided at the end of this section in *Table 5-7*. Graphs of total costs per unit for each property (hard and soft costs) are provided in Appendix

B. A closer analysis of the specific contractors who performed the upgrades on high performing properties is recommended.

*Table 5-7*6 below summarizes the energy-related upgrade costs for this program, showing the total PHFA costs per upgrade category, the upgrade hard cost per unit and per property, and the total number of properties and housing units that received each energy-related upgrade. On a total cost and per-unit and per-property basis, heat pumps were the most expensive upgrade, costing an average of $3,475 per unit and $290,125 per property. The lowest per-unit upgrade was the installation of vending misers, for an average of $13 per housing unit or $1,094 per property.

Table 5-6: PHFA Program Upgrade Hard Costs

Upgrade Category	Total Units	Total PHFA Hard Cost	Hard Cost Per Unit	Number of Properties	Hard Cost per Property
Appliance: Dehumidifier	48	$1,162	$24	1	$1,162
Appliance: Dishwasher	22	$1,495	$68	2	$748
Appliance: Elevator	88	$10,997	$125	1	$10,997
Appliance: Other	101	$13,260	$131	1	$13,260
Appliance: Refrigerator	2,786	$1,287,631	$462	35	$36,789
Appliance: Vending Miser	1,192	$15,322	$13	14	$1,094
Appliance: Washing Machine	332	$64,963	$196	3	$21,654
Building Envelope Air Seal	3,770	$1,007,848	$267	59	$17,082
Building Envelope Air Seal Openings	1,210	$190,971	$158	12	$15,914
Building Envelope Entry Door Sensor	75	$1,781	$24	1	$1,781
Building Envelope Insulation	2,053	$1,105,815	$539	26	$42,531
Building Envelope Repair	244	$392,151	$1,607	2	$196,076
Building Envelope Windows	332	$13,650	$41	2	$6,825
Cooling Upgrade	829	$486,489	$587	7	$69,498
Domestic Hot Water Control	1,718	$68,994	$40	22	$3,136
Domestic Hot Water Insulation	1,283	$50,903	$40	15	$3,394
Domestic Hot Water Upgrade	1,041	$389,882	$375	18	$21,660
Heating Boiler	1,474	$1,879,346	$1,275	14	$134,239
Heating Controls	1,423	$537,622	$378	11	$48,875
Heating Furnace	455	$860,290	$1,891	7	$122,899
Heating Hydronic	6	$69,000	$11,500	1	$69,000
Heating Insulation	655	$91,127	$139	8	$11,391
Heating Upgrade	129	$305,603	$2,369	2	$152,802
Heating & Cooling Controls	435	$38,044	$87	3	$12,681
Heat Pump	1,670	$5,802,508	$3,475	20	$290,125
Lighting Control/Sensor	2,167	$182,646	$84	28	$6,523

Upgrade Category	Total Units	Total PHFA Hard Cost	Hard Cost Per Unit	Number of Properties	Hard Cost per Property
Lighting Upgrade Whole Building	2,387	$708,782	$297	25	$28,351
Lighting Upgrade Common	4,295	$594,807	$138	47	$12,655
Lighting Upgrade Exterior	978	$15,920	$16	10	$1,592
Lighting Upgrade In-Unit	3,236	$352,878	$109	40	$8,822
Master Meter	351	$10,164	$29	2	$5,082
Thermostat	2,357	$878,317	$373	35	$25,095
Ventilation	2,376	$1,277,719	$538	23	$55,553
Variable Frequency Drive	1,081	$247,337	$229	6	$41,223

5.5 Regression Analysis: Correlation between Energy Savings and Upgrade Hard Cost

CMU used multiple regression to evaluate the relationship between upgrade hard costs and energy savings for the six upgrades identified above and associated with above-average EUI savings. The regression of energy saving versus cost data is used to examine the strength of the influence of a particular upgrade on energy saving by assuming there is a positive correlation between cost and energy savings for all kinds of upgrades. The R square here represents the strength of that influence. When R square is large, it means the total energy savings for properties that implemented this particular upgrade is strongly correlated with the cost of that single upgrade, indicating that the cost of that upgrade influences the energy saving. A small R square indicates the correlation between the cost of that upgrade method and energy savings is low. A low R square may indicate that the contribution to total energy savings from this upgrade method is small and its contribution will vary among different properties. Alternatively, it may mean that the correlation of the cost of that upgrade and the energy savings due to that upgrade is low (e.g., this appears to be the case with the ventilation upgrade).

The results of the regression analysis showed a positive relationship between EUI savings and cost for heat pumps and building insulation, with reasonable likelihood that the relationship between these two variables is valid (reasonable R^2). This means that greater expenditures for these kinds of upgrades were associated with increased energy savings.

For the 20 properties with 1,670 housing units that implemented heat pump upgrades, there is a positive correlation between electricity EUI savings and the upgrade cost per unit with $R^2 = 0.32$ (Figure 5-25). Properties that spent more per unit on heat pump upgrades tended to have higher EUI electricity savings. CMU considers this to be a reasonable R^2 because of the amount of variability in the data, reflecting the impact of multiple upgrades and of similar upgrades performed differently in different properties.

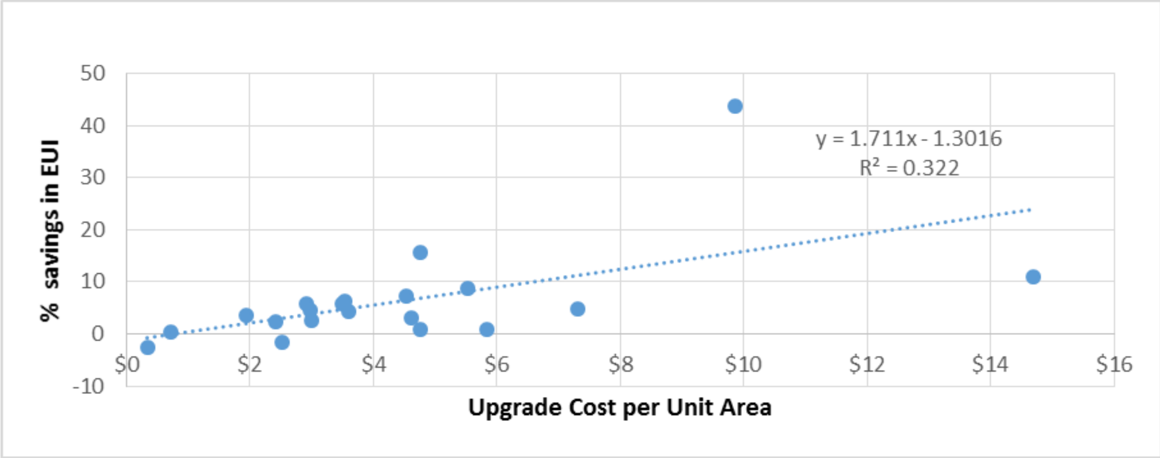


Figure 5-25: Correlation between Heat Pump Electricity Savings and Cost per Housing Unit Area

CMU also did regression analysis with heat pump data to evaluate EUI % savings and total project cost, and EUI % savings and cost per square foot. A positive correlation was found in both instances, with an R^2 of 0.13 and 0.16 respectively.

For the 26 properties with 2053 housing units the received a building envelope insulation upgrade, a positive correlation was found between total EUI savings (fossil fuel and electricity) and project cost (R= 0.47) and cost per square foot (R=0.51). Properties that spent more for building envelope insulation on a total project or cost-per-square-foot basis tended to have higher total EUI savings. Figure 5-26 and Figure 5-27 show these results.

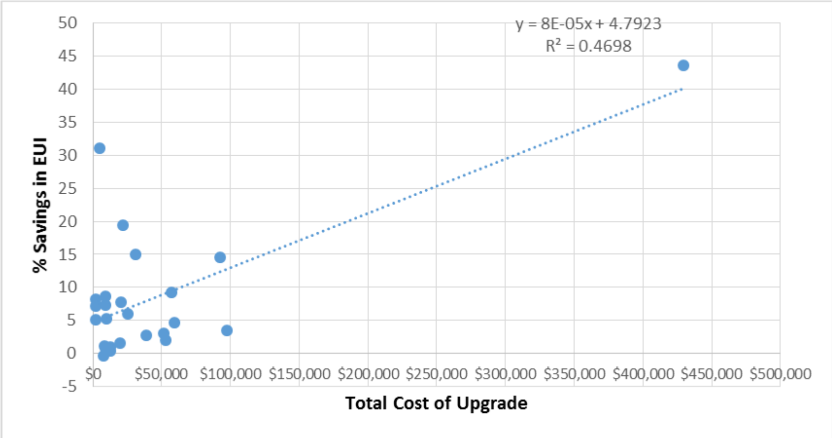


Figure 5-26: Correlation between Building Envelope Insulation Electricity Savings and Cost of Upgrade

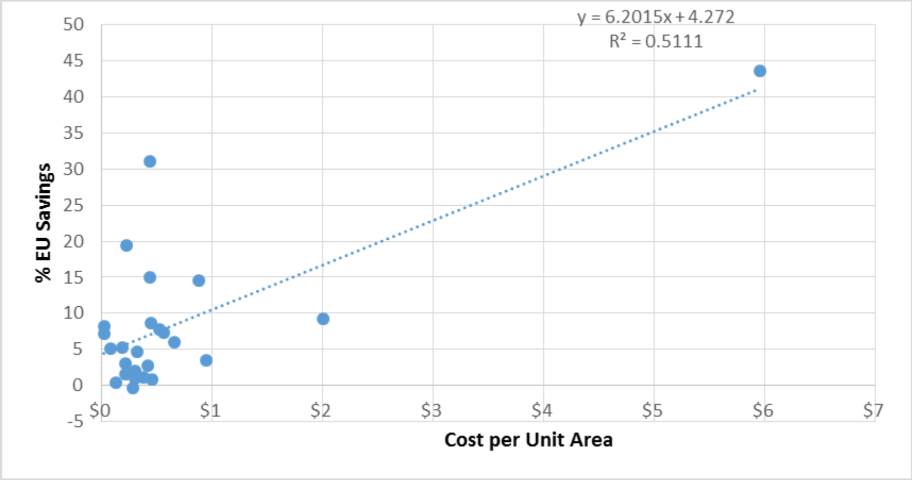


Figure 5-27: Correlation between Building Envelope Insulation Electricity Savings and Cost per Unit Area

It is important to note that if the property associated with the data point in upper right corner of Figure 5-26 and Figure 5-27 were removed, the correlation would disappear. The high cost and high savings associated with that property impact the regression.

Additional regression analysis using EUI % savings, project cost and unit area cost was done for the six upgrades associated with above-average savings. Preliminary results from that analysis suggest that:

- When the impact of a heat pump or boiler upgrade is removed, there is poor correlation between EUI % savings and the four other individual upgrade measures explored here.

- The EUI % savings for building envelope insulation may be greater in properties with fewer than 75 housing units.

- It may be necessary to remove properties that increased their energy consumption from this analysis (similar to the approach in the water upgrade analysis) in order to detect correlation between specific measures and EUI % savings. This may be a valid approach if the reason for the energy increase is unrelated to the performance of the upgrade.

5.6 Individual Property Upgrade Profiles

Finally, for additional insight into the combinations of upgrades implemented either successfully or unsuccessfully within these properties, CMU examined a few properties in detail.

5.6.1.1 Property 34

Property 34 is a 1996 apartment building with 48 units and 48 bedrooms in eastern PA. It occupies 65,423 GSF. Tenants pay utilities here.

Ten upgrades were implemented including air sealing for the building envelope and ducts, the installation of lockable and programmable thermostats, the installation of a vending miser and an Energy Star dehumidifier, lighting controls in the form of motion detectors and timers, and the replacement of metal halide exterior lamps with high pressure sodium lamps.

