Performance Results for Massachusetts and Rhode Island Deep Energy Retrofit Pilot Community

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Definitions

ACH	Air changes per hour
ACH50	Air changes per hour at 50 Pascal test pressure
AFUE	Annual fuel utilization efficiency
ASHP	Air source heat pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	Building America Program
BSC	Building Science Corporation
Btu	British thermal unit
CDD	Cooling degree day
CFM50	Cubic feet per minute at 50 Pascal test pressure
DER	Deep energy retrofit
DHW	Domestic hot water or service hot water
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
ERV	Energy recovery ventilator
EUI	Energy use intensity
ft^2	Square foot, square feet
GSHP	Ground source heat pump
HDD	Heating degree day
HRV	Heat recovery ventilator
kBtu	Thousand British thermal units
kWh	Kilowatt-hour
MMBtu	Million British thermal units
OSB	Oriented strand board
RECS	Residential Energy Consumption Survey
SPF	Spray polyurethane foam (insulation)
TMY3	Typical Meteorological Year 3

Executive Summary

Between December of 2009 and December of 2012, participants in a deep energy retrofit (DER) pilot program sponsored by National Grid and conducted in Massachusetts and Rhode Island completed 42 DER projects. Building Science Corporation (BSC) provided technical support to program participants and verification of measures for the program sponsor, National Grid. The pilot program required aggressive upgrades to building enclosure systems, implementation of ventilation and combustion safety measures, and also provided incentives to upgrade mechanical systems. Thirty-seven of the projects completed through the pilot were comprehensive retrofits while five were partial DERs, meaning that high performance retrofit was implemented for a single major enclosure component or a limited number of major enclosure components. The collection of 42 DER projects represents 60 units of housing.

Pre- and post-retrofit air leakage measurements were performed for each of the projects. Each project also reported information about project costs including identification of energy-related costs. Pilot program application forms collected pre-retrofit energy use data for 35 of the projects. BSC used energy modeling to estimate pre-retrofit energy use for seven projects for which measured data were not available. Post-retrofit energy-use data were obtained for 29 of the DER projects. Post-retrofit energy use was analyzed based on the net energy used by the DER project regardless of whether the energy was generated on site or delivered to the site. Homeowner surveys were returned by 12 of the pilot participants.

Post-retrofit energy use data are analyzed with the objective of learning what post-retrofit energy performance one can expect from implementation of the retrofit package. In other words, the focus of the study was to project where a DER project will “end up” rather than to project the savings that any one project might realize.

All but two of the comprehensive DER projects achieved household source energy use below the Energy Information Administration Northeast regional household average. The mean for the group is 107.2 MMBtu/year, or approximately 38% below the regional household average. In terms of site energy use intensity (EUI), all of the projects perform below the regional average, with the mean values for both the multifamily and single-family DER projects below 50% of the respective Northeast region average. Two of the multifamily projects and three of the single-family projects meet the 2015 site EUI goal for the Architecture 2030 Challenge (Architecture 2030 2006) without taking any credit for on-site electricity generation.

Based on the experience of this sample of DER projects, this DER package is expected to result in yearly source energy use on the order of 110 MMBtu/year for a typical home. This is approximately 40% below the Northeast regional average for household energy use. Larger and medium-sized homes that successfully implement these retrofits can be expected to achieve source EUI that is comparable to Passive House program targets for new construction.

All full DER projects achieved better than 50% reduction in total CFM50; all partial DER projects achieved better than 40% reduction in total CFM50. More than half of the full DER projects achieved post-retrofit ACH 50 results below 1.5 ACH50. Some variations in airtightness performance are noted to accompany variations in DER implementation approach. For example, the group of DER projects that included the basement in the air control enclosure had a better overall airtightness result than the group that excluded the basement (i.e., insulation and air control at basement ceiling). Also, the group of DER projects with unvented attics had a better overall airtightness result than the group with vented attics.

In this group of DER projects, the reported energy-related portion of project costs ranged from slightly more than \$31,500 to approximately \$194,350. The reported energy-related costs averaged \$34.59/ft^2 (post-retrofit conditioned floor area) for the sample of DER projects. Noted variations in heating, ventilation, and air conditioning measure costs appear to relate to homeowner preferences, and do not appear to be correlated with a noticeable difference in performance (with the possible exception of one project that installed a ground source heat pump).

Projects in this group of DER projects implemented three different approaches for attic/roof retrofit. The reported energy-related cost for a vented attic approach with insulation at the attic floor averaged \$8.40/ft^2. The unvented attic approach with rafter cavity insulation averaged only \$11.59/ft^2. The unvented attic with insulation both exterior to the roof sheathing and between roof framing averaged \$14.21/ft^2. Excluding some noted outliers, the reported energy-related cost for the most typical wall retrofit approach ranged from \$4.67/ft^2 to \$19.15/ft^2 with an average of \$10.51/ft^2.

1 Introduction

The U.S. housing stock accounts for a significant portion of national energy usage. The volume of existing housing (approximately 130 million housing units) relative to the rate of housing unit construction (between approximately 500,000 and 2 million per year in recent years) makes energy performance retrofit absolutely essential to goals of reducing the energy use of the residential sector.

Home retrofits have been targeted as an area of great potential for significant energy savings, employment opportunities, and market growth. Typical residential retrofit activity aims at mitigating performance liabilities of existing housing (NJIT 2013). High performance retrofit techniques are aimed at improving the performance of existing building components or whole buildings to equal or surpass current high performance new construction practices.

Barriers to widespread adoption of high performance retrofit strategies remain high. Knowledge, skill, and even availability of building products represent persistent supply-side barriers to high performance retrofit. Vigorous market demand for high performance retrofit would provide the impetus for these barriers to fall. Two factors that constrain the market demand for high performance retrofit are: (1) the lack of confidence in or a lack of appreciation for the benefits of high performance retrofit; and (2) perceptions relative to the high cost of a comprehensive energy retrofit.

Some in the industry have asserted that better modeling tools and methods are needed to predict savings resulting from retrofit measures.[1] Clearly, a large body of evidence from actual retrofit projects is also needed to demonstrate the benefits and reveal the costs.

This project reports the measured energy performance, airtightness and costs for 42 high performance residential retrofit projects. The projects are all participants in a National Grid-sponsored deep energy retrofit (DER) pilot program. The projects implemented a consistent package of measures according to the requirements of this pilot program. Variations in the method of implementing measures as well as variations permitted in the overall package provide opportunities to investigate apparent impacts of these variations.

The evaluation of retrofit performance focuses on the level of performance (in terms of energy use and airtightness) achieved rather than on reductions relative to pre-retrofit conditions. In other words, the analysis aspires to provide an idea of where a DER project implementing a similar package of measures is likely to “end up,” in terms of energy performance and airtightness. This is afforded by the comprehensive nature of the retrofits and by the measured post-retrofit performance. This approach sidesteps the complication of characterizing the pre-retrofit existing conditions. *Relative* savings projections are hugely dependent upon accurate characterization of existing conditions. Existing conditions in residential buildings are hugely variable and difficult to define for a project that is not known. By seeking to identify and describe a relatively consistent level of performance achieved through a package of measures, the project is able to project the results of high performance retrofit in a way that is much more stable and more widely applicable than savings projections. In other words, an understanding of the level of performance attained

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[1] McIlvaine, et al. 2013 and Neymark and Roberts as discussed in Aspen Publishing 2013.

through application of a package of measures allows one to project the *savings* achieved for a particular home with better certainty. One has only to compare the measured performance (or history) of the home in it its pre-retrofit state to the expected performance. Quantifying savings achieved for a package of retrofit measures is of limited value, as the savings would be repeatable only for homes that not only implement the same package of measures, but also have a similar pre-retrofit situation.

As participants in the DER pilot program, these retrofit projects all used the same set of enclosure performance targets, taken here as a “package of measures.” This report assesses the effectiveness of the overall package of measures as well as the relationship between different implementation strategies used and measures of performance. This is accomplished by analyzing the full set of performance data for the group rather than looking at individual case studies. This approach results in post-retrofit energy use and cost ranges based on the total community data that can be reasonably projected to other implementations of the DER package. The resulting energy use and airtightness projections as well as cost ranges constitute concrete evidence that can be used by homeowners to assess the potential benefit and cost of a DER.

This study does not include an analysis of retrofit package and measure costs relative to various effects sought from the measures. An analysis of cost and effect for some of the early completed projects in this pilot is included in a previous study (Gates and Neuhauser 2013). This earlier study found that non-energy benefits were either primary or significant motivations for a substantial portion of DER project expenditures. This finding highlights the importance of defining the “effect” whenever “cost effectiveness” is evaluated or discussed. The study also points to the need to acknowledge and value the range of desired effects obtained through a measure.

While the relative site energy savings from pre-retrofit to post-retrofit conditions ranges widely for this project—from 28% to 90%—the level of energy performance achieved is much more consistent. For the 27 comprehensive retrofit projects for which sufficient post-retrofit energy use data are available, the median and mean post-retrofit annual site energy use per household is slightly less than 50% of the regional average. The measured site energy use is within 20% of the mean for slightly fewer than half of the projects.

The results of the pilot demonstrate that a relatively consistent level of performance can be achieved. But perhaps more importantly, the results demonstrate that the DER retrofits can meet energy performance goals and benchmarks representative of best-in-class new home construction.

2 Background

2.1 New Construction, Retrofits, and DERs

There are a substantial number of existing homes in the United States. The U.S. Census Bureau estimates that there were more than 130 million housing units in the United States in 2011 (U.S. Census Bureau 2013). This compares to typical new home construction rate of between approximately 500,000 and 2 million per year. In the years between 2007 and 2011, the construction industry added 3.1 million homes. The rate of new home construction relative to existing housing stock tells us that the majority of houses are likely to remain more than three decades old for some time to come. The rate also indicates that even super-efficient new construction will have a very limited impact on the overall energy use of the housing sector.