The weather normalized pre-retrofit EUI for this property was below average: 41.93 kBTU/ft2. The post-retrofit EUI based on bills was still below average but higher at 48 kBTU/ft2. This is an **increase of 14.48% and equates to an annual energy increase of 397,118 BTUs** in the first pre-retrofit year (Figure 5-28). The increase occurred in natural gas consumption, so it is likely related to the change in thermostats. Fortunately, adjustments and/or user education can correct this. The total cost for energy-related upgrades was **$1.68 per square foot or $2,294 per housing unit.**

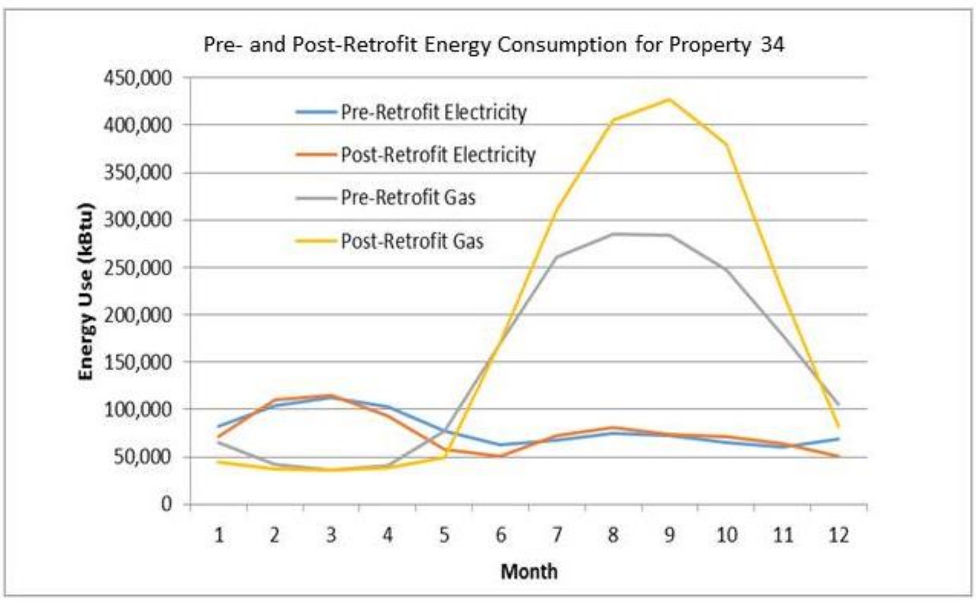


Figure 5-28 Pre- and Post- Retrofit Energy Consumption for Property 34

5.6.1.2 Property 38

Property 38 is a 1977 6-story senior apartment building with 101 single-bedroom housing units in eastern PA. It is 77,454 GSF.

The building still uses oil for space heating and DHW. There were 5 energy-related upgrades in this property: replacing existing refrigerators with Energy Star models, air sealing in common areas and apartments, reducing the DHW setpoint temperature to 120^0F, modifying the oil boiler controls and installing a controller for nighttime heating setback, installing lighting motion sensors in common areas, and installing LEDs in exit signs. Only one of these upgrades is among those associated with above-average EUI savings, yet this property achieved high savings, particularly in oil consumption, at low cost (Figure 5-29).

The weather normalized pre-retrofit EUI for this property was 70.78 kBTU/ft2 and the post-retrofit EUI based on bills was 50 kBTU/ft2. This is a **reduction of 20.78 kBTU/ft2 or 29%** and equates to an annual energy savings of 1,609,494 kBTUs in the first pre-retrofit year. The total cost for energy-related upgrades was **$0.93 per square foot or $714 per unit.**

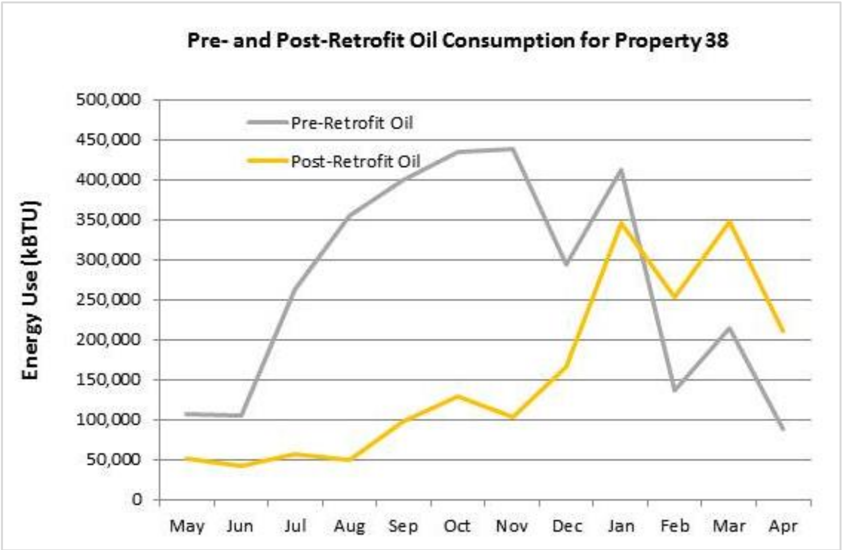


Figure 5-29 Pre- and Post- Retrofit Oil Consumption for Property 38

5.6.1.3 Property 59

Property 59 is a 1923 brick masonry building with concrete roof, located in western PA. It has 6 floors of commercial space and 11 floors of residential space with 259 SRO units and 72,157 GSF. The upgrades occurred in the residential floors only. Because occupancy data were not provided, occupancy was assumed to be 1 person/SRO in the pre- and post-retrofit years.

There were three energy-related upgrades to the residential floors: whole building lighting, building envelope insulation and installation of heat pumps. Prior to the retrofit, the residential floors were heated with steam from an old district system and were not cooled. After the retrofit, steam is still used, but only to heat DHW and to boost the temperature of a building heat pump loop (with distributed heat pump configuration) as needed during the winter. In addition, the residential units are now cooled. Figure 5-30 shows a large decrease in steam energy associated with this upgrade. It also shows an increase in electricity with the addition of heat pumps for heating and cooling.

The weather normalized pre-retrofit site EUI for this property was among the highest in the dataset at 124 kBTU/ft2. The first-year post-retrofit EUI based on bills was 82 kBTU/ft2. This is a **reduction of 42 kBTU/ft2 or 34%** and equates to **annual energy savings of 3,030,594 kBTUs in the post-retrofit year despite the addition of cooling to all 259 housing units**. The total cost for the energy-related upgrades was $17.16/ft2 or $4,782 per housing unit. Property 59 is a good example of DOE's reasoning that increased investment in retrofits can result in greater energy savings.

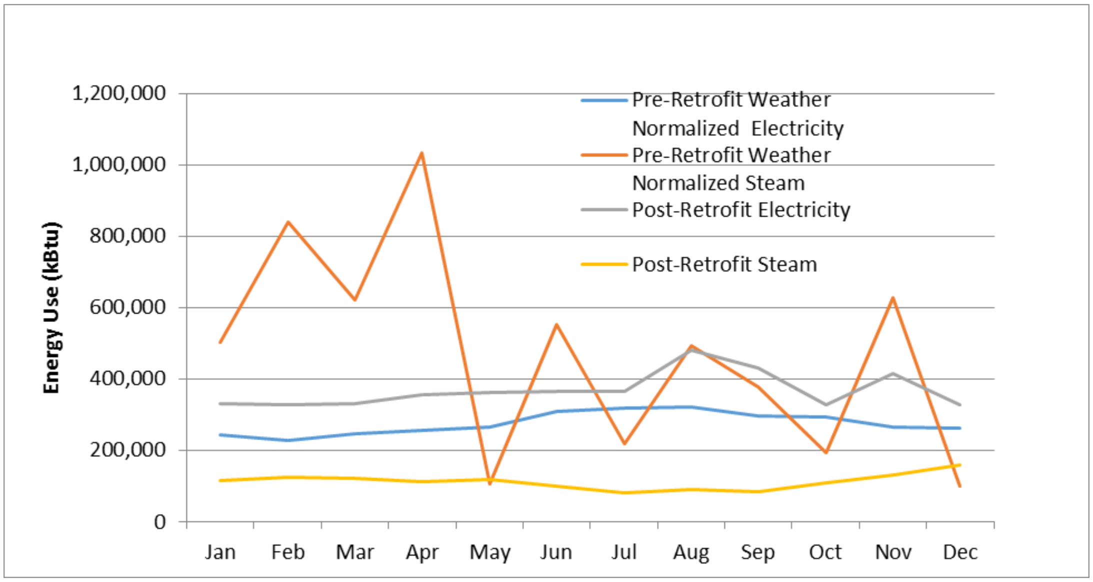


Figure 5-30 Pre- and Post-Retrofit Energy Consumption for Property 59

5.6.1.4 Property 62

Property 62 is a 1960s 19-story galvanized steel frame high rise in eastern PA. It has 288 housing units in approximately 137,400 GSF. The owner pays all utilities.

Three boilers provide space heating and DHW and a central chiller and cooling tower cool the building. A two-pipe FCU system distributes heating and cooling to each apartment. Eight energy-related upgrades were recommended and PHFA approved two: the space heating and DHW boilers were replaced and bathroom ventilation was upgraded with more efficient fans that no longer run 24/7. These upgrades saved both electricity and natural gas (Figure 5-31).

The weather normalized pre-retrofit EUI for this property was 98.54 kBTU/ft2 and the post-retrofit EUI based on bills was 67.36 kBTU/ft2. **Energy use was reduced 31.18 kBTU/ft2 or 32%** and this equates to an annual energy savings of 4,284,132 kBTUs in the first pre-retrofit year. The audit-estimated savings for the implemented upgrades was 17% higher (approximately 5.18 million BTUs/year).

The estimated cost for the implemented upgrades was approximately $1.1 million and the actual cost was $653,000. This equates to **$5.08 per square foot or $2,423 per unit.**

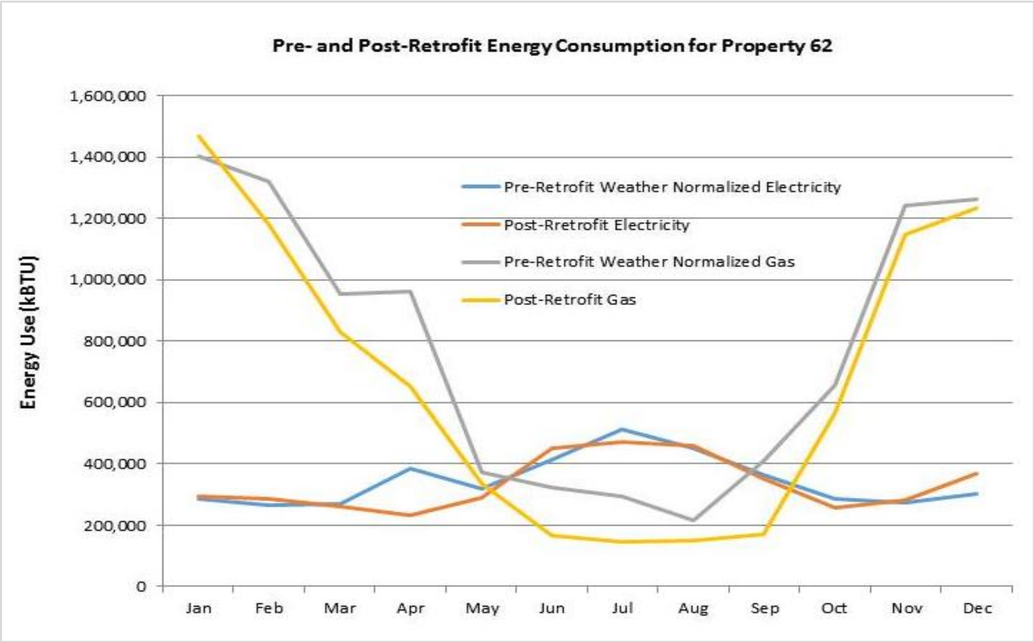


Figure 5-31 Pre- and Post- Retrofit Energy Consumption for Property 62

5.6.1.5 Property 74

Property 74 is a 1980 two-story, 46-unit wood-frame apartment building in central PA, about 42,000 GSF. It is an all-electric property for senior and disabled residents and tenants pay for in-unit heating, cooling and hot water. Packaged terminal heat pumps condition the residential units. Prior to the upgrades, common areas were heated with electric baseboards and air conditioning was provided via split systems.

During the upgrades, the common area split AC systems were replaced with Energy Star heat pumps. In addition, weather stripping was installed around attic hatches and stairwell doors, common area thermostats were replaced with digital models, lighting occupancy sensors were installed in common areas, and more efficient lighting was installed in the parking lots. In all, five of seven recommended energy upgrades were installed. This property did not save energy in the first post-retrofit year, however.

The weather-normalized pre-retrofit for this property was 25.11 kBTU/ft2 and the post-retrofit EUI based on bills was 27.76 kBTU/ft2[18]. This is a modest **increase of 2.65 kBTU/ft2 (11%)** and equates to **additional annual energy consumption of roughly 111,300 kBTUs** in the first pre-retrofit year. The estimated cost for the implemented energy upgrades was approximately $22,556 (upgrades only; excluding A&E and program fees) and the actual cost was $21,266. This equates to **$0.51 per square foot or $462 per unit.**

As shown in Figure 5-32, the energy increase in Property 74 occurred in the warmer months, spring through early fall; some savings were achieved in winter months. Based on the upgrades, this may be related to the new thermostats and/or their integration with the heat pumps and could possibly be corrected with minor adjustments. The audit-estimated savings for the implemented upgrades was 47,494 kWh or 162,409 kBTU/year.

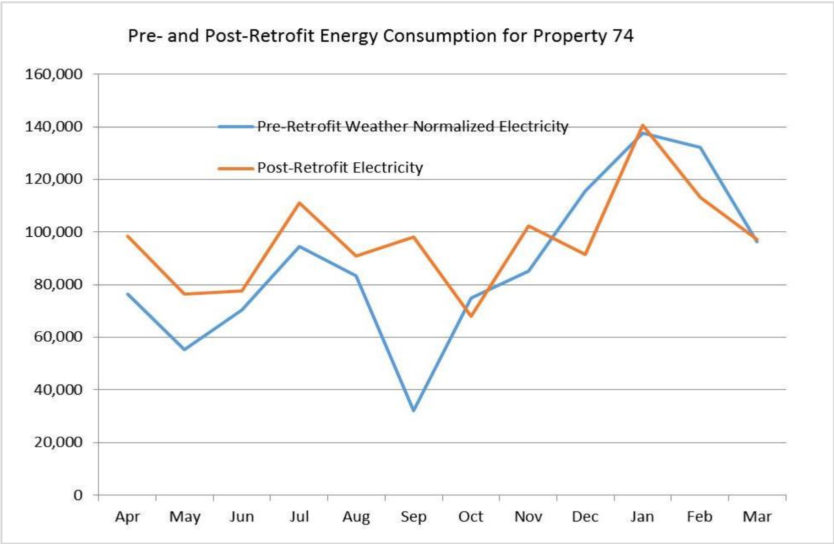


Figure 5-32 Pre-and Post-Retrofit Energy Consumption for Property 74

[18] CMU considers this EUI to be suspiciously low. It's possible that the floor area used in the calculation contains unconditioned area, resulting in a lower EUI.

Although detailed property reviews were beyond the scope of this study, these preliminary reviews highlight how distinct the upgrade approaches were for each property and how widely the results could vary. The average energy savings and percent savings do not reveal the seasonal pattern of energy use for each property and for each fuel in a property, or the variety of upgrade "solution sets" and the variety in savings achieved across the dataset. Although properties received an average of 7.7 energy upgrades, more than 30% savings was achieved in some properties with only two. The implementation of one or more of the six upgrades discussed above—heat pumps installation or replacement, boiler replacement, whole building lighting upgrades, DHW control, building envelope insulation and ventilation upgrades—produced above-average % energy savings across all properties that used them. Among the 14 properties for which energy consumption rose slightly in the post-retrofit year, however, four installed or upgraded heat pumps.

The detailed reviews also suggested a pattern in the upgrades used for newer construction (post-1990). It is possible that the combination of upgrades in these properties was more diverse and more focused on controls than on substantial improvements to the building envelope or mechanical equipment. That possible pattern and its implications will be explored in future work. Weatherization in more recent multifamily properties may require new strategies and perhaps new modeling tools to predict energy savings. A separate analysis of multifamily upgrades in post-1990 construction may yield important insights about structuring future weatherization programs.

*Table 5-7: Total Upgrade Hard Costs per Property, with Cost per Unit and Cost per Square Foot**

Prop ID	Gross SF	Total Units	EUI % Savings	Total Upgrade Hard Costs	Hard Cost per Unit	Hard Cost per SF
1	20,210	24	-19%	$39,175	$1,632	$1.94
2	4,862	10	-2%	$25,344	$2,534	$5.21
3	4,652	6	-23%	$10,635	$1,773	$2.29
4	16,426	16	-26%	$96,742	$6,046	$5.89
5	30,000	32	-21%	$126,341	$3,948	$4.21
7	50,564	58	-19%	$79,470	$1,370	$1.57
8	38,562	41	-23%	$40,850	$996	$1.06
9	50,000	50	2%	$203,422	$4,068	$4.07
10	78,214	28	5%	$171,593	$6,128	$2.19
11	19,392	24	-3%	$136,791	$5,700	$7.05
12	71,172	88	4%	$250,776	$2,850	$3.52
13	61,668	50	5%	$187,907	$3,758	$3.05
14	72,002	80	-19%	$45,205	$565	$0.63
15	33,394	40	-12%	$139,000	$3,475	$4.16
16	75,602	84	-8%	$274,707	$3,270	$3.63
17	25,314	20	-9%	$14,815	$741	$0.59
18	92,204	41	-8%	$155,470	$3,792	$1.69
19	25,783	24	-18%	$58,750	$2,448	$2.28
20	17,514	18	8%	$68,371	$3,798	$3.90
21	21,000	29	-19%	$153,358	$5,288	$7.30
23	82,140	108	-10%	$76,545	$709	$0.93
24	36,658	44	8%	$27,907	$634	$0.76
25	61,080	95	-6%	$282,521	$2,974	$4.63
26	26,167	22	-11%	$32,070	$1,458	$1.23
27	64,523	75	-16%	$194,776	$2,597	$3.02
28	13,800	36	-3%	$48,965	$1,360	$3.55
29	95,122	124	-7%	$562,875	$4,539	$5.92
31	84,454	103	-10%	$292,646	$2,841	$3.47
32	92,155	121	0%	$132,195	$1,093	$1.43
34	65,423	48	14%	$110,099	$2,294	$1.68
35	27,488	28	-9%	$52,002	$1,857	$1.89
36	80,624	101	3%	$256,972	$2,544	$3.19
37	27,218	38	4%	$91,395	$2,405	$3.36
38	77,454	101	-29%	$72,120	$714	$0.93
39	45,600	70	-15%	$425,551	$6,079	$9.33
40	90,211	136	-6%	$154,614	$1,137	$1.71
41	49,600	66	-10%	$158,840	$2,407	$3.20

Prop ID	Gross SF	Total Units	EUI % Savings	Total Upgrade Hard Costs	Hard Cost per Unit	Hard Cost per SF
42	97,000	105	-18%	$368,662	$3,511	$3.80
43	54,426	59	-6%	$84,320	$1,429	$1.55
44	103,656	81	-9%	$134,027	$1,655	$1.29
45	97,000	150	-8%	$122,240	$815	$1.26
46	38,760	55	-12%	$21,449	$390	$0.55
47	40,778	48	-9%	$78,218	$1,630	$1.92
48	102,880	165	4%	$553,310	$3,353	$5.38
49	74,200	104	-12%	$246,397	$2,369	$3.32
50	118,990	135	-1%	$111,610	$827	$0.94
51	95,179	120	-26%	$143,660	$1,197	$1.51
52	247,367	273	-4%	$231,227	$847	$0.93
53	10,940	13	-32%	$73,462	$5,651	$6.71
54	68,382	78	-23%	$84,227	$1,080	$1.23
55	81,340	75	-21%	$168,890	$2,252	$2.08
56	38,532	50	-9%	$60,380	$1,208	$1.57
57	108,405	60	-5%	$188,830	$3,147	$1.74
58	191,391	282	-8%	$555,540	$1,970	$2.90
59	72,157	259	-34%	$1,255,688	$4,848	$17.40
61	84,100	100	-4%	$136,762	$1,368	$1.63
62	137,400	288	-32%	$698,000	$2,424	$5.08
63	4,680	12	-8%	$13,298	$1,108	$2.84
64	49,876	150	-16%	$344,272	$2,295	$6.90
65	40,572	87	-16%	$108,356	$1,245	$2.67
67	19,620	59	17%	$23,217	$394	$1.18
68	167,957	211	-11%	$842,052	$3,991	$5.01
69	233,372	224	-3%	$928,649	$4,146	$3.98
70	182,384	200	-31%	$1,499,403	$7,497	$8.22
74	41,981	46	11%	$22,046	$479	$0.53
75	40,956	35	-2%	$160,658	$4,590	$3.92
77	13,380	15	21%	$148,136	$9,876	$11.07
79	63,540	64	-21%	$1,234,384	$19,287	$19.43
81	28,674	36	-19%	$67,636	$1,879	$2.36
82	22,242	24	-4%	$40,685	$1,695	$1.83
83	24,980	24	-21%	$106,632	$4,443	$4.27
84	28,000	20	-22%	$14,876	$744	$0.53
85	28,496	26	-11%	$149,014	$5,731	$5.23
86	42,252	20	-17%	$37,010	$1,851	$0.88
89	22,313	96	-19%	$194,656	$2,028	$8.72

Prop ID	Gross SF	Total Units	EUI % Savings	Total Upgrade Hard Costs	Hard Cost per Unit	Hard Cost per SF
91	97,632	100	-20%	$57,425	$574	$0.59
92	70,876	78	-17%	$32,684	$419	$0.46
94	70,000	35	-29%	$86,666	$2,476	$1.24
95	62,653	85	-14%	$1,393	$16	$0.02
96	54,777	80	-20%	$76,650	$958	$1.40
97	50,700	40	-18%	$4,119	$103	$0.08
98	53,683	80	-26%	$115,978	$1,450	$2.16
101	126,882	210	3%	$538,000	$2,562	$4.24
106	104,616	101	-7%	$468,455	$4,638	$4.48
107	99,696	127	-11%	$756,169	$5,954	$7.58
108	176,000	152	-4%	$105,292	$693	$0.60
109	70,000	64	-29%	$428,581	$6,697	$6.12
110	102,061	101	-3%	$279,636	$2,769	$2.74
112	30,500	36	-18%	$82,699	$2,297	$2.71
113	181,000	216	-10%	$543,712	$2,517	$3.00
116	4,366	6	-45%	$70,850	$11,808	$16.23

*Include energy, water, and health/safety upgrades

6 WATER PERFORMANCE

6.1 PROFILE OF PROPERTIES IMPLEMENTING WATER UPGRADES

Of the 109 properties and 8,288 housing units in the original dataset, 77 properties with 5,311 total housing units and 6,996 bedrooms received water upgrades and had sufficient water utility data for analysis. There is some, but not complete, overlap between these properties and those used for the energy analysis, i.e., some of the properties that did not have sufficient energy consumption data did have sufficient water data. The owner pays the water bills in 76 of these properties.

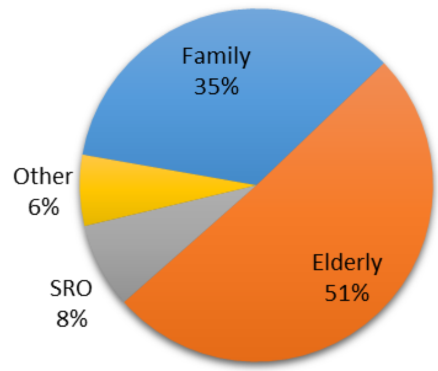


Figure 6-1: Property type distribution of 77 properties with water upgrades

Unlike residential energy consumption, residential water consumption is strongly correlated with the number of occupants. Occupancy assumptions were handled in the same way as they were for the energy analysis: because the majority of these properties offer housing to senior citizens, disabled persons, or are single-room-occupancy units, and because occupancy data were not provided, one person per bedroom was assumed. For the water analysis, water savings and retrofit costs were weighted by the number of bedrooms rather than by the number of housing units.

Among the 77 properties, 27 are family housing with 3,204 total bedrooms. The remaining 50 properties with 3,792 total bedrooms are housing units for seniors, disabled individuals, or single-room-occupancy (SRO) units, as shown above in Figure 6-1.