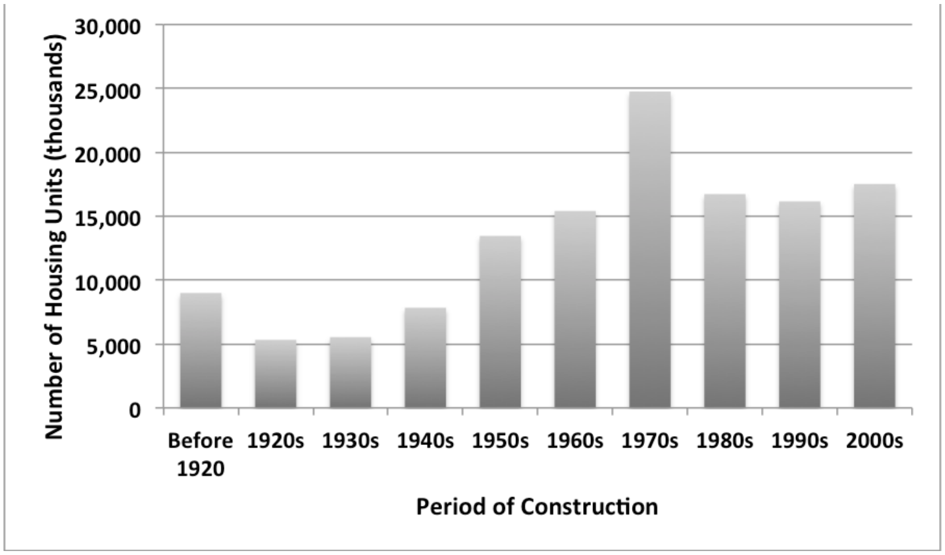

Figure 1. U.S. housing units by decade of construction

(U.S. Census Bureau, Annual Housing Survey data)

Until recent years, the primary focus of the Building America (BA) program has been research and development of techniques for new construction. The near-term goal of the BA program for new construction homes is to reduce energy use in new construction homes by 30% relative to a baseline established by the 2009 International Residential Code (Bianci 2011). The program has already succeeded in demonstrating performance packages achieving savings of 30%–50% relative to the baseline. Despite the impressive level of savings demonstrated for these packages, the new home packages represent a modest potential impact on national energy use due to the small percentage of new homes added to the aggregate national housing stock every year.

Retrofit packages can be applied to a substantially greater portion of the U.S. housing stock than to new construction packages. The BA program near-term goal for the existing homes is to reduce energy consumption by 30% relative to the *current condition* of the existing home. For many existing homes, a 30% reduction in energy consumption will not be enough to elevate the performance to a level comparable to current standard practice (as defined by 2009 International Residential Code, for example). But at current rates of construction/replacement, it will take an extremely long time to replace the current housing stock with housing built to modern performance standards. Even if rapid replacement were possible, retiring and replacing a significant portion of existing housing with high performance housing is not a reasonable proposition. Doing so would represent an unreasonable displacement and disruption of population, abandonment of physical and cultural resources embodied in existing buildings, and astronomical financial cost.

Obviously, reducing—by any significant measure—the energy use of the residential sector will require retrofitting existing housing. The DER pilot sponsored by National Grid provides an opportunity to assess whether a repeatable advanced retrofit package can elevate performance beyond that of typical new construction. The pilot also allows evaluation of the cost of achieving this level of performance through retrofit.

2.2 Previous Work

The BA program has been working to overcome the obstacles associated with DERs. There are several other BA teams evaluating the performance effectiveness of cold climate home retrofit approaches at the community scale. They include the Consortium for Advanced Residential Buildings' role in the Retrofit NYC Block by Block project (Eisenberg et al. 2012) and in the recently completed retrofit of the Chamberlain Heights duplex and quad affordable housing complex (Donnelly and Mahle 2012) as well as the Partnership for Advanced Residential Retrofits team's work in the Chicagoland project development of energy efficiency retrofit packages for typical houses in the Chicago area (Spanier et al. 2012).

These research projects have the potential to provide a significant set of post-retrofit performance data using utility bills and other testing to evaluate the energy use level achieved (and achievable) by fairly comprehensive retrofit measure packages. However, the current reports have only limited results available (if any), and most results are presented in terms of software models rather than actual performance data. In this current research project, Building Science Corporation (BSC) is making use of a year of post-retrofit utility bills and performance data for retrofit projects. BSC then uses this actual performance information to project achievable performance levels for the DER retrofit measure package.

The Consortium for Advanced Residential Buildings and Partnership for Advanced Residential Retrofits research projects adopt the approach of tailoring retrofit measure packages to particular house types—e.g., ranch house, NYC row house, or triple-decker. In contrast, BSC has found that each retrofit project has its own set of unique constraints that are based not so much on house type and age as on its history and existing conditions. Therefore, tailoring retrofit measure packages to specific house types may not be necessary. In the results described in the current report, a single DER measure package has been applied to a variety of housing types, as well as across significantly different ages and existing conditions.

Other previous work related to high performance retrofit has focused on individual components or measures. For example, in one recent BA project, BSC worked with a weatherization program to evaluate and develop plans for inclusion of roof or attic insulation in the weatherization program (Neuhauser 2012). The current study evaluates the impact of a comprehensive measure package.

2.3 Building Science Corporation and the National Grid DER Pilot Program

BSC has conducted several research projects using information, data, and experiences from retrofit projects participating in the National Grid DER pilot program. In one project, BSC performed a case-by-case evaluation of the implementation of the DER measures for five of the DER pilot program participants (Neuhauser 2011). In a second project, BSC looked at the pre- and post-retrofit performance data for seven DER projects, four of which were early participants in the DER pilot program (Osser et al. 2012).

The thrust of these earlier research projects dealt with the individual projects—either in terms of how the DER measures were implemented or the post-retrofit performance that each one achieved. None of them compared and analyzed the performance data as a group. Now that additional projects have been completed in the National Grid DER pilot program, there are enough data available to warrant the analysis of all of these projects as a community of retrofits rather than as individual cases. The number of completed projects is large enough that the impact of the retrofit measures as a package can be analyzed, and trends from the available data about these projects begin to emerge. Using this approach, the emphasis is shifted from the post-retrofit performance for the individual case to the post-retrofit performance achievable by using the DER package.

As the designated technical support provider to the National Grid DER pilot program since its inception in 2009, BSC has had the opportunity to learn from more than 40 residential DER projects. BSC, in its role as the technical support team, provided technical review of project plans for all projects participating in the pilot program, and conducted in-field review and verification of measures for most of the projects. BSC also contributed to pilot program design and implementation. A significant portion of BSC's involvement with the National Grid DER pilot program was supported through the BA program.

Four DER projects were completed through the pilot program in 2010. Eleven DER projects reached completion in 2011. By the close of the pilot program in December 2012, 42 projects had been successfully implemented through the program.

The individual projects participating in the pilot program have adhered to a common basic outline of target building enclosure performance. Project teams devised a variety of approaches to meet these targets. Particular conditions and configurations of the existing buildings resulted in a variety of implemented methods and ways of addressing challenges.

Under a previous task order, BSC produced a review of methods employed and challenges faced by the early program participants (Neuhauser 2011). Also under a previous task order, BSC analyzed performance data for a sample of homes for which the DER project was completed or substantially completed prior to the last year of the program (Gates and Neuhauser 2013).

Now, with 42 DER projects representing approximately 60 dwelling units complete at the December 2012 close of the pilot, BSC has seized upon a unique opportunity to analyze performance data for a large population of DER projects. Studying this population of DER projects also reveals successful approaches for common retrofit challenges.

3 National Grid Deep Energy Retrofit Pilot Program

The National Grid DER pilot program was launched in 2009 with the goal of demonstrating advanced comprehensive retrofit and evaluating the viability of such retrofits as the target of a large-scale energy efficiency program. The performance aspiration in the pilot was to achieve 50% energy reductions compared to a typical home in the region (National Grid 2009).

In order to protect the interests of its customers National Grid insisted that energy efficiency measures implemented through the program would also support building durability and indoor environmental quality. National Grid partnered with BSC as a technical support team to help ensure that the measures supported through the program are effective and that "The project plan and implementation… demonstrate sound building physics as it relates to moisture management of the enclosure and effectiveness of the mechanical system configuration" (National Grid 2011).

The program offers significant financial incentives. Incentives are intended to offset a portion of net incremental costs specifically related to energy performance measures. Base incentive limits for one- and two-family dwellings are indexed to conditioned floor area of the building and range from $35,000 to $42,000 for detached single-family residences and $50,000 to $60,000 for duplexes. The incentive offered to multifamily buildings of three units or more varies according to the number of units in the building. The base incentive for the three-family building is $72,000 and for a building with 10 or more units, the base program incentive is $106,000.

The program was open to residential ratepayers and building owners within National Grid's Massachusetts and, later, Rhode Island service territory. Projects were accepted into the pilot program after successfully completing an in-depth application and review process.

3.1 Measures and Targets

The DER homes included in this report are all of those that successfully completed the National Grid DER pilot program.[2] Participants in the DER pilot program are required to meet:

- Health, safety, and indoor air quality guidelines
- Specific thermal targets for each enclosure component (e.g., roof, above-grade walls)
- An overall airtightness target
- Minimum efficiency of mechanical equipment
- Water management and durability requirements.

While there are not specific instructions for how these targets are to be met, all implementation plans are reviewed for sound building science before the project is accepted into the pilot program. After the review, field verification of each completed measure is required in order to receive the financial incentives. In addition, all project teams must include a qualified contractor or design consultant with previous DER experience and approval by National Grid.

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[2] Analysis of post-retrofit energy performance is limited to those projects that were also occupied by January 2013 and for which sufficient post-retrofit energy use data were made available to BSC.

Implementation of a DER will change the behavior of existing building systems, including effects of airtightness and reduced heat flow through assemblies. The measures shown in Table 1 include some essential prerequisites put in place to address possible ramifications of those changes.

Table 1. Overall Measures and Targets or Requirements for National Grid DER Pilot Retrofit

Measure	Target or Requirement for Measure	Project Implications and Practices Followed
Combustion Safety	**Requirement**: No atmospherically vented combustion appliances or fireplaces	Projects used direct vent, closed combustion, or power-vented mechanical equipment
Indoor Air Quality	**Requirement**: Meet ASHRAE 62.2 ventilation requirements	Provide background ventilation system with sufficient capacity and easily accessible controls that allow residents to adjust the ventilation rate according to occupant needs.
Durability	**Requirement**: Robust water management and vapor control required of the retrofit enclosure system	Use appropriate flashings (including step and kickout flashings); integrate flashings effectively into the water control layer; ensure that vapor control methods do not trap moisture within building components
Air Infiltration Control	**Target**: CFM50 $\leq$ 0.10 * total 6-side enclosure surface area (ft^2)	Identify the air control layer for each enclosure component and indicate how the air control function is transitioned between components
Appliances and Lighting	**Target**: ENERGY STAR® appliances; 90% of lighting to be compact fluorescent or better	Incentives and provision of energy-efficient lighting facilitated by National Grid

The enclosure targets, shown in Table 2, are given for each enclosure component and are in terms of the installed R-value of insulation; the targets are consistent with Straube (2011).

Table 2. Enclosure Insulation Measures and Targets for National Grid DER Pilot Retrofit

Measure	Target for Measure	Comments
Roof	R-60+	For unvented attics
Attic	R-60+	For a vented attics
Above-Grade Exterior Walls	R-40+	
Insulated Foundation Walls	R-20+	For walls that are below or partially below grade
Insulated Basement Floor	R-10+	
Basement Ceiling	R-30+	Applies only if the basement is not included in the thermal enclosure
Floor Over Unheated Garage or Overhang	R-40+	
Windows and Doors	R-5+	

This set of enclosure measures allows the project to choose between a vented or unvented attic, and between insulated basement walls or an insulated basement ceiling. In addition, some projects were unable to provide insulation to the basement floor because of head height or structural constraints. This type of flexibility of measures is necessary when working with retrofits, as existing conditions may preclude certain approaches.

The heating, ventilation, and air conditioning (HVAC) measures are shown in Table 3.

Table 3. HVAC Measures and Targets for National Grid DER Pilot Retrofit

Measure	Target for Measure	Comments
Mechanical Ventilation	Heat recovery, balanced, distributed	HRV[a], ERV[b], exhaust only, or supply only are acceptable provided ASHRAE 62.2 is met and there is a means of distribution; mechanicals and ductwork to be within the thermal enclosure.
Heating Equipment	High efficiency heating	Furnace, condensing boiler, GSHPs[c] or ASHPs[d]; AFUE[e] 95+%, heating season performance factor 8.2+ equipment rating with configuration or operating sequences to allow efficient operation; mechanicals and ductwork to be within the thermal enclosure.
Cooling Equipment	16 seasonal energy efficiency ratio, 13 energy efficiency ratio	Cooling is not required; air handling equipment and ductwork (if any) to be within the thermal enclosure.

[a] Heat recovery ventilator
[b] Energy recovery ventilator
[c] Ground source heat pump
[d] Air source heat pump
[e] Annual fuel utilization efficiency

3.2 The Community of Retrofits

This report examines the airtightness and construction costs of 42 projects (representing 60 housing units), all of which were participants in the National Grid DER pilot program. Therefore, all of the retrofits used the same DER measure package and targets in their planning; had plans reviewed for sound building science and for durability, combustion safety, and air quality; and received site verification of the DER measures. Of the 42 projects that successfully completed the National Grid DER pilot program, 37 are full DER projects and five are partial DER projects. In the following sections, the results of these projects are reported and analyzed in terms of energy use, airtightness, construction cost, and homeowner satisfaction.

Table 4 and Table 5 provide some basic information about each of the completed retrofit projects that participated in the pilot. The tables also include information about the three enclosure components for which different implementation approaches were followed—roof and attic, above-grade walls, and basement. Additional information about the retrofit projects is provided in Section 4.1, Section 4.2, and Section 4.3.

Table 4. DER Community—37 Comprehensive DERs

House Location	Year Built	Pre-Retrofit Cond. Area (ft^2)	Post-Retrofit Cond. Area (ft^2)	Roof/Attic Measure (Installed R-Value)	Above-Grade Walls Measure (Installed R-Value)	Basement Measure	HVAC and DHW Measures
Belchertown, MA	1760	1,435	1,907	Below roof deck insulation only	Double wall with interior insulation Existing porch roof/deck not detached	Foundation walls and slab insulated	HRV; propane furnace; tankless propane water heater; no air cooling
Belmont, MA (2 units)	1925	3,417	4,768	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls insulated	HRV for each unit; gas furnace and central air conditioner for each unit; solar thermal water heating with electric backup
Millbury, MA	1953	1,868	1,868	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and slab insulated	Supply-only ventilation; mini-split ASHP for heating and cooling w/ two ducted air handlers; direct vent existing wood pellet stove for heating backup; tankless propane water heater
Milton, MA	1960	2,368	2,368	Below roof deck insulation only	Exterior and wall cavity insulation	Foundation walls and slab insulated	HRV; gas water heater with hydronic air handler for heating; central air conditioner
Quincy, MA	1905	3,484	4,567	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; solar thermal integrated with gas water heater for radiant heating and hot water; ASHP for heating and cooling
Arlington, MA (2 units)	1910	2,502	3,627	Below roof deck insulation only	Exterior and cavity insulation Existing porch roof/deck not detached	Basement ceiling insulated	HRV for each unit; condensing gas furnace for each unit; central air conditioner for upper unit; tankless gas water heater for each unit

House Location	Year Built	Pre-Retrofit Cond. Area (ft^2)	Post-Retrofit Cond. Area (ft^2)	Roof/Attic Measure (Installed R-Value)	Above-Grade Walls Measure (Installed R-Value)	Basement Measure	HVAC and DHW Measures
Newton, MA	1930	1,815	2,199	Exterior and below roof deck insulation	Exterior and wall cavity insulation Existing porch roof/deck not detached	Foundation walls and floor slab insulated	ERV; condensing gas boiler for heating and indirect water heating; ASHP for cooling and shoulder season heating
Jamaica Plain-A, MA (3 units)	1907	3,885	3,885	Vented attic with attic floor insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV for each unit; existing gas boiler for heating and indirect water heating; removable window air conditioners
Northampton-A, MA	1859	2,032	2,747	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	ERV; GSHP; mini-split ASHP for upper floor office; ASHP water heater
Lancaster-A, MA	1900	980	1,440	Vented attic with attic floor insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	ERV; two mini-split ASHPs (1 head each); tankless gas water heater
Brookline, MA	1899	3,174	3,174	Previous retrofit phase: below roof deck insulation only to R-48	Exterior and wall cavity insulation	Foundation walls insulated	HRV; gas boiler with indirect water heating; no air cooling
Westford, MA	1993	2,906	3,955	Below roof deck insulation only	Exterior and wall cavity insulation	Foundation walls insulated	ERV; existing gas furnace; central air conditioner; gas water heater
Gloucester, MA	1920	2,171	2,424	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; two mini-split ASHPs (one with 2 heads, the other with 3 heads–2 of which are ducted) with backup electric resistance heat; solar thermal water heating with electric backup

House Location	Year Built	Pre-Retrofit Cond. Area (ft^2)	Post-Retrofit Cond. Area (ft^2)	Roof/Attic Measure (Installed R-Value)	Above-Grade Walls Measure (Installed R-Value)	Basement Measure	HVAC and DHW Measures
Medford, MA (2 units)	1916	3,200	3,200	Vented attic with attic floor insulation	Exterior and wall cavity insulation Existing porch roof/deck not detached	Basement ceiling insulated	HRV for each unit; gas water heater (integrated with solar thermal) for each unit with hydronic air handler; central air conditioner
Northampton-B, MA	1972	1,126	2,209	Vented attic with attic floor insulation	Exterior and wall cavity insulation	Foundation walls insulated	Exhaust only ventilation; gas boiler for heating and indirect water heating; no air cooling
Haverhill, MA (2 units)	1900	1,542	2,542	Exterior and below roof deck insulation non-chainsaw	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV for each unit; mini-split ASHP (1 head) for heating and cooling for each unit; solar thermal water heating with electric backup
Dorchester, MA (3 units)	1880	4,200	4,200	Vented attic with attic floor insulation and roof with insulation below roof deck	Exterior and wall cavity insulation Existing porch roof/deck not detached	Basement ceiling insulated	ERV for each unit; gas furnace and central air conditioner for each unit; tankless gas water heater for each unit
Rutland, MA	1977	1,415	2,720	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; propane boiler for heating and indirect water heating; no air cooling
Methuen, MA	1940	767	1,528	Vented attic with attic floor insulation	Exterior and wall cavity insulation	Foundation walls insulated	HRV; mini-split ASHP (3 heads) for heating and cooling; solar thermal water heating with electric backup
Wakefield, RI	1979	2,200	2,873	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; existing propane boiler for heating; ASHP water heater; 2 existing mini-split air conditioners

House Location	Year Built	Pre-Retrofit Cond. Area (ft^2)	Post-Retrofit Cond. Area (ft^2)	Roof/Attic Measure (Installed R-Value)	Above-Grade Walls Measure (Installed R-Value)	Basement Measure	HVAC and DHW Measures
Groton, MA	1961	2,222	3,547	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; gas boiler for heating and indirect water heating; removable window air conditioner
Williamstown, MA	1940	759	1,827	Vented attic with attic floor insulation	Exterior and wall cavity insulation Existing deck and porch roof not detached	Foundation walls and floor slab insulated	HRV; gas boiler for heating and indirect water heating; no air cooling
North Kingstown, RI (2 units)	1962	3,520	3,520	Below roof deck insulation only	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV for each unit; mini-split ASHP (2 heads) for heating and cooling for each unit; tankless gas water heater for each unit
Cohasset, MA	1983	2,050	4,380	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; propane furnace for heating; central air conditioner; propane water heater
Sudbury, MA	1960	1,670	3,054	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; gas boiler for heating and indirect water heating; mini-split air conditioner (4 heads)
Worcester, MA (3 units)	1890	2,100	2,240	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV for each unit; mini-split ASHP (1 head) for heating and cooling for each unit; tankless gas water heater for each unit
Northampton-C, MA	1900	1,284	2,201	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls insulated	HRV; existing gas boiler for heating and indirect water heating; no air cooling
Warwick, MA	1979	1,196	2,033	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; mini-split ASHP (1 head) for heating and cooling; solar thermal water heating with electric backup (also provides backup heating)

House Location	Year Built	Pre-Retrofit Cond. Area (ft^2)	Post-Retrofit Cond. Area (ft^2)	Roof/Attic Measure (Installed R-Value)	Above-Grade Walls Measure (Installed R-Value)	Basement Measure	HVAC and DHW Measures
Lexington, MA	1946	1,979	2,791	Below roof deck insulation only	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; gas furnace; no air cooling; gas water heater
Melrose, MA	1945	2,150	2,706	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; mini-split ASHP (2 heads) for heating and cooling; ASHP water heater
Providence-A, RI (3 units)	1915	4,449	4,449	Below roof deck insulation only	Exterior and wall cavity insulation	Basement ceiling insulated	HRV per unit; gas boiler per unit and indirect water heating; electric resistance heating in common areas; through wall air conditioners
Roslindale, MA	1865	2,165	2,685	Exterior and below roof deck insulation partial chainsaw	Exterior and wall cavity insulation	Foundation walls insulated	HRV; existing gas boiler plus electric resistant heating in bath; solar thermal water heating with existing gas water heater backup
Lowell, MA	1924	1,336	2,501	Exterior insulation partial chainsaw	Exterior and wall cavity insulation	Foundation walls and part of floor slab insulated	HRV; existing gas boiler with radiant heat and indirect water heating; no air cooling
Waltham, MA	1960	1,240	2,010	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	HRV; gas furnace; tankless gas water heater; central air conditioner
Northampton-D, MA (2 units)	1900	4,784	4,784	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	Unit 1: ERV; mini-split ASHP (1 head) for heating and cooling; electric water heater. Unit 2: 2 ERVs; mini-split ASHP (3 heads) for heating and cooling; electric water heater