6.2 CLASSIFICATION AND DISTRIBUTION OF WATER UPGRADES AMONG PROPERTIES

Three major types of water upgrades were used in PHFA properties: low flow sink aerators, low flow showerheads, and low flow toilets. The specific combinations of upgrades across the dataset were:

- Faucet aerators + low flow showerheads + toilet replacement (faucet + showerhead + toilet)
- Faucet aerators + low flow showerheads (faucet + showerhead)
- Faucet aerator only (faucet-only)
- Low flow showerhead only (showerhead-only)
- Toilet replacement only (toilet-only)

The distribution of these individual or combined methods is shown in Table 6-1 based on the properties. Most properties adopted a combined faucet + showerhead upgrade.

Table 6-1: Water Retrofits by Property and Bedroom (77 Properties)

Type of Upgrade	Number of Properties	Number of Bedrooms	Percent of Total by # of Bedrooms
Faucet + showerhead	52	4,978	71.2%
Faucet + showerhead + toilet	8	641	9.2%
Faucet-only	9	656	9.4%
Showerhead-only	3	122	1.7%
Toilet-only	5	599	8.6%

6.3 Overall Water Upgrade Results

The overall pre- and post-retrofit water consumption of each property is shown in Figure 6-2. The range of the pre-retrofit consumption is quite large, from a maximum of 200 gallons per bedroom per day to a minimum of 4 gallons per bedroom per day.

Figure 6-2 also shows that at six properties, water consumption increased noticeably after the retrofit (>10%). In one case, the property manager confirmed there was an undetected leak; the reason was not given for other properties. Because these outliers may misrepresent the entire dataset of water conservation retrofit measures, these six properties were treated as outliers and eliminated from the dataset for water saving analysis. The analysis below excludes those six properties and is based on the remaining 71 properties with 6,646 bedrooms.

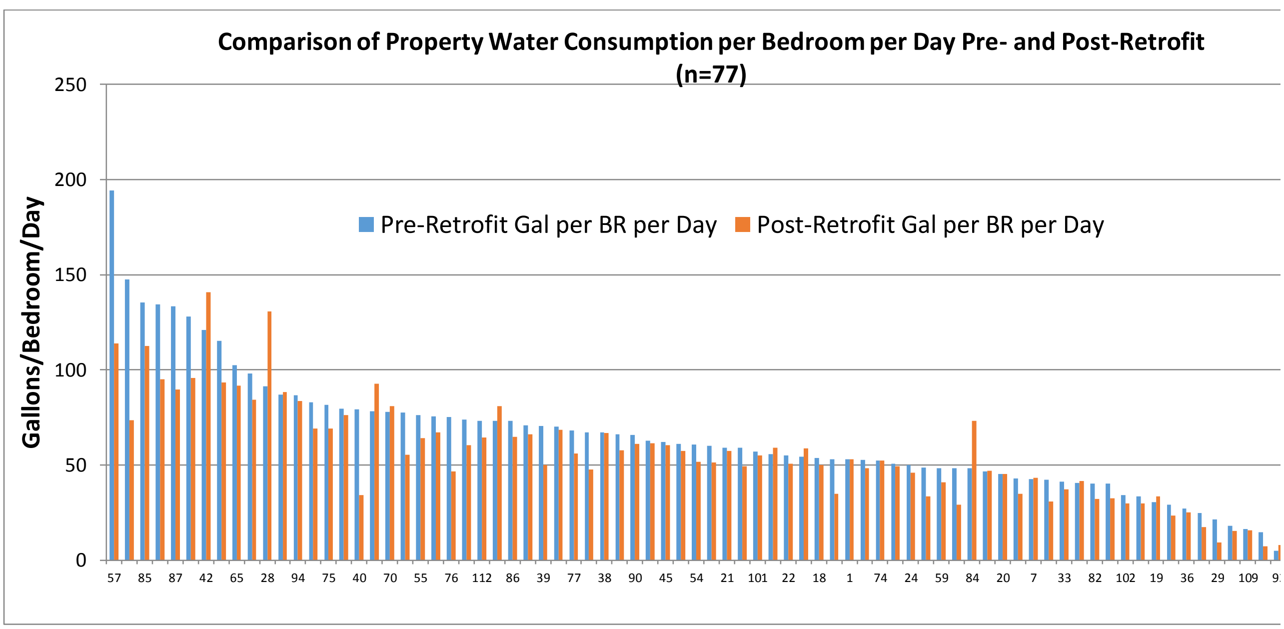


Figure 6-2: Before and after water consumption of each property

The distribution of water upgrade strategies is shown in Table 6-2.

Table 6-2: Water Retrofits by Property and Bedroom (71 Properties)

Type of Upgrade	Number of Properties	Number of Bedrooms	Percent of Total by # of Bedrooms
Faucet + showerhead	48	4,728	71.1%
Faucet + showerhead + toilet	7	581	8.7%
Faucet-only	8	616	9.3%
Showerhead-only	3	122	1.8%
Toilet-only	4	599	9.0%

Figure 6-3 shows that the highest pre-retrofit water consumption was 135.25 gallons/bedroom/day. Several properties had a pre-retrofit consumption of around 15 gallons/bedroom/day. Most of the properties were in the 40 to 80 range of pre-retrofit water consumption. The weighted average pre-retrofit water consumption is 66.6 gallons per bedroom per day. **The weighted average post-retrofit water consumption is 55.5 gallons per bedroom per day, reflecting a reduction of 16%.** It is worth noting that the combined strategies, Faucet + Showerhead and Faucet + Showerhead + Toilet, were only implemented in properties where pre-retrofit water consumption exceeded 80 gallons per bedroom per day.

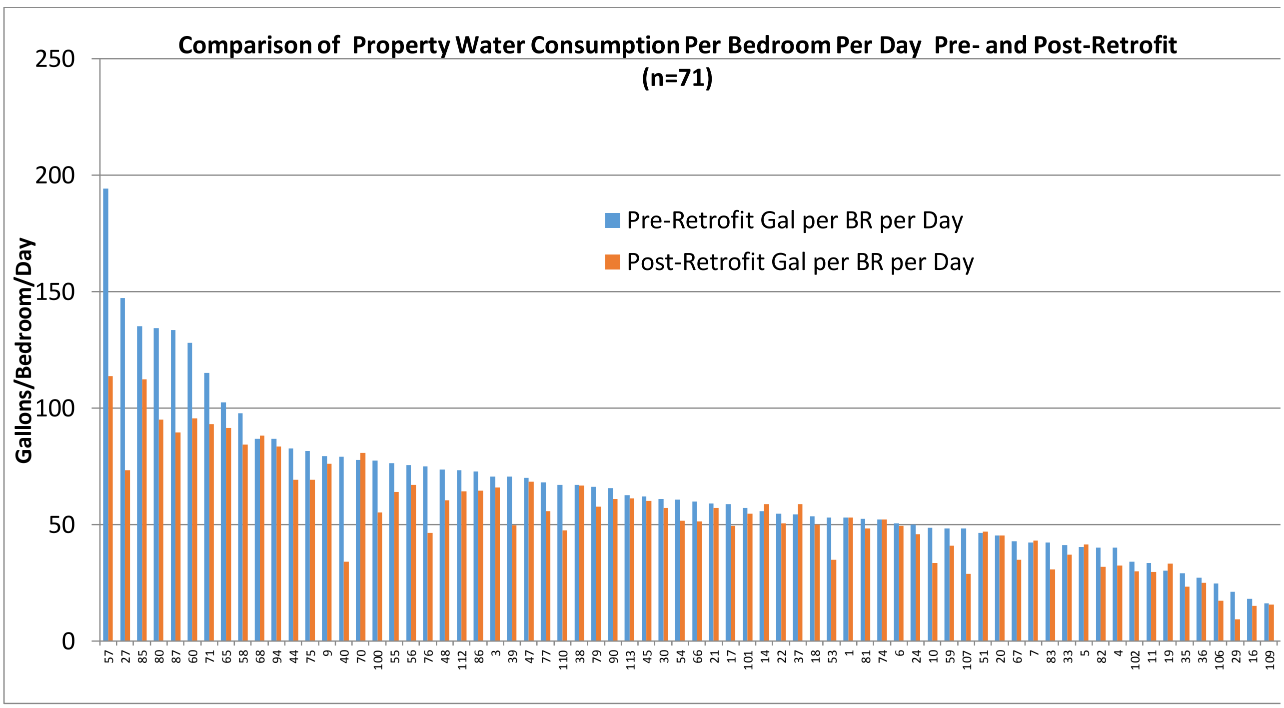


Figure 6-3: Before and after water consumption of each property (71 Properties)

6.4 Assessing the Impact of Specific Water Upgrade Measures

Upgrade strategies were analyzed to determine their effectiveness both for water savings and retrofit cost.

Faucet + Showerhead: Figure 6-4 shows the water savings achieved with a faucet + showerhead retrofit. This was implemented in most of the properties (71% of the bedrooms). The faucet + showerhead combination has a fairly large range of performance, from 80 gallon per bedroom per day reduction to 5 gallon per bedroom per day increase, or from a 57% reduction to a 10% increase. Most properties are within 0 to 20 gallon per bedroom per day reduction and the weighted average is 9.5 gallon per bedroom per day reduction, a 12% reduction.

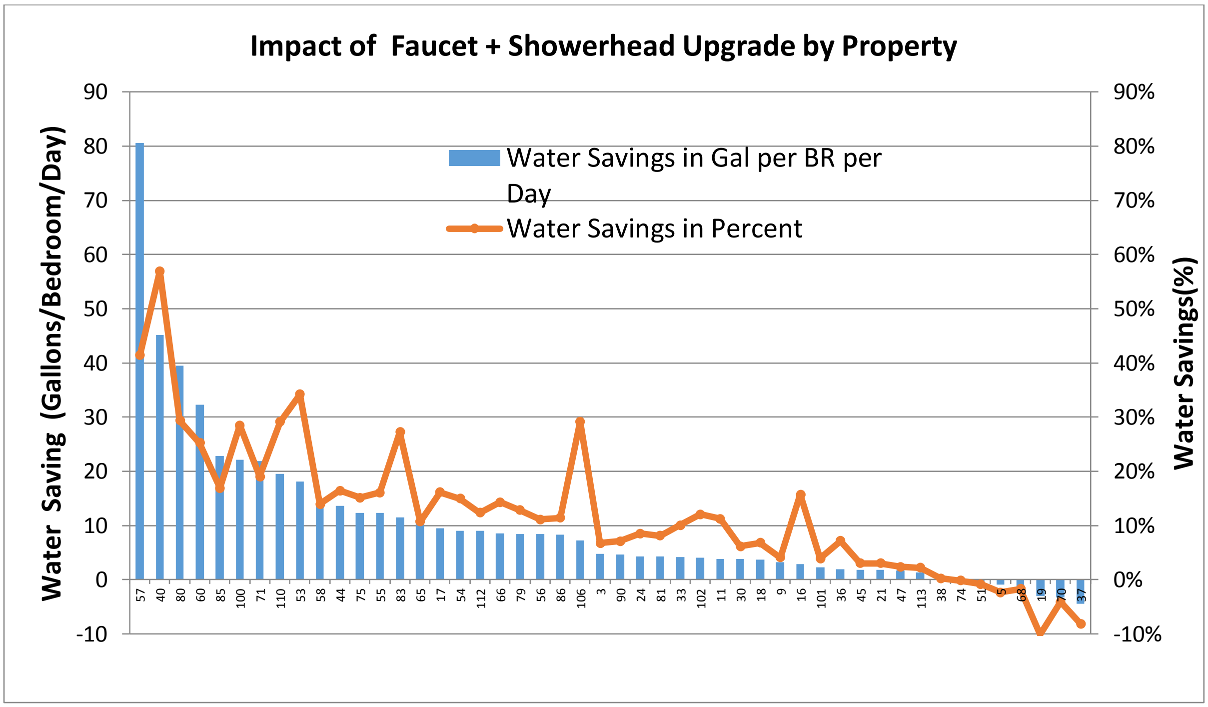


Figure 6-4: Faucet and Showerhead retrofit impact on water usage

Faucet + Showerhead + Toilet: Figure 6-5 illustrates that properties implementing the faucet + showerhead + toilet strategy show a wide range of post-retrofit performance, from 73 gallons per bedroom per day reduction to no change, or from 50% reduction to 0%. However, five of the seven properties achieved reductions >15 gallons/bedroom/day. This resulted in a weighted average reduction of 32.5 gallons per bedroom per day or 31.6% reduction. This makes the faucet + showerhead + toilet strategy the most effective with respect to water usage reduction. This is much higher than the faucet and showerhead upgrade not only in the gallons saved but also the percent saved.