House Location	Year Built	Pre-Retrofit Cond. Area (ft^2)	Post-Retrofit Cond. Area (ft^2)	Roof/Attic Measure (Installed R-Value)	Above-Grade Walls Measure (Installed R-Value)	Basement Measure	HVAC and DHW Measures
Lancaster-B, MA (2 units)	1986	3,172	3,792	Exterior and below roof deck insulation	Exterior and wall cavity insulation	Foundation walls and floor slab insulated	Unit 1: 2 HRVs; two mini-split ASHPs for heating and cooling; tankless propane water heater. Unit 2: 1 HRV; existing propane boiler for heating and indirect water heating; mini-split ASHP for cooling
Providence-B, RI (3 units)	1930	3,054	3,054	Below roof deck insulation only	Exterior and wall cavity insulation	Basement ceiling insulated	HRV per unit; gas boiler per unit (located in unconditioned basement) for heating and indirect water heating; electric resistance heating in common areas; through-wall air conditioners

Table 5. DER Community—5 Partial DERs

House Location	Year Built	Pre-Retrofit Cond. Area (ft^2)	Post-Retrofit Cond. Area (ft^2)	Roof/Attic Measure (Installed R-Value)	Above-Grade Walls Measure (Installed R-Value)	Basement Measure	HVAC and DHW Measures
Jamaica Plain-B, MA	1878	5,663	5,663	Below roof deck insulation only	n/a	Foundation walls and floor slab insulated	Supply-only ventilation; existing gas boiler with hydronic air handlers and indirect water heating; existing central air conditioning
Florence, MA	1880	2,690	3,976	Vented attic with attic floor insulation	n/a	Foundation walls and floor slab insulated	HRV; gas boiler for heating and indirect water heating; direct vent wood stove; no air cooling
Concord, MA	1956	3,620	3,620	Exterior and below roof deck insulation partial chainsaw	n/a	n/a	Exhaust-only ventilation; existing gas boiler for heating and indirect water heating; 2 existing mini-split air conditioners
Watertown, MA (2 units)	1928	2,645	2,899	Exterior and below roof deck insulation chainsaw	n/a	Foundation walls and floor slab insulated	Lower unit: existing gas furnace and gas water heater. Upper unit: HRV; mini-split ASHP for heating and cooling; tankless gas water heater
Jamaica Plain-C, MA (3 units)	1918	3,748	3,748	Exterior and below roof deck insulation no chainsaw (internal drain low slope roof)	n/a	n/a	Exhaust only ventilation; central gas water heater and hydronic air handler for each unit

In the “Roof/Attic Measure” column of Table 4 and Table 5, some DER projects are identified as using the “chainsaw” technique. This refers to a retrofit technique used at the intersection of the roof and exterior wall whereby the existing rafter tails and rake overhangs are cut off during the retrofit and new overhangs are built and attached at completion (Orr and Dumont 1987; Holladay 2009). This approach is often used in a DER when exterior insulation is to be applied to both the roof and the wall, since it allows a continuous layer of insulation to be applied across the intersection, thus reducing thermal bridging. More importantly, it simplifies the air control connection between the roof and the wall when the air control layers for both the roof and the wall are on the outside of the existing sheathing, since the intersection becomes a simple edge condition.

In the “Above-Grade Walls Measure” column of Table 4 and Table 5, there is a note “existing porch roof/deck not detached” for some of the projects. When exterior insulating sheathing is used on the above-grade walls for a DER, it is recommended that any porches or decks that are attached to the above-grade wall (i.e., not integral to the structure of the building) be temporarily detached during the retrofit so that the air control layer and the insulation can be applied continuously between the porch or deck and the wall. This note indicates that the project did not use this approach.

It is clear from Table 4 and Table 5 that the teams implemented retrofit measures in several ways. Key variations are summarized below:[3]

- Variation in above-grade wall treatment:
    - One project used interior insulation only (a new stud wall was built around the interior perimeter to create a deeper cavity for insulation).
    - Thirty-six projects applied insulation to the exterior of the existing walls.
    - Of the 36 projects that applied insulation to the exterior, eight also used spray polyurethane foam insulation in the wall cavities.
- Variation in roof and attic treatment:
    - Eight projects used a vented attic with insulation on the attic floor and intentional ventilation openings.
    - Eleven projects created an unvented attic with all of the required insulation below the existing roof sheathing.
    - Twenty-four projects created an unvented attic using insulation applied over the existing roof sheathing;
        - Nineteen of these projects used the “chainsaw” technique.
        - Three implemented significant elements of the “chainsaw” technique.
        - One project involved a wood-framed sloped roof and did not implement any elements of the “chainsaw” technique.

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[3] Note that the number for each variation under the major components does not sum to the total number of projects in the study because the study includes partial DER projects that did not treat each of these components.

        - One project involved an unvented attic beneath a low-sloped roof of a building with masonry parapets.
- Variation in basement treatment:
    - Five projects insulated the basement ceiling rather than the basement walls.
    - Seven projects insulated the basement walls but did not insulate the basement floor.
    - Twenty-eight projects insulated the basement walls and the basement floor.

As participants in the DER pilot program, all of these DER projects provided data in the application forms, had pre- and post-retrofit blower door testing performed, and are contractually obligated to provide energy use information for at least the first 2 years following completion of the DER. Data from the application form include facts about the house, information on existing conditions, past energy use, performance concerns, existing R-values, as well as descriptions of plans for implementing the measures and projected costs. This, together with on-site verification of the DER project measures, provided a consistent set of data about each retrofit analyzed in this research report.

4 Energy Use Results and Analysis

A key goal of the National Grid DER pilot project was to demonstrate that energy use reduction of 50% or more relative to typical homes could be achieved through enclosure upgrades and efficiency upgrades to mechanical equipment. To meet that goal, the program used aggressive performance targets for retrofit of enclosure components (see Table 2). These thermal enclosure specifications, together with improved airtightness, were expected to reduce heating and cooling loads significantly. In addition, participants were encouraged to replace old equipment—appliances, HVAC equipment, and lighting—with energy-efficient equipment (see Table 3). In the case of HVAC equipment, this provided opportunity for right-sizing the equipment to better match the reduced heating and cooling loads. The major leverage of the pilot program, therefore, related to heating and cooling energy use. The program also encouraged reduction of lighting energy use by providing free or reduced-cost efficient lamps and lighting fixtures. The program documentation also required that major appliances in the retrofit homes be ENERGY STAR qualified. Other major end uses in the homes were outside of the purview of the program.

4.1 Reduction Versus Performance Achieved

For retrofit measures aimed at reducing energy use (and primarily heating and cooling energy use) the relative energy use reduction that can be achieved for any one home reflects not only the effectiveness of the measures but also the pre-retrofit state of the building and how the building is used by its occupants. The pre-retrofit energy use is highly variable between different homes. Because occupant behavior and building pre-retrofit conditions have a determining effect on the apparent relative savings associated with a retrofit measure, the apparent reductions or “savings” associated with a measure are difficult to translate from one house/household to another without knowing a significant amount of information about each.

Further muddying the relationship between energy use reduction and retrofit measures is that a retrofit project is often combined with other home improvements that result in a change in the size of the home (usable conditioned floor area).

Although thorough characterization of the pre-retrofit condition and meticulous “tuning” of energy models may allow for translation of savings projections from one building to another, this work diverts resources from the retrofit itself. Extensive modeling of the pre-retrofit condition may be of limited value when the performance resulting from a comprehensive package can be projected with reasonable certainty. With a projection of the resulting performance, the relative savings or reduction can be calculated by comparing current use to the expected post-retrofit performance.

In this section, the post-retrofit energy use of the group of DER projects is analyzed to assess the level of energy performance achieved by the retrofit package implemented in the National Grid DER pilot. The level of energy performance achieved is compared to energy performance benchmarks. Energy performance of the group of DER projects is also analyzed to assess whether different implementation strategies have significant energy performance implications. While projection of post-retrofit energy use resulting from implementation of the package might be more stable and more readily generalized than relative savings, it is important to note that measured post-retrofit energy use is also subject to highly variable occupant behavior and other operating conditions.

4.2 Site and Source Energy

Energy performance can be shown as site or source (or “primary”) energy. Looking at site energy allows an analysis of energy consumption directly in the house; at this level, homeowners can precisely measure energy consumption using meters or monitors. On the other hand, in order to appropriately assess the environmental impact and total energy consumption of the home’s energy use (including production and transport of the fuel or electricity), source energy use is the vital metric. In addition, source energy is typically comparable to the energy cost for the end user (Ueno and Straube 2010). The analysis presented in this report considers both source energy and site energy use.

Source energy use is calculated using the source to site energy conversion factors shown in Table 6 (nationwide averages from EPA 2011). The total site and source energy use reported in Table 7 presumes that all electricity was from the grid.

Table 6. Source-Site Ratios for All Portfolio Manager Fuels

(EPA 2011)

Fuel Type	Source-Site Ratio
Electricity (Grid Purchase)	3.34
Natural Gas	1.047
Fuel Oil (1, 2, 4, 5, 6, Diesel, Kerosene)	1.01
Propane and Liquid Propane	1.01
Wood	1.0

4.3 On-Site Generation

Eleven of the houses in this retrofit community generate some electricity on site through photovoltaic installations. While the electricity produced by these systems can offset some or all of the energy that the building would otherwise need to import from the grid, in this study, the on-site generation facility is not a part of the package of measures evaluated. The aim of the research effort is to ascertain the level of performance achievable through a particular package of retrofit measures. Therefore electrical energy used by the DER projects in this study is the gross energy, and not the net energy, used by the building.

4.4 Energy Use Data

The actual post-retrofit energy use data are derived from the monthly energy use reported by the electricity and gas utility companies, delivery amounts and dates for periodic delivery fuels (such as propane and wood pellets), and on-site electricity production data made available to BSC by the DER homeowners. The data were processed for use in the analysis by allocating energy use to calendar months so that monthly energy use could be associated with monthly weather data. In most cases, this involved adjusting the data relative to energy units used per day in the billing periods. In some cases, periodic delivery fuels, such as propane and wood pellets, had to be distributed according to daily use portions and weather-affected portions using daily weather data.

To have sufficient energy use data representative of expected operational conditions, the projects had to be completed (and back to full occupancy) by January of 2013. Data were collected for the entire post-retrofit period through July, August, or September of 2013.

For projects with on-site generation, determining the gross electricity usage of the house required monthly generation data as well as the net electricity supplied to/from the grid. The net electricity position with respect to the grid plus the monthly on-site generation yields the gross electric consumption of the home. Some utility bills do not indicate net electricity supplied to the grid: months with a net supply to the grid are represented as 0 kWh usage rather than showing a negative kilowatt-hour position. In some cases, the homeowner was able to provide the net electricity supply data. The DER program manager at National Grid was able to track down raw meter read data that helped determine the gross electrical energy use data for other projects. For some projects, it was not possible to determine the gross energy usage and, therefore, data for that project could not be included in the analysis.

In all, BSC received sufficient post-retrofit energy usage data for 28 of the DER projects. For another project, a previous year of post-retrofit data provided suitable information. The energy use analysis in this report includes 29 of the DER pilot projects. Twenty-seven of these are comprehensive DER projects, two are partial (or “staged”) DER projects.[4] In this section, “all DER projects” or “the entire group of DER projects” is used to refer to the entire group of projects for which adequate post-retrofit energy use data were available.

The pre-retrofit data are from monthly energy use data provided by the utility companies or provided by the homeowner on program application forms. Energy modeling was used to generate pre-retrofit usage when the building was not occupied by the current owners prior to the retrofit.

Table 7 and Table 8 summarize the pre-retrofit and post-retrofit energy use data, respectively, for the houses included in this section of the report.

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[4] Included among the comprehensive DER projects is one project that had implemented high performance retrofit for the roof and basement prior to participating in the National Grid program. Participation in the National Grid program resulted in a comprehensive retrofit for this home.

Table 7. DER Community Pre-Retrofit Energy Use—12 Months

House Location	Time Period or Energy Modeling Tool Used	Primary Heating Fuel	Electricity (kWh)	Natural Gas (therm) or Propane (gal)		Fuel Oil (gal)	Other Energy Source	Total Site Energy (MMBtu)	Total Source Energy (MMBtu)
Belchertown, MA	Jul 08–Jun 09	Wood	2,079	174	(P)		7 cords wood	195	211
Belmont, MA (2 units)	BEopt v 2.0	Gas	9,273	322	(NG)	2,791		451	530
Millbury, MA	May 09–Apr 10	Oil	7,730			375	150, 40-lb bags pellets	125	187
Milton, MA	BEopt v 2.0	Gas	8,089	865	(NG)			114	183
Quincy, MA	Jan 09–Dec 09	Oil	12,557			550		119	220
Arlington, MA (2 units)	BEopt v 2.0	Gas	9,059	2,852	(NG)			316	402
Newton, MA	Oct 09–Sep 10	Gas	7,639	1,222	(NG)			148	215
Jamaica Plain-A, MA (3 units)	Aug 09–Jul 10	Gas	7,456	1,760	(NG)			201	269
Northampton-A, MA	Jan 09–Dec 09	Gas	4,443	1,164	(NG)			132	173
Lancaster-A, MA	BEopt v 2.0	Oil	5,677			668		112	158
Brookline, MA	Sep 09–Aug 10	Gas	3,284	773	(NG)			89	118
Westford, MA	Jan 10–Dec 10	Gas	9,763	1,761	(NG)			209	296
Gloucester, MA	Jun 09–May 10	Oil	5,428			910		145	189
Medford, MA (2 units)	Jun 08–May 09	Gas	12,517	3,069	(NG)			350	464
Northampton-B, MA	BEopt v 2.0	Gas	5,756	832	(NG)			103	153
Haverhill, MA (2 units)	BEopt v 2.0	Oil	7,403	36	(NG)	943		160	220
Rutland, MA	Aug 08–Jul 10	Oil	10,443	58	(P)	465	0.3 cords wood	113	197
Methuen, MA	Dec 10–Nov 11	Oil	8,089			584		109	174
Wakefield, RI	Jan 11–Dec 11	Propane	9,573	754	(P)			102	179
Groton, MA	Jun 10–May 11	Oil	8,724			878		152	222
Cohasset, MA	BEopt v 2.0	Oil	12,611			1,597		265	367

House Location	Time Period or Energy Modeling Tool Used	Primary Heating Fuel	Electricity (kWh)	Natural Gas (therm) or Propane (gal)		Fuel Oil (gal)	Other Energy Source	Total Site Energy (MMBtu)	Total Source Energy (MMBtu)
Sudbury, MA	May 10–Apr 11	Oil	10,939			743		37	125
Northampton-C, MA	Aug 10–Jul 11	Gas	4,105	567	(NG)			71	106
Warwick, MA	Sep 10–Aug 11	Oil/wood	1,351			80	1.3 cords wood	48	58
Melrose, MA	Jan 11–Dec 11	Oil	6,012	227	(NG)	1,725		282	334
Lowell, MA	Dec 10–Nov 11	Gas	6,757	558	(NG)			79	135
Waltham, MA	Nov 09–Oct 10	Gas	4,563	694	(NG)			85	125
Jamaica Plain-B, MA	May 09–Apr 10	Gas	7,059	2,499	(NG)			274	342
Concord, MA	Nov 10–Oct 11	Gas	14,265	1,815	(NG)			230	353

Table 8. DER Community Post-Retrofit Energy Use

House Location	Time Period	Primary Heating Fuel	Electricity (kWh)	Natural Gas (therm) or Propane (gal)		Other Energy Source	Total Site Energy (MMBtu)	Total Source Energy (MMBtu)
Belchertown, MA	Aug 12–Jul 13	Propane	1,916	362	(P)		40	55
Belmont, MA (2 units)	Aug 12–Jul 13	Gas	12,070	274	(NG)		69	166
Millbury, MA	Nov 11–Oct 12	Electricity	10,693	72	(P)	~12, 40-lb bags pellets	47	132
Milton, MA	Aug 12–Jul 13	Gas	4,956	361	(NG)		53	94
Quincy, MA	Aug 12–Jul 13	Gas	12,046	350	(NG)		76	174
Arlington, MA (2 units)	Aug 12–Jul 13	Gas	13,162	688	(NG)		114	222
Newton, MA	Aug 12–Jul 13	Gas	6,974	466	(NG)		70	128
Jamaica Plain-A, MA (3 units)	Aug 11–Jul 12	Gas	6,153	800	(NG)		101	154
Northampton-A, MA	Aug 12–Jul 13	Electricity	7,229				25	82
Lancaster-A, MA	Aug 12–Jul 13	Electricity	8,602	249	(NG)		54.26	124.12
Brookline, MA	Aug 12–Jul 13	Gas	3,321	449	(NG)		56	85
Westford, MA	Aug 12–Jul 13	Gas	10,514	904	(NG)		126.33	214.55
Gloucester, MA	Aug 12–Jul 13	Electricity	15,030				51	171
Medford, MA (2 units)	Aug 12–Jul 13	Gas	14,296	576	(NG)		106	223
Northampton-B, MA	Aug 12–Jul 13	Gas	3,388	472	(NG)		59	88
Haverhill, MA (2 units)	Aug 12–Jul 13	Electricity	11,484				39	131
Rutland, MA	Aug 12–Jul 13	Propane	4,394	468	(P)		58	93

House Location	Time Period	Primary Heating Fuel	Electricity (kWh)	Natural Gas (therm) or Propane (gal)		Other Energy Source	Total Site Energy (MMBtu)	Total Source Energy (MMBtu)
Methuen, MA	Aug 12–Jul 13	Electricity	12,198				42	139
Wakefield, RI	Sep 12–Aug 13	Propane	6,531	356	(P)		55	107
Groton, MA	Aug 12–Jul 13	Gas	7,763	806	(NG)		107	173
Cohasset, MA	Oct 12–Sep 13	Propane	6,494	634	(P)		80	133
Sudbury, MA	Oct 12–Sep 13	Gas	5,017	289	(NG)		46	87
Northampton-C, MA	Sep 12–Aug 13	Gas	4,463	306	(NG)		46	83
Warwick, MA	Nov 12–Aug 13	Electricity	2,725				9	31
Melrose, MA	Dec 12–Sep 13	Electricity	7,289				25	83
Lowell, MA	Jan 13–Sep 13	Gas	2,776	220	(NG)		31	55
Waltham, MA	Jan 13–Jul 13	Gas	2,590	199	(NG)		29	50
Jamaica Plain-B, MA	Aug 12–Jul 13	Gas	11,153	1,666	(NG)		205	302
Concord, MA	Dec 12–Jun 13	Gas	7,040	1,331	(NG)	~¼ cord wood	162	224

4.4.1 Energy Use Data Normalization and Disaggregation

Total energy use for a given house is a function of weather conditions during the time period, the size of the house, the number of households, the number of residents, and the life style of the residents. To compare and analyze the energy use among different houses across different time periods, it is necessary to use performance metrics that normalize for at least some of these variables.

Weather conditions vary between different post-retrofit periods. In order to compare post-retrofit performance for different time periods, and to compare post-retrofit performance to static benchmarks, the energy use data for each project were normalized to "typical" weather conditions using a simple linear regression method. Typical Meteorological Year 3 (TMY3) data files were selected to represent "typical" weather conditions. TMY3 data files contain weather data meant to represent typical conditions at a particular geographic location over a long period of time (Wilcox and Marion 2008).

In most cases, the normalization involved a linear regression of the relationship between monthly heating fuel usage and the corresponding monthly heating degree days (HDDs) with a base of 65°F for the same period. Monthly electrical energy use was evaluated for a relationship to cooling degree days (CDDs, also with a base of 65°F) during cooling months. For projects that use electricity for heating and cooling (e.g., heat pump system), the linear regression compared electrical energy use to HDDs during heating months and to CDDs during cooling months. The linear regression factors (slope and intercept) were then applied to monthly HDDs and CDDs derived from TMY3 data for the same weather station that provided the HDD and CDD data for the post-retrofit period for the project.

For energy use that is not associated with heating or cooling, the year-to-date usage was combined with the normalized heating (or heating and cooling) energy usage to yield a normalized post-retrofit annual energy usage.

For projects that have less than a full year of post-retrofit data, the linear regression factors were used to generate heating (or heating and cooling) energy use for a year based on monthly TMY weather data. This regression-derived heating and cooling energy was then combined with a year of actually non-heating and cooling energy use. In some cases, the year of non-heating and cooling energy use included data from months prior to (but not during) the retrofit project. This is taken as a reasonable and conservative approximation, given that the non-heating and cooling energy use is typically only marginally impacted, and tends to be reduced by the retrofit.

The normalization resulted in very minor (typically < 5%) adjustments to the total energy use data for each project. With the exception of some cases involving electric fuel used for heating and cooling, the correlation (R^2) between measured energy use and weather data tended to be reasonably good (> 0.9). The weather-normalized data should be viewed as a rough approximation, due to the low resolution of the energy use data (approximately monthly), the varying correlation accuracy with HDDs (and as applicable, CDDs), and the simple method used.[5]

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[5] A previous study conducted by BSC (Osser et al. 2012) found that elaborate methods of weather normalizing energy use data provided marginal, if any useful refinement relative to more simple methods.