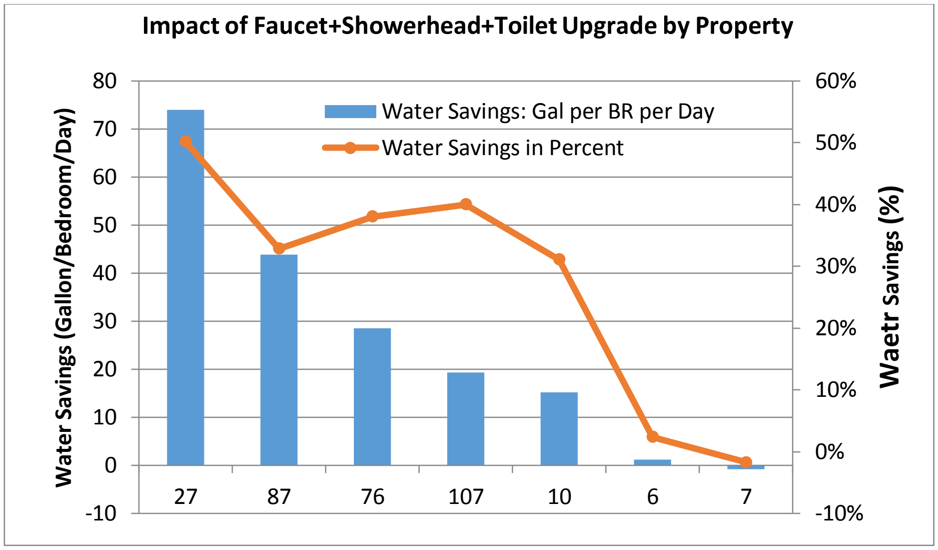


Figure 6-5: Faucet, Showerhead, and Toilet retrofit impact on water usage

Faucet-Only: The faucet-only strategy had a smaller reduction in gallons than each of the combined strategies, as seen in Figure 6-6. While this strategy only has a maximum reduction of 12 gallons per bedroom per day, many of the properties with this strategy had lower water consumption than most of the other properties as all the properties with more than 80 gallons per bedroom per day before retrofit used either of the two combined strategies. While the savings percentage ranged from 56% to 0%, the weighted average water reduction was 7.3 gallons per bedroom per day and the corresponding percentage decrease was 22%. This is higher than the faucet + showerhead upgrade.

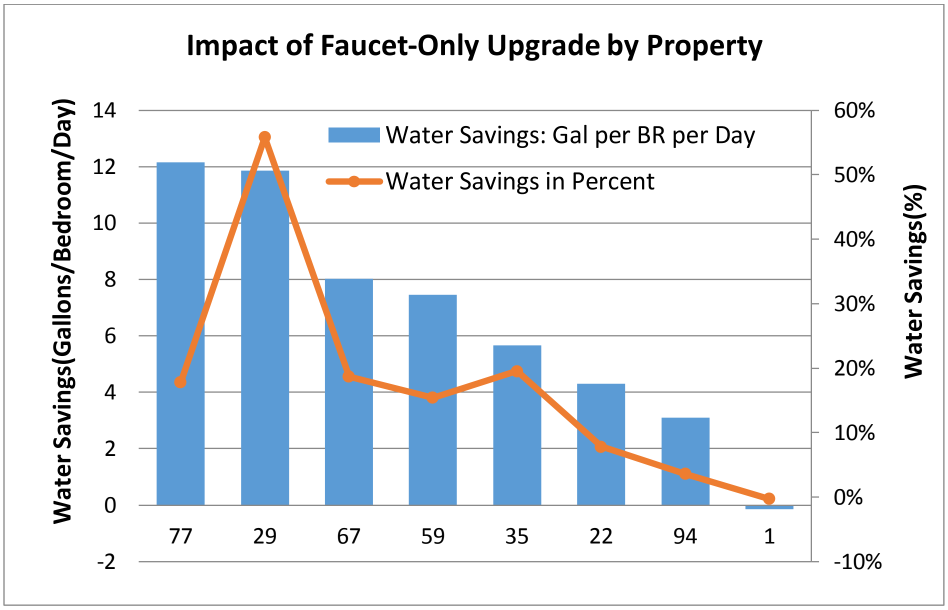


Figure 6-6: Faucet-Only retrofit impact on water usage

Showerhead-Only: The showerhead-only is the one strategy with a slight increase in water usage post-retrofit. Figure 6-7 shows that the impact ranges from 8 gallons saved per bedroom per day to a 3-gallon increased, or from 20% reduction to 6% increase. The weighted average post-retrofit performance is a one gallon increase per bedroom per day or 0.3% increase. A potential reason that a showerhead retrofit may not provide water savings is that the occupants may compensate for reduced water flow by taking longer showers. For this type of retrofit, the quality of the replacement fixture may have substantial impact on its success.

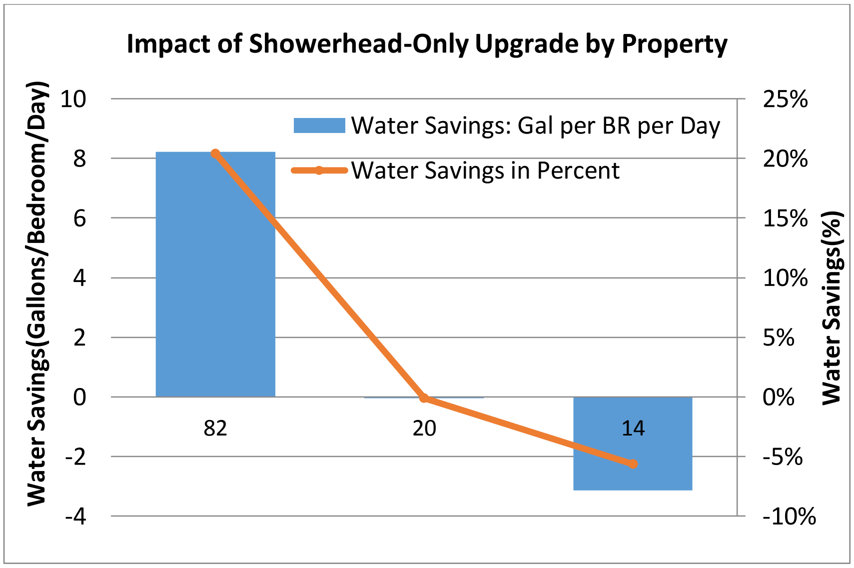


Figure 6-7: Showerhead-Only retrofit impact on water usage

Toilet-Only: The Toilet-Only retrofit provided a range of 1-21 gallons saved per bedroom per day, or a 3% to 50% reduction. This is shown in Figure 6-8. The weighted average performance is 9 gallons reduction per bedroom per day or a 27% reduction. Since all of the properties with more than 80 gallons per bedroom per day before retrofit adopted combined strategies, the Toilet-only upgrade occurred in buildings with lower pre-retrofit water consumption.

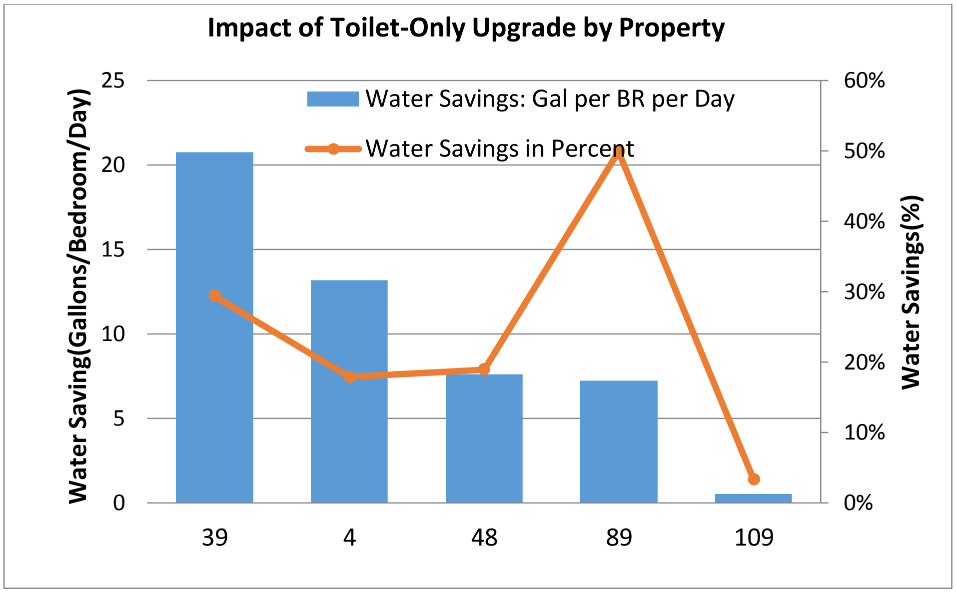


Figure 6-8: Toilet-Only retrofit impact on water usage

6.4.1 Comparison of Individual Upgrades

Most properties had a water savings from 0 to 20 gallons per bedroom per day as shown in Figure 6-9. The faucet + showerhead upgrade and the faucet +showerhead +toilet upgrade have relatively larger water savings than the three individual upgrades. The combined strategies were used for all properties that had a pre-retrofit water usage greater than 80 gallons/bedroom/day. As a result, the individual upgrades show a smaller reduction in water consumption due to the smaller scale of the upgrade and the low initial per-bedroom water usage**. Absolute water savings in gallons do not fully reflect the impact of different upgrade strategies and thus the relative water saving in percent better indicates the performance.**

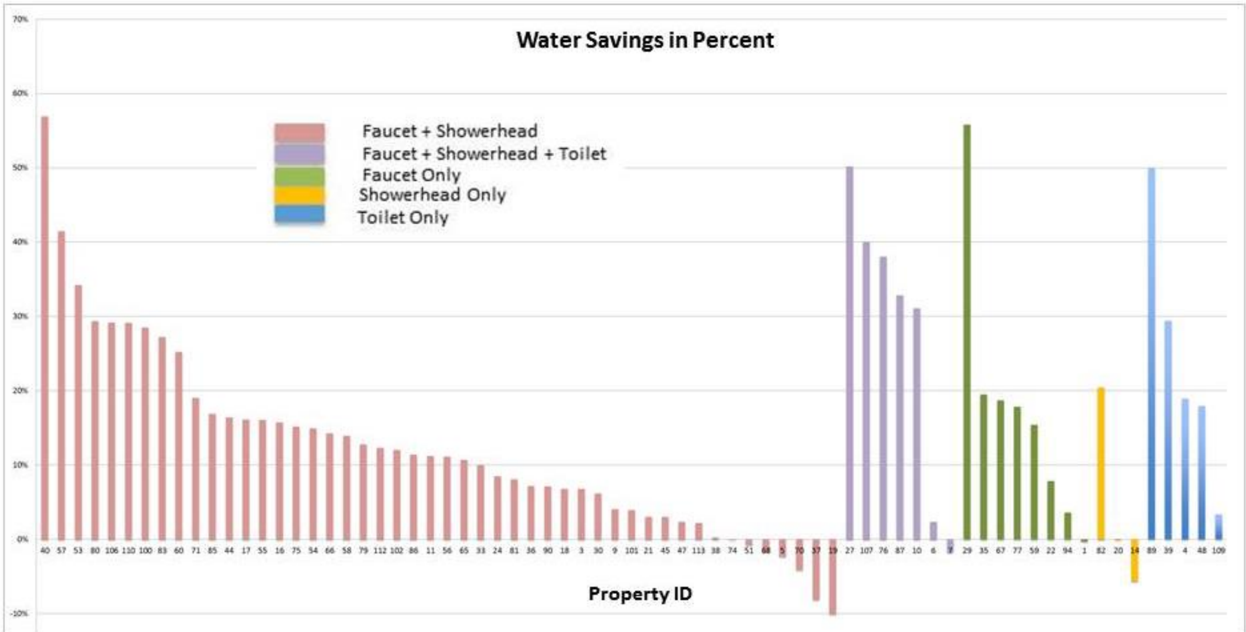


Figure 6-9: Post-retrofit water reduction in percent

When comparing percent water reduction, the faucet-only, toilet-only, and faucet+showerhead+toilet upgrades had the highest impact. This is shown in Figure 6-10. Although the faucet + showerhead upgrade has the highest water saving in gallons, it also had the lowest percent savings and its range of performance is fairly wide. The showerhead- only strategy shows a poor performance as evidenced by having a slight average increase in water usage after retrofit.