Heating and cooling energy use were disaggregated from non-heating and cooling energy use either by using the linear regression intercept or by identifying minimum monthly heating and/or cooling energy use outside of heating and cooling seasons, respectively. It should be noted that some portion of domestic hot water (DHW) heating energy use may be captured in the heating energy use where the same fuel is used for both DHW and space heating. This is because the inlet water temperature to the water heating appliance tends to decrease, thus increasing DHW energy use for a given load, as monthly HDDs increase.

Table 9 below presents the normalized post-retrofit site and source energy use as well as the normalized post-retrofit heating and cooling site and source energy use for each project.

Table 9. Summary of DER Community Pre- and Post-Retrofit Energy Use, Normalized Post-Retrofit Energy Use, and Normalized Heating and Cooling Post-Retrofit Energy Use

House Location	Pre-Retrofit Energy Use (MMBtu)		Post-Retrofit Energy Use (MMBtu)		(# Months For Less Than Full Year of Post-Retrofit Data)	TMY3 Weather-Normalized Post-Retrofit Energy Use (MMBtu)		TMY3 Weather-Normalized Post-Retrofit Heating and Cooling Energy Use (MMBtu)	
	Site	Source	Site	Source		Site	Source	Site	Source
Belchertown, MA	195	211	40	55		44	60	27	28
Belmont, MA (2 units)	451	530	69	166		70	168	34	51
Millbury, MA	125	187	47	132		47	133	19	61
Milton, MA	114	183	53	94		54	95	27	34
Quincy, MA	119	220	76	174		78	176	39	59
Arlington, MA (2 units)	316	402	114	222		112	221	61	83
Newton, MA	148	215	70	128		73	131	43	55
Jamaica Plain-A, MA (3 units)	201	269	101	154		113	166	56	60
Northampton-A, MA	132	173	25	82		27	90	13	43
Lancaster-A, MA	112	158	54	124		54	123	5	18
Brookline, MA	89	118	56	85		58	87	36	38
Westford, MA	209	296	126	215		119	206	68	84
Gloucester, MA	145	189	51	171		49	164	17	56
Medford, MA (2 units)	350	464	106	223		109	226	66	93
Northampton-B, MA	103	153	59	88		60	90	38	42
Haverhill, MA (2 units)	160	220	39	131		37	124	18	59
Rutland, MA	113	197	58	93		60	95	19	22
Methuen, MA	109	174	42	139		40	134	15	49
Wakefield, RI	102	179	55	107		55	107	25	28
Groton, MA	152	222	107	173		101	166	64	68
Cohasset, MA	265	367	80	133		83	137	64	78

House Location	Pre-Retrofit Energy Use (MMBtu)		Post-Retrofit Energy Use (MMBtu)		(# Months For Less Than Full Year of Post-Retrofit Data)	TMY3 Weather-Normalized Post-Retrofit Energy Use (MMBtu)		TMY3 Weather-Normalized Post-Retrofit Heating and Cooling Energy Use (MMBtu)	
Sudbury, MA	37	125	46	87		44	85	27	35
Northampton-C, MA	71	106	46	83		47	84	28	36
Warwick, MA	48	58	9	31	10 months post-retrofit data	11	36	5	17
Melrose, MA	282	334	25	83	10 months post-retrofit data	32	106	14	46
Lowell, MA	79	135	31	55	9 months post-retrofit data	41	70	21	22
Waltham, MA	85	125	29	50	7 months post-retrofit data	46	86	24	25
Jamaica Plain-B, MA	274	342	205	302		210	307	140	147
Concord, MA	230	353	162	224	7 months post-retrofit data	231	340	102	107

4.5 Characterization of Post-Retrofit Energy Use

4.5.1 Pre- and Post-Retrofit Energy Use Comparison

Figure 2 compares pre-retrofit and post-retrofit site energy use, for the 29 projects for which sufficient post-retrofit energy use data were available. The chart indicates where the pre-retrofit usage is derived from an energy model as opposed to actual utility bills. Also, for some projects for which BSC obtained less than a full year of post-retrofit energy use data, the chart shows post-retrofit energy use generated from weather normalization. Figure 3 provides a similar comparison in terms of source energy use.

These charts highlight the huge range in pre-retrofit energy use among the group of projects. There is a factor of approximately 9 between the minimum and maximum pre-retrofit energy use for both site and source energy. There is also variation in the post-retrofit energy use, with a similar relative range between the minimum and maximum observations for the comprehensive retrofits. However, the absolute magnitude of the spread between the minimum and maximum values is much smaller for the post-retrofit energy use.

It follows from the huge variation in pre-retrofit energy use that the relative reduction of energy use achieved would also exhibit significant variation. Figure 4 shows the percent reduction in energy use achieved in terms of both site and source energy. For the 27 comprehensive DER projects, the site energy use reductions range from a low of 25% and a high of 84%. The median site energy use reduction for these projects is 53% and the mean is 55%. In terms of source energy use, the reductions range from 10% to 75%. The median source energy use reduction for these projects is 44%, the mean is 43%.