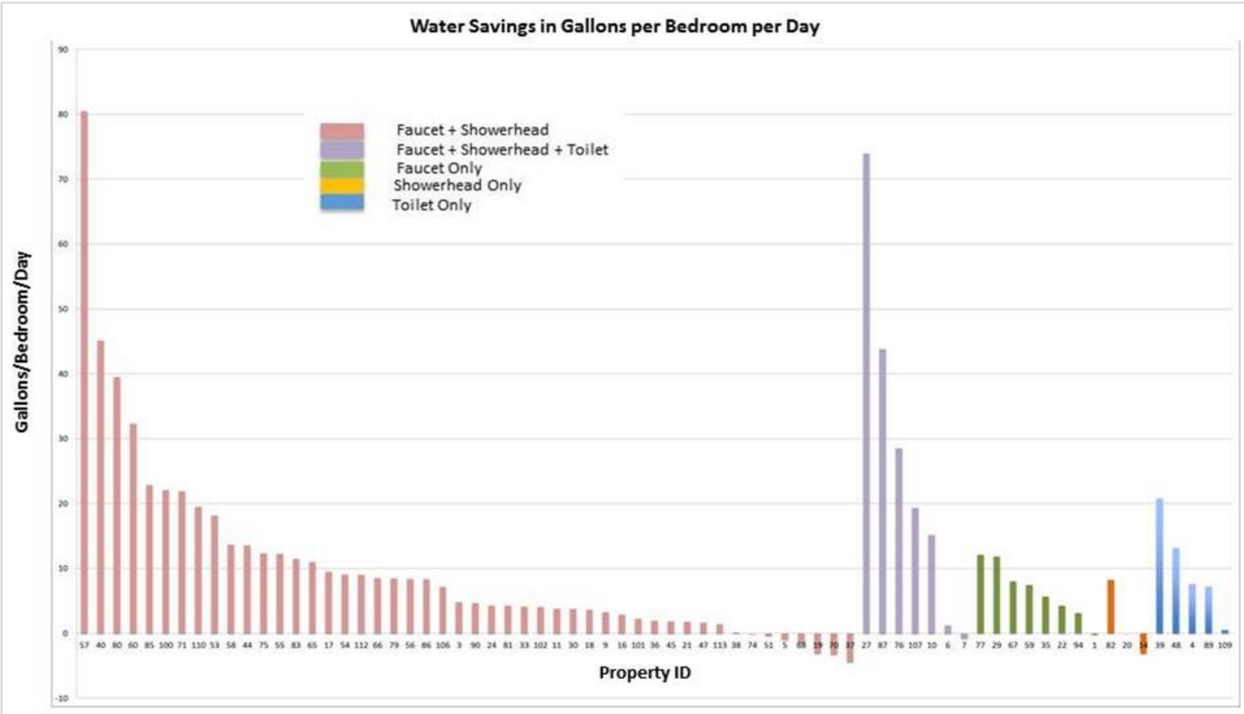
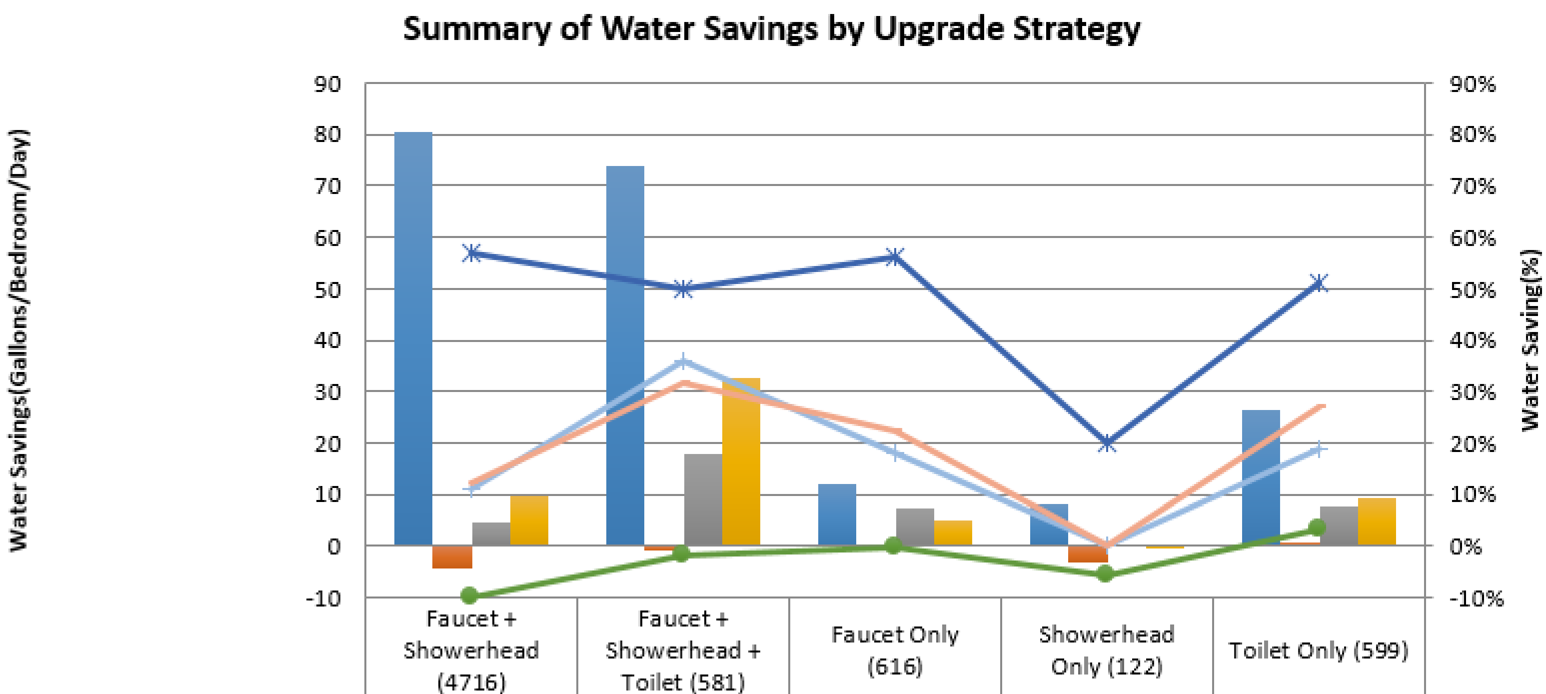


Figure 6-10: Post-retrofit water reduction in gallons per bedroom per day

Figure 6-11 shows the summary of each of the upgrade strategies and compares them to each other. Based on water conservation performance alone, the most successful strategies include Faucet+Showerhead+Toilet, Toilet-Only, and Faucet-Only.



	Faucet + Showerhead (4716)	Faucet + Showerhead + Toilet (581)	Faucet Only (616)	Showerhead Only (122)	Toilet Only (599)
Maximum Saving(Gallons)	80.5	74.0	12.1	8.2	26.5
Minimum Saving(Gallons)	-4.4	-0.7	-0.2	-3.1	0.6
Median Saving(Gallons)	4.7	17.8	7.5	0.0	7.6
Average Saving(Gallons)	9.5	32.5	5.2	-0.4	9.3
Maximum Saving(%)	57.0%	50.0%	56.0%	20.0%	51.0%
Minimum Saving(%)	-10.0%	-1.7%	-0.3%	-5.6%	3.4%
Mediam Saving(%)	11.1%	36.0%	18.0%	0.0%	19.0%
Average Saving(%)	12.3%	31.6%	22.4%	0.0%	26.9%

Figure 6-11: Summary statistics of post-retrofit water reduction

6.5 WATER UPGRADE COST ANALYSIS

In addition to water conservation performance, upgrade costs are important to understand the economic feasibility of each strategy.

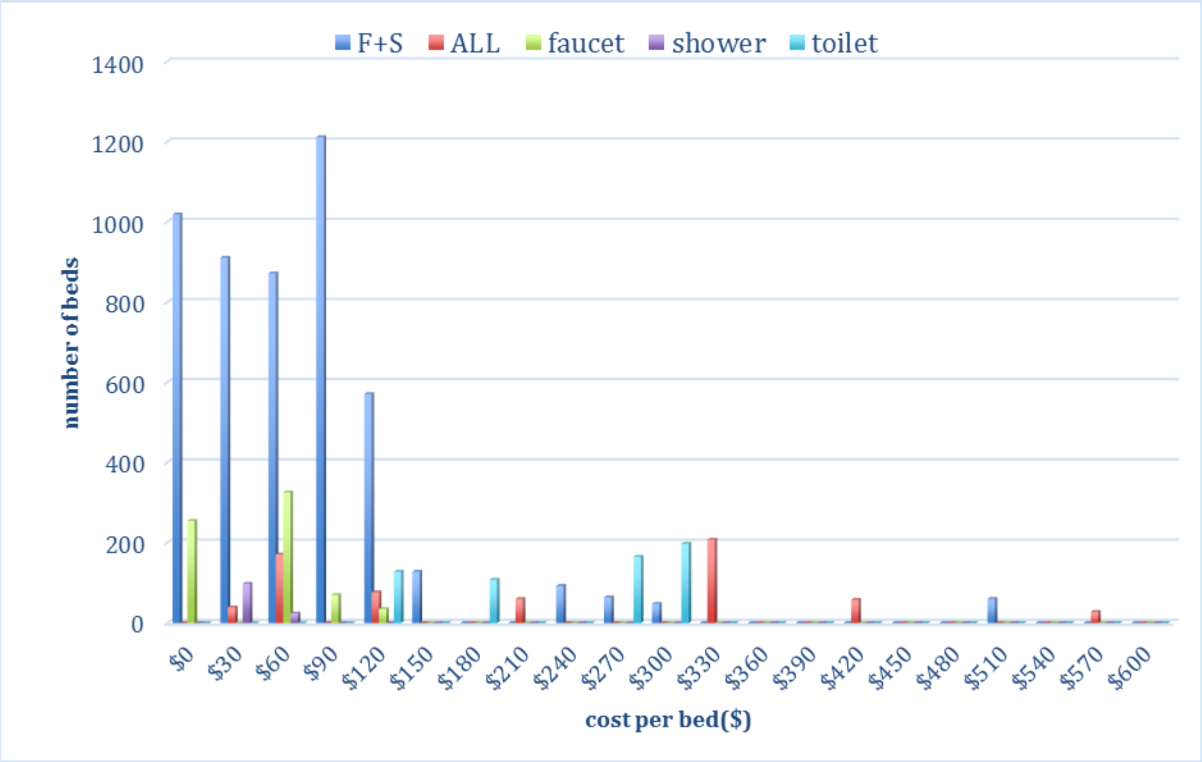


Figure 6-12: Cost per bedroom ranges for each retrofit strategy

Figure 6-12 shows the distribution of the retrofit cost per bedroom, with different colors for different retrofit methods. The number below the bars shows the dollar amount at the beginning of the range (for example $30 designates the $30 to $60 range). The graph starts with cost within range of $0 to $30 per bedroom, and end at $570 to $600 per bedroom. The $600 to $630 range has no samples, but is included to show the last range in the dataset. For most scenarios, the cost per bedroom is between $30 to $90 USD, while the total range is from $7.70 to $571.00 dollars per bedroom. Faucet + Showerhead upgrades are much less expensive than toilet replacement, which costs between $120 to $400 dollars per bedroom.

6.5.1 Correlation between Water Upgrade Hard Cost and Water Savings

Figure 6-13 plots water reduction vs hard cost to evaluate the correlation. The X axis shows the retrofit cost in dollars per bedroom and the Y axis shows water saving in gallons per bedroom per day. It was expected that there would be a positive correlation for each retrofit strategy. However, the data show no correlation between retrofit cost and water savings, or even negative correlation since the R square becomes higher if the trend is negative. Faucet-only and faucet + showerhead upgrades performed very well compared to others with respect to the upgrade costs.

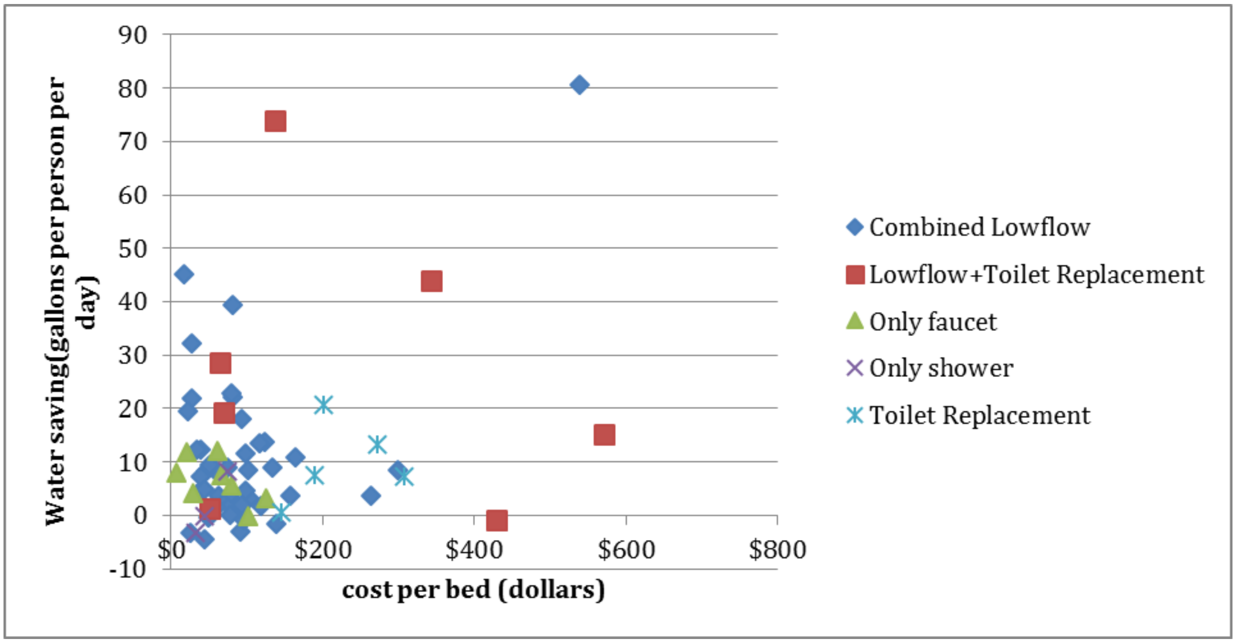


Figure 6-13: Water reduction and cost per bedroom scatter plot

Figure 6-14 shows the calculation of a water savings-per-cost factor. The factor is obtained by a dividing the water savings per bedroom per day by the retrofit cost. Based on that factor, the faucet + showerhead and faucet-only upgrades are very cost effective.

Substantial additional analysis was undertaken to look for a correlation between water savings and water utility costs. None was found. In fact, some properties showed an increase in water utility costs despite reduced water consumption. This may be the result of water rate increases that are intended to fund infrastructure upgrades. Further analysis would be required.

Finally, the Savings to Investment Ratio (SIR) originally estimated by the auditor was compared with an SIR based on the actual retrofit costs and utility bill savings. There were 40 properties for which there was sufficient original SIR data to support this analysis. The average percentage difference between the estimated SIR and actual SIR was -97.8% with a standard deviation of 115.4%. Four out of 40 audits provided an over-estimation of payback time, and only two of the estimates were within 50% of the actual SIR. The majority of payback times were under-estimated, and the estimation was not close to the actual value. Additional years of water bills will provide a better insight into the actual vs. estimated SIR.

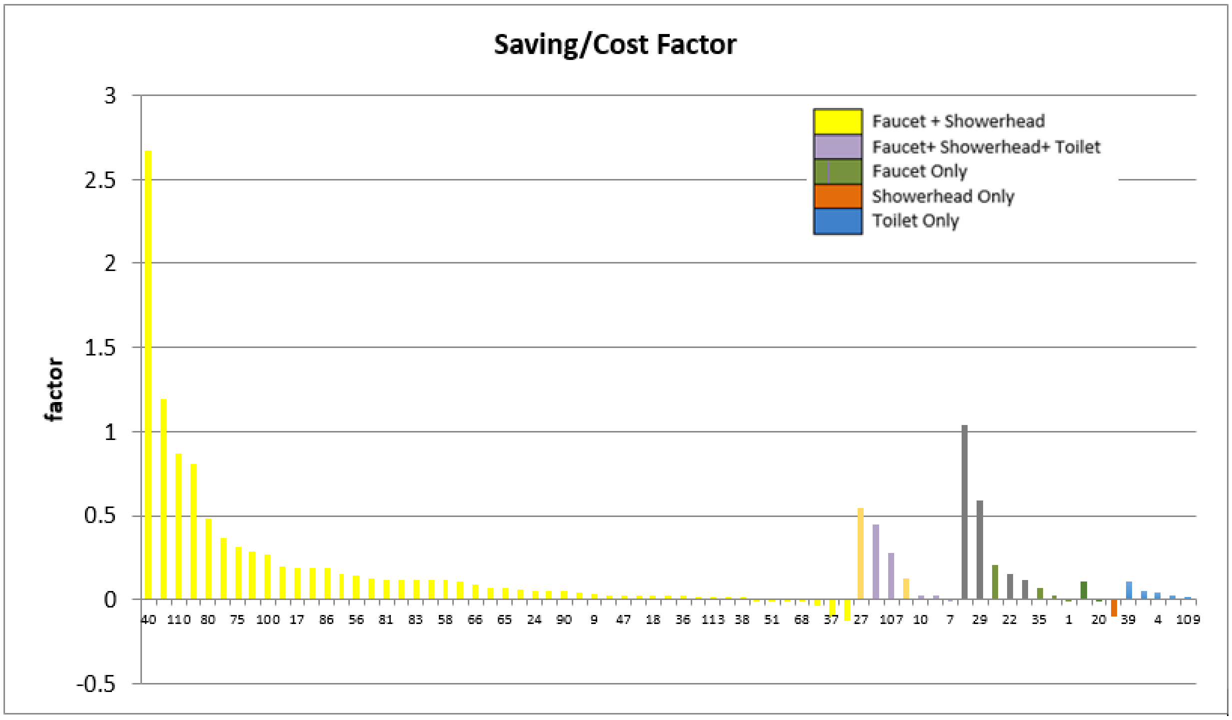


Figure 6-14: Savings over cost factor (gallons / retrofit cost)

7 SUMMARY & RECOMMENDATIONS

One of the demands of ARRA funding was that projects be "shovel-ready." PHFA's commitment to the preservation and improvement of multifamily affordable housing *prior to* the 2008-2009 recession allowed the Agency to move quickly with their Preservation through Smart Rehab program to secure and allocate $22.5 million in ARRA funds. These monies were used to conduct energy audits and implement energy, water and safety upgrades in 8,288 Pennsylvania multifamily affordable housing units between 2010 and 2012.

Although DOE authorized up to $6,000 per housing unit with ARRA-funded weatherization, PHFA spent an average of only $2,188 of WAP funds per unit for hard and soft costs. For energy-related hard costs only, the average WAP funding was $2,548 per unit. Even with the use of additional monies to support recommended upgrades, the average total spending per unit was only $3,094. Modest spending allowed a large number of units to be upgraded (7,439 units in this dataset) and resulted in substantial energy and water savings in the first post-retrofit year. The average reduction in EUI in the first post-retrofit year was 8.21 kBTU/ft2 per year. The average percent savings in EUI per property was 12.34%.

The EUIs for the multifamily properties in the PHFA dataset appear to compare favorably with those of other datasets, both pre- and post-retrofit. However, there is a remarkable lack of consistency in metered and modeled energy use intensity for multifamily housing in the US. These inconsistencies make it difficult to evaluate building energy performance. Ongoing analysis of the PHFA dataset and other multifamily and multifamily affordable property datasets will benefit national understanding of effective energy performance in such properties.

The strongest statistical results associated with a single upgrade measure in this dataset are those for heat pump upgrades. Properties that installed or upgraded existing heat pumps achieved above-average percent savings in EUI (17%) and realized a larger savings in electricity per month for eleven of the twelve pre-retrofit months than all other properties. These properties also had much lower average electricity EUIs in summer months than those in all other properties.

For the properties that implemented water upgrades, the average savings in water consumption was 55.5 gallons per bedroom per day for a 16% savings. The annual water savings among these properties is approximately 135 million gallons of water per year. The analysis indicated that the faucet + showerhead + toilets replacement resulted in the greatest water use reduction (median savings of 36%), but this measure was only implemented in properties that had pre-retrofit water consumption in excess of 80 gallons per bedroom per day. Both the energy and water savings in these properties will continue to benefit multifamily tenants, property owners and the environment.

PHFA commented that upgrade hard costs were often much higher than the auditors estimated. CMU's analysis of the savings-to-investment ratios (SIRS) predicted for water upgrades showed that only two estimates were within 50% of the actual first-year SIR. The average percentage difference between the estimated SIR and actual SIR was -97.8% with a standard deviation of 115.4%.

Weather normalization allows a building's annual energy consumption to be compared over time by adjusting for changes in weather from year to year. Three weather normalization models were tested for this study and all 91 properties in the dataset were modeled with each method. When the average EUI percent savings was summed for each method, the total for the dataset was within roughly 1% of the results for the other two methods and for non-weather normalized data. However, the differences from property to property with each method could be large. If the weather normalization model is working properly, the size of the differences in weather normalization results across properties may indicate which properties would particularly benefit from weather-related upgrades such as insulation and air sealing.

The Preservation through Smart Rehab program was ambitious and is producing a rich and valuable dataset that will augment our national understanding of multifamily affordable housing characteristics and performance.

Preliminary recommendations based on this analysis include:

a) Consider standardizing the format for building audits. This might include the creation of a tablet-based audit form. This should increase the uniformity and consistency of building audits and would help to ensure that key information is not omitted. If the data fields in the audit form are linked to a central database, data entry and storage would be streamlined tremendously. The electronic format could potentially be linked to an audit report template so that a report could be generated more quickly and easily after an audit. A PHFA audit program manager CMU interviewed commented that a "fill-in-the-blanks" audit report might distract an auditor from important visual inspection. CMU anticipates that a well-designed tablet-based form could prompt the auditor for information without creating an overly-rigid audit process.

b) Consider establishing quality control procedures for building audit models and guidelines for estimating project costs. CMU understands the complexity of these activities. However, in two of the three models CMU received for review, there were errors. The largest of these was the omission of windows from the building model, which substantially alters estimated energy use. The other was a substantial under-estimation of the upgrade cost. Had the actual cost been input, the SIR would not have been acceptable. Some additional level of QC may improve the correlation between predicted energy or water savings and cost.

c) Consider supporting ongoing training of multifamily property auditors. The audit program manager CMU interviewed emphasized how variable multifamily properties can be with respect to their age, size, construction and equipment and how diverse a skill set is needed to conduct such audits effectively. Ensure that both auditors and upgrade contractors have a demonstrated track record of successful weatherization work.

d) Consider using weather normalization modeling to identify properties in which energy use is strongly influenced by weather differences from year to year. This may be a time- and cost-effective method to guide the selection of building upgrades. Newer models such as those used in this analysis could be developed further.

e) Consider implementing methods to standardize upgrade costs and/or reward weatherization contractors who provide high-quality, cost-effective work.

f) Consider using GIS to identify areas within the state that may need more focused efforts for multifamily upgrades. The maps of the locations of properties in this dataset show that many areas of the state were untouched by the ARRA-funded Preservation through Smart Rehab program.

g) Consider identifying high-EUI properties for which tenants pay utilities and work with owners/provide incentives to implement energy and water upgrades in these properties so that more low-income tenants can also benefit from efficiency upgrades. For the majority of the properties in this dataset (68%), the owner pays all the utility bills.

h) Consider reaching out to other stakeholders—DOE, utilities, multifamily property owners and developers, data management firms and others—to discuss improvements in collecting and aggregating utility data in multifamily affordable housing. In addition, investigate opportunities and funding for installing sub-meters and real-time feedback devices for occupants, and eliminate the use of master-metering as an energy "upgrade." Sub-metering would allow the impact of specific upgrade measures to be evaluated more effectively and real-time metering feedback devices may allow PHFA and similar organizations to achieve even greater savings through occupant feedback. Master-metering lowers utility costs but eliminates important detail about energy consumption by housing unit.