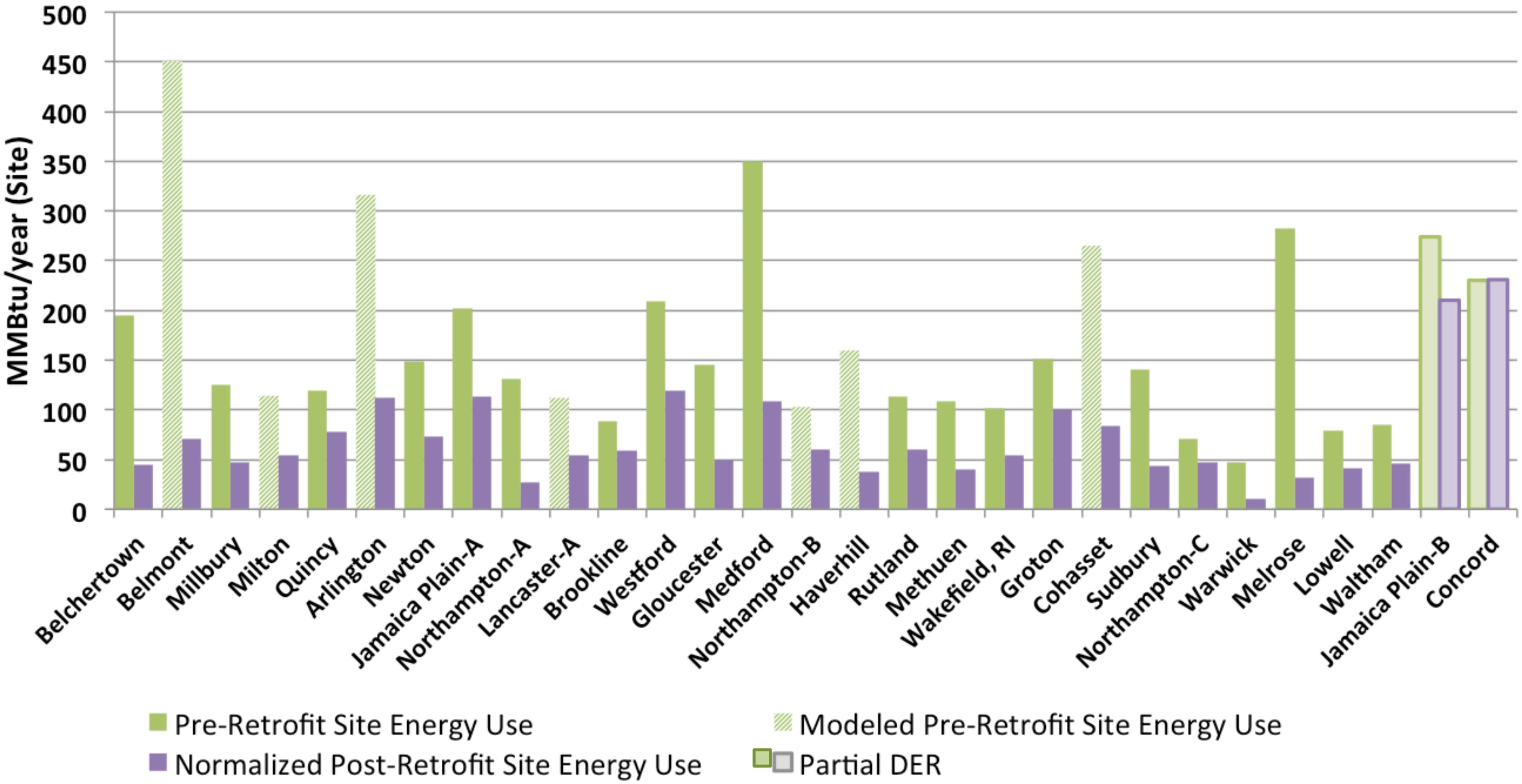


Figure 2. Pre- and post-retrofit site energy use for all DER projects

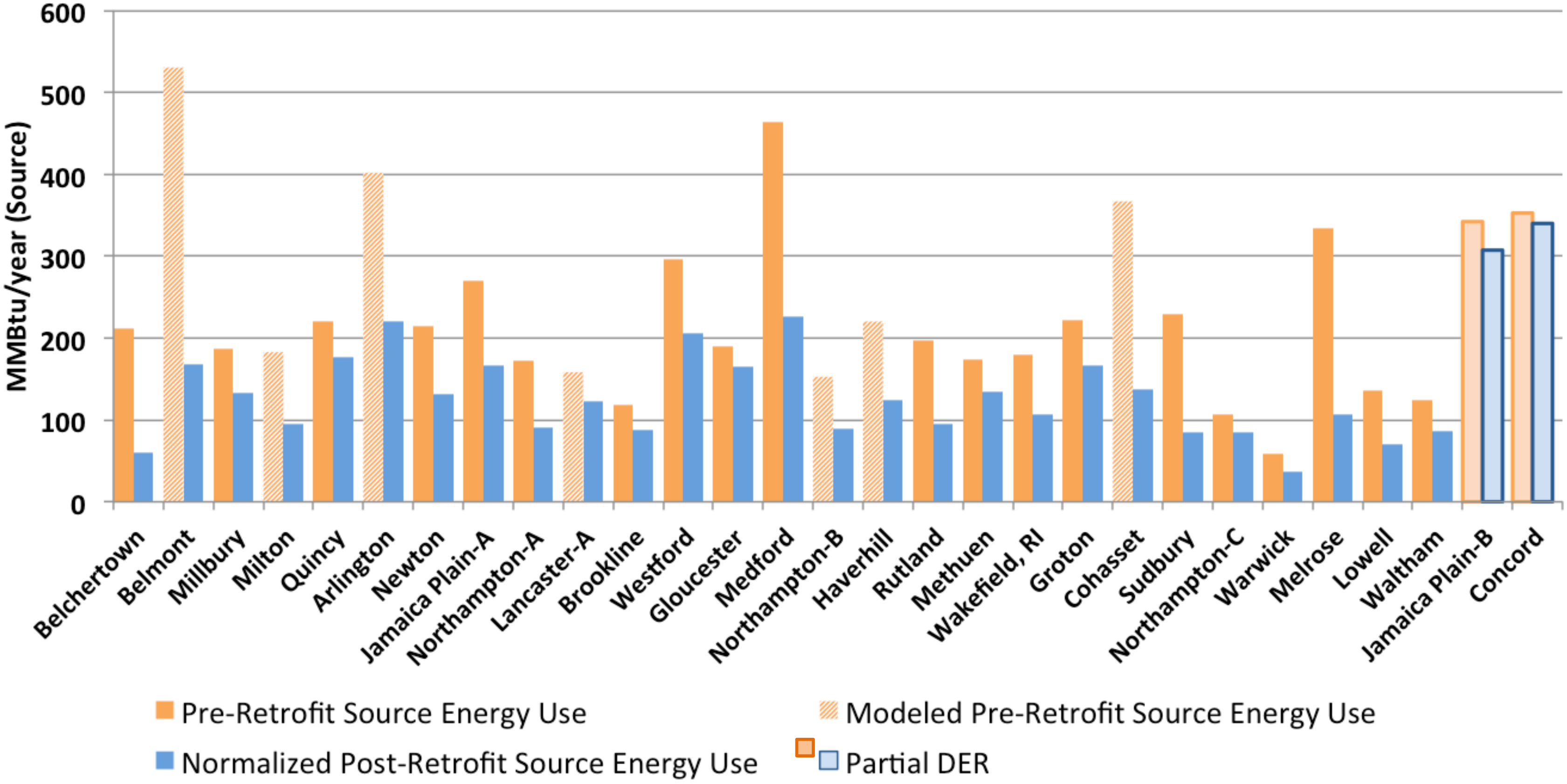
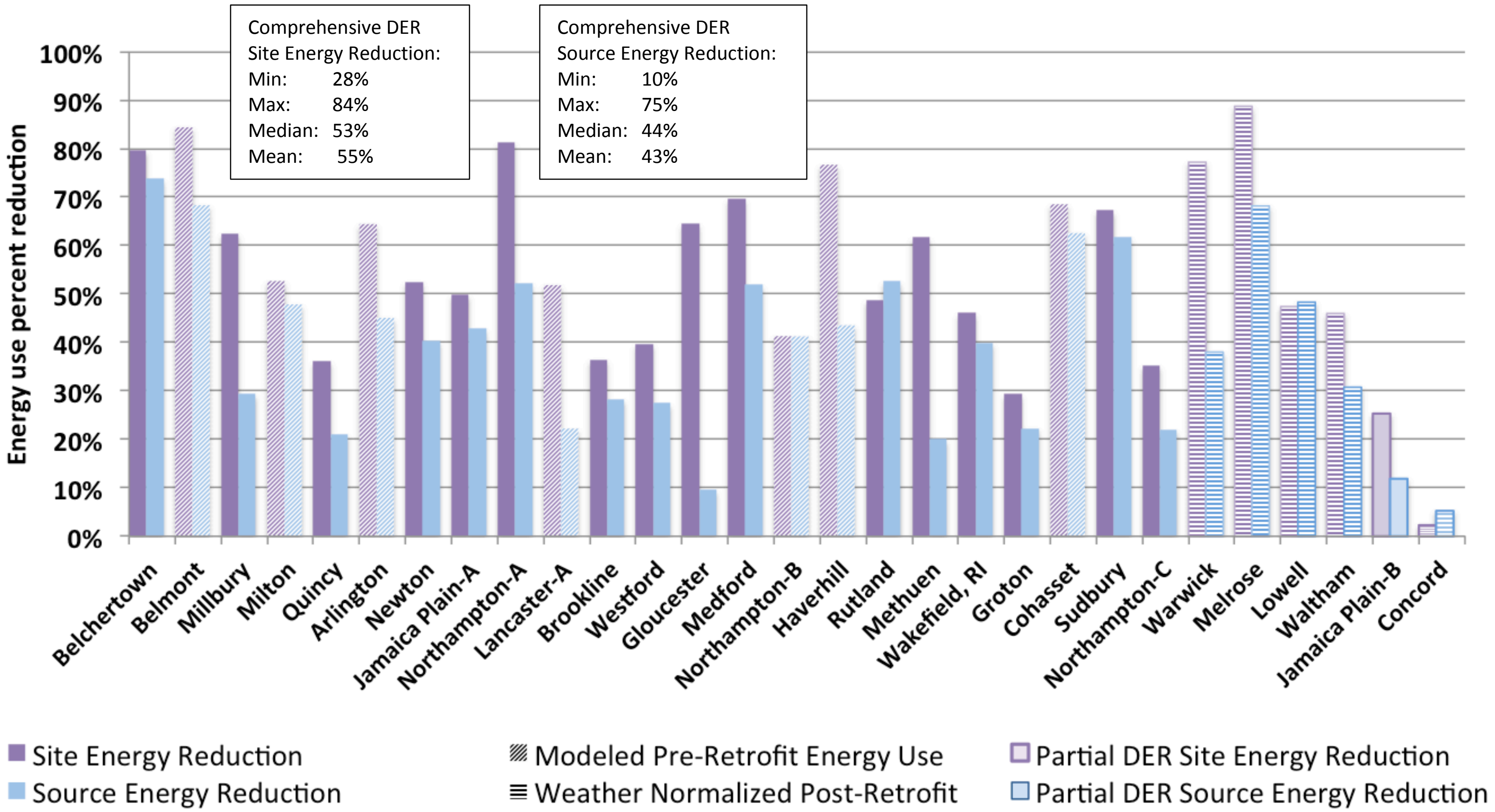


Figure 3. Pre- and post-retrofit source energy use for all DER projects



Comprehensive DER
Site Energy Reduction:
Min: 28%
Max: 84%
Median: 53%
Mean: 55%

Comprehensive DER
Source Energy Reduction:
Min: 10%
Max: 75%
Median: 44%
Mean: 43%

Figure 4. Energy use reduction (percent reduction) achieved in terms of both site and source energy for all DER projects

It is tempting to presume that the greater relative reductions among these projects are associated with relatively greater pre-retrofit energy use. However, through most of the range of pre-retrofit energy use, there is a wide range of energy use reductions. This is demonstrated in Figure 5 and Figure 6: the graphs show a "scatter" rather than a relationship.

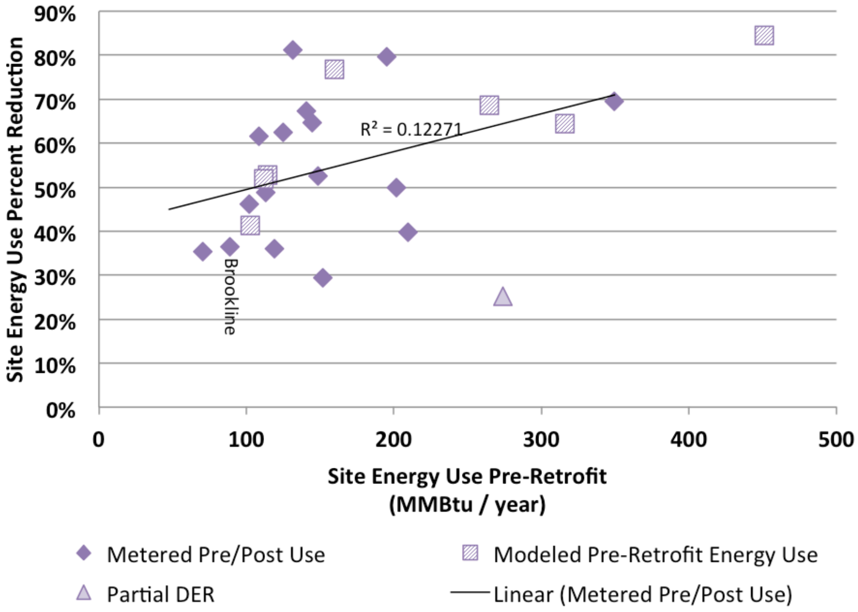


Figure 5. Site energy use percent reduction relative to pre-retrofit site energy use

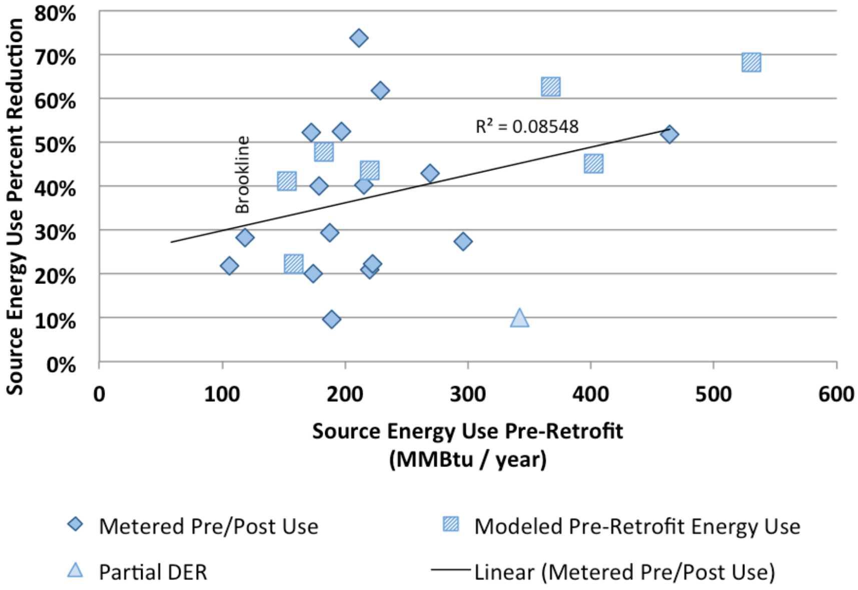


Figure 6. Source energy use percent reduction relative to pre-retrofit source energy use

The percentage reduction achievable is dependent on the pre-retrofit state of the house. For example, the Brookline retrofit (labeled in Figure 5 and Figure 6) was the final stage of a two-stage DER project; the roof and basement components had been completed several years earlier. Thus, the 28% source energy use reduction does not capture the effect of the prior stage(s) of the DER.

One might expect that larger homes would exhibit greater relative reductions from a package of measures aimed at reducing heating and cooling energy use; however, this is not seen in the data (Figure 7 and Figure 8).