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APPENDIX A: CHANGE POINT MODEL WEATHER NORMALIZATION

This text is excerpted from the Energy Explorer Users' Guide.

3P Model Algorithm

Energy Explorer constructs three parameter change-point models using a search routine combined with an indicator variable regression technique. The form of the regression equation is:

$$y = a + b\,(I\,(x - xcp))$$

where y is the dependent variable, x is the independent variable, a and b are parameters determined by regression, I is an indicator variable and xcp is the x change-point. I is set to 0 or 1 according to the following rule:

For 3P-CP-C: I = 0 when x <= xcp

I = 1 when x > xcp

For 3P-CP-H: I = 1 when x <= xcp

I = 0 when x > xcp

To identify the x change-point, Energy Explorer utilizes a two-pass search routine. On the first pass it divides the entire x interval (xmax - xmin) into ten equal sub-intervals. It then sets each sub-interval boundary equal to x change-point, performs the above regression, and stores the x change-point value and sum of squared error for the regression. Energy Explorer then selects the x change-point value that yielded the lowest sum of squared error as the best x change-point on the first pass.

On the second pass, Energy Explorer divides an interval from one sub-interval to the left and one sub-interval to the right of the best x change-point into ten new sub-intervals. In the case that the best x change-point value lies at one of the end points of the original x interval, only the adjacent sub-interval is re-divided into ten new sub-intervals. The search is then repeated as before and Energy Explorer selects the x change-point that yielded the lowest sum of squared error.

Energy Explorer reports the standard error of the y change-point as the standard error of the parameter and the standard error of the slope as the standard error of the parameter b. The standard error of the x-coordinate of the change point is reported as the width of the smallest x-interval in the search procedure to locate the best-fit model.

5P Model Algorithm

The five parameter change-point model algorithm is similar to the three and four parameter change-point model algorithms. The regression equation is:

$$Y = b1 + b2\,(X – Xcp1)\,I1 + b3\,(X – Xcp2)\,I2$$

where Y is the dependent variable, X is the independent variable, b1, is y intercept of the slope, b2 is the left slope, b3 is the right slope, I1 and I2 are indicator variables and Xcp1 and Xcp2 are the left and right change points respectively. I1 and I2 are set to 0 or 1 according to the following rules:

$$I1 = 1 \text{ when } X \leq Xcp1$$

$$I1 = 0 \text{ when } X > Xcp1$$

$$I2 = 0 \text{ when } X \leq Xcp2$$

$$I2 = 1 \text{ when } X > Xcp2$$

To identify the x change-points, Energy Explorer utilizes a two-pass search routine. On the first pass it divides the entire x interval (X max - X min) into ten equal sub-intervals. It then finds all possible combinations of Xcp1 and Xcp2 subject to the constraints that change points are interval boundaries and Xcp2 > Xcp1. Next Energy Explorer performs the above regression for each possible combination of change points, and stores the x change-point values and sum of squared error for each regression. Energy Explorer selects the x change-point values that yielded the lowest sum of squared error as the best x change-points on the first pass.

On the second pass, Energy Explorer divides an interval from one sub-interval to the left and one sub-interval to the right of the best Xcp1 and Xcp2 change-points into ten new sub-intervals for each change point. It then finds all possible combinations of Xcp1 and Xcp2 change points subject to the constraint that Xcp2 > Xcp1. Regressions are performed as before and Energy Explorer selects the x change-points that yielded the lowest sum of squared error.

The regression equation above reduces to:

$$Y = b1 + b2\,(X - Xcp1) \text{ when } X \leq Xcp1$$

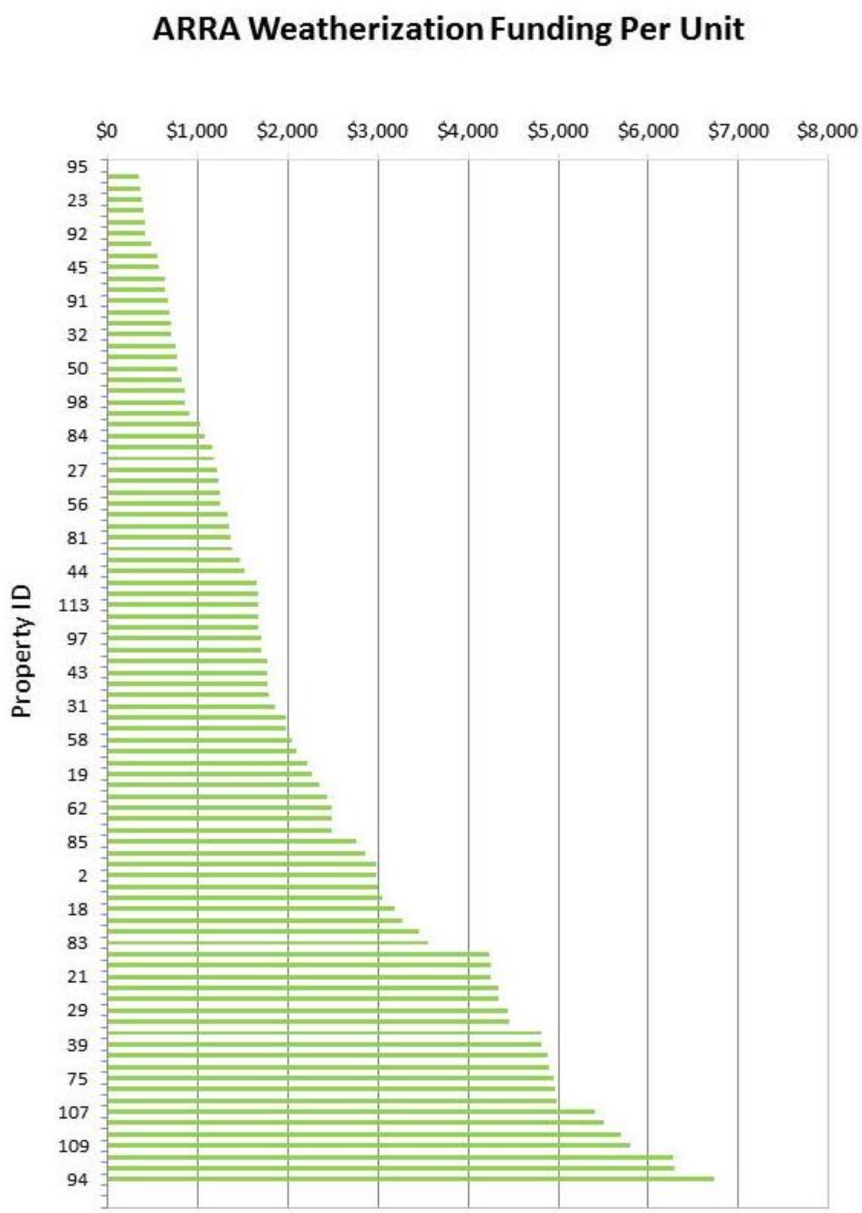
$$Y = b1 \text{ when } X > Xcp1 \text{ and } X \leq Xcp2$$

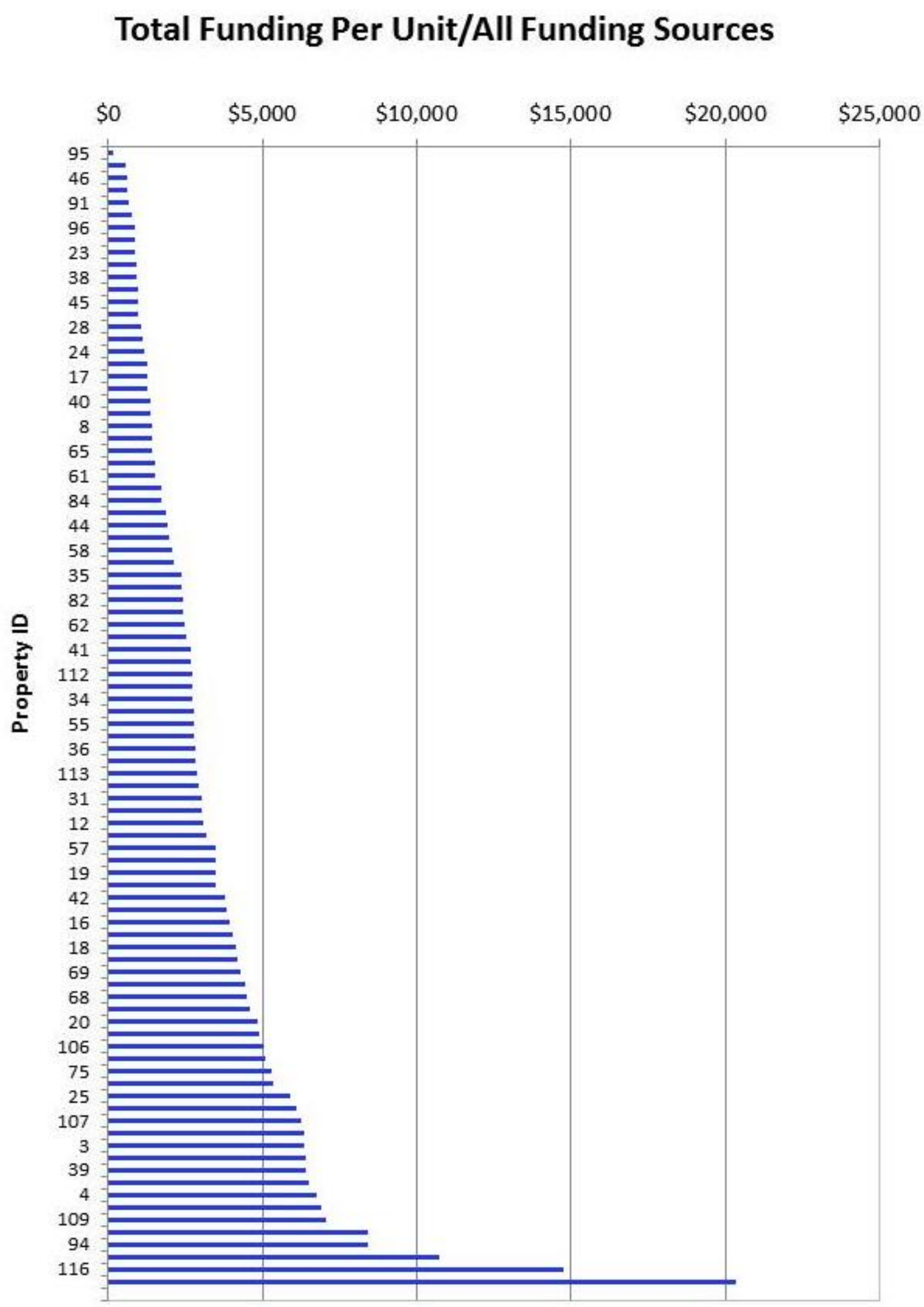
$$Y = b1 + b3\,(X - Xcp2) \text{ when } X > Xcp2$$

Energy Explorer reports the standard error of the y change-point as the standard error of the parameter b1, the standard error of the left slope as the standard error of the parameter b2 , the standard error of the right slope as the standard error of the parameter b23 and the standard errors of the x-coordinates of the change points as the width of the smallest x-interval in the search procedure.

APPENDIX B: WEATHERIZATION FUNDING PER UNIT AND TOTAL FUNDING PER UNIT (HARD AND SOFT COSTS)

The graphs below show the range in the funding per unit, with weatherization funds only and all sources of funding. Weatherization funding per unit ranged from $16 to $6,729 per unit. The per-unit funding from all sources ranged from $157 to $ $20,367.




Total Funding Per Unit/All Funding Sources
$0
$5,000
$10,000
$15,000
$20,000
$25,000
Property ID
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96
23
38
45
28
24
17
40
8
65
61
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44
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