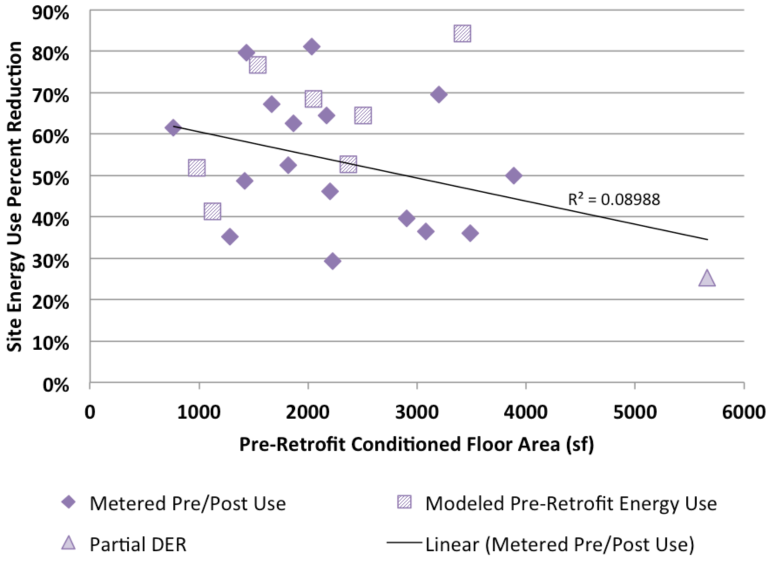


Figure 7. Site energy use percent reduction relative to pre-retrofit conditioned floor area

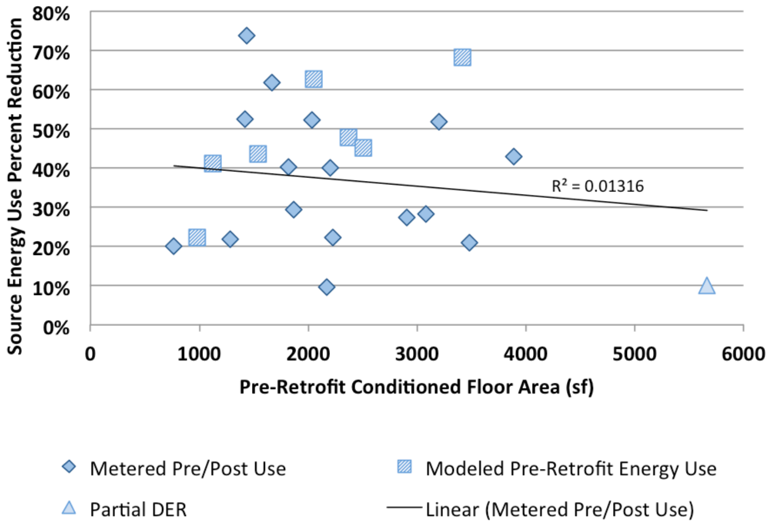


Figure 8. Source energy use percent reduction relative to pre-retrofit conditioned floor area

Neither do the data appear to show a significant relationship between relative energy use reduction and either pre-retrofit air leakage (Figure 9 and Figure 10) or age of the home (Figure 11 and Figure 12).

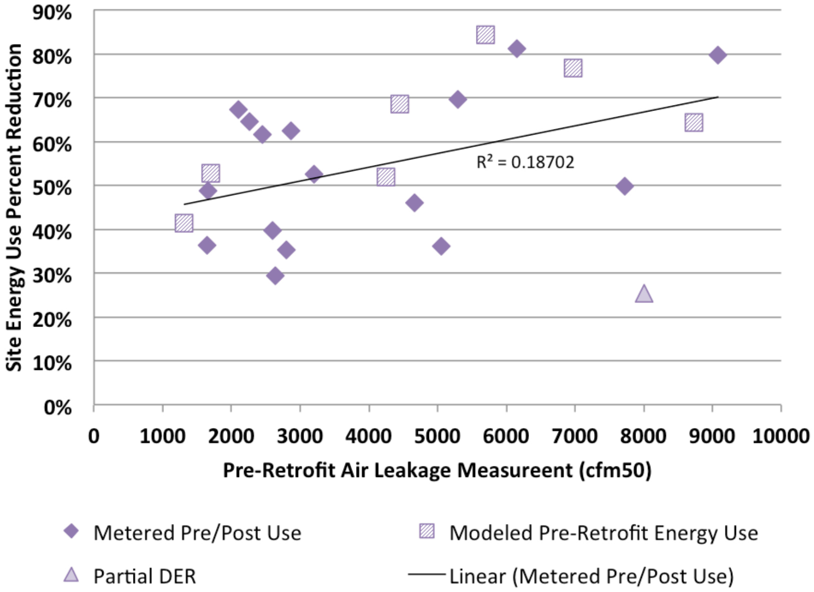


Figure 9. Site energy use percent reduction relative to pre-retrofit air leakage measurement

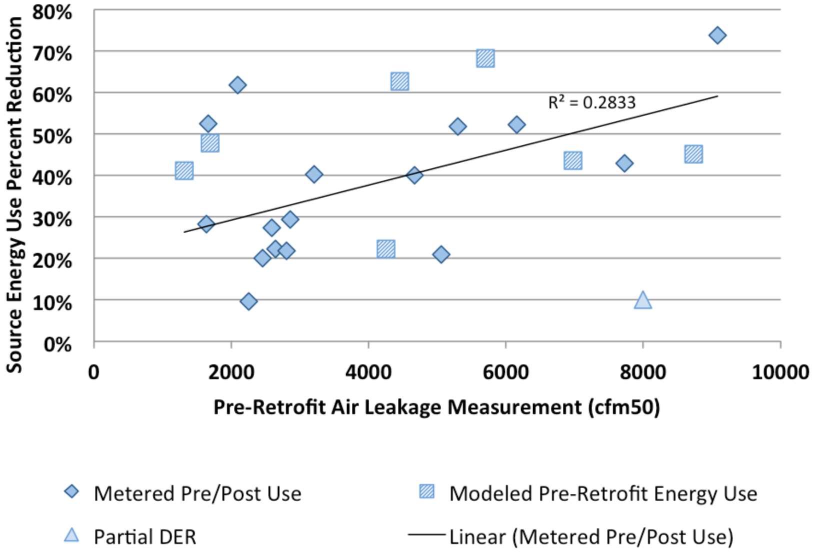


Figure 10. Source energy use percent reduction relative to pre-retrofit air leakage measurement

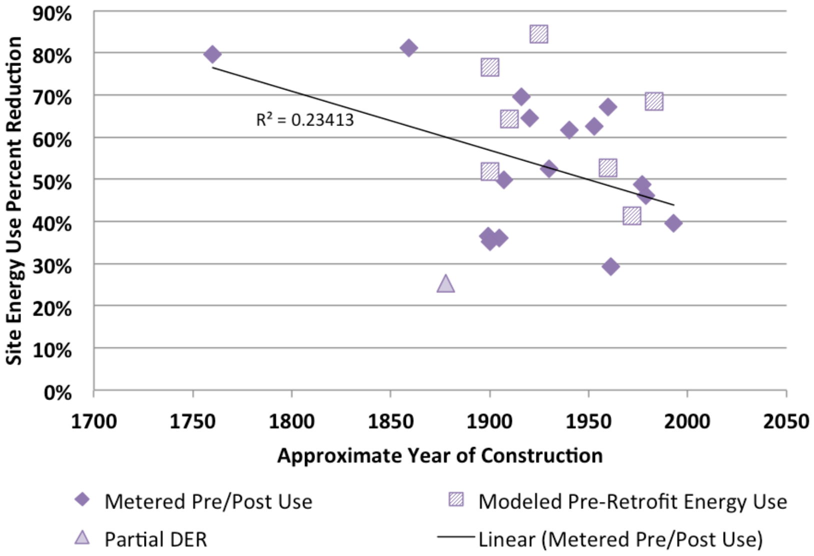


Figure 11. Site energy use percent reduction relative to approximate year of construction

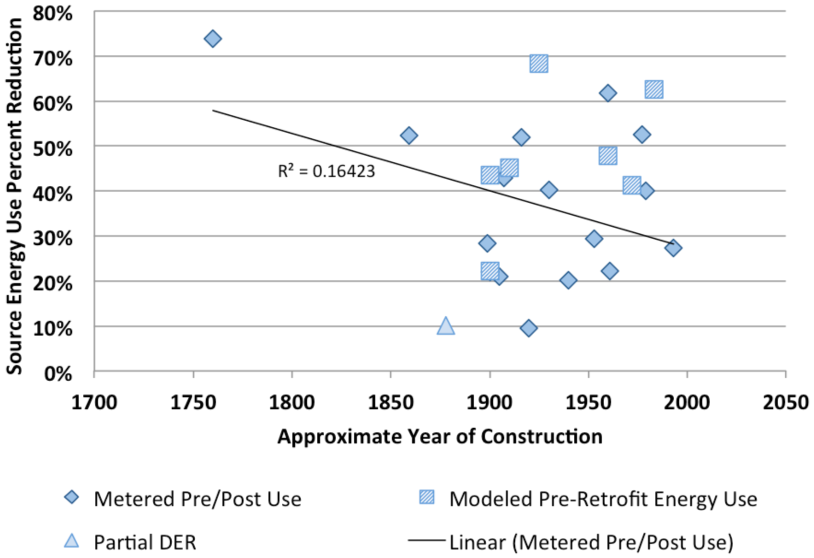


Figure 12. Source energy use percent reduction relative to approximate year of construction

From these data there does not appear to emerge a single pre-retrofit factor that can serve as a significant predicter of relative energy use reduction for the retrofit package.

4.5.2 Post-Retrofit Energy Use per Household

Several of the houses in this community are multifamily, therefore an important performance metric to consider for benchmarking the results is the total energy use per household. This metric is computed by dividing the total building energy use by the number of households in the building. Figure 13 shows weather-normalized post-retrofit site energy use in MMBtu per household for 12 months. Figure 14 shows similar post-retrofit usage in terms of source energy. The northeast regional household averages for site and source energy use, derived from data available from the Energy Information Administration (EIA), are shown in the figures for comparison.

The U.S. Department of Energy maintains regional energy performance metrics per household that are based on information contained in the EIA Residential Energy Consumption Survey (RECS). The most recent information available is from 2009 (DOE/EIA 2009). Unless indicated otherwise, the regional average energy use presented in this analysis corresponds to this survey year. For the Northeast region, the EIA average site energy consumption per household is 107.6 MMBtu/year. The EIA performance information does not include average source energy consumption per household. To convert EIA site energy consumption to source energy use, the average site energy use per household was distributed among fuel types according to the distribution of the total fuel consumption for the northeast households in the RECS. The ENERGY STAR source-to-site ratios (EPA 2011; Table 6) were applied based on this distribution yielding an EIA Northeast regional average household source energy use of 174 MMBtu/year. Therefore, a 30% reduction in energy use relative to average household source energy use is 122 MMBtu/year and post-retrofit source energy use of 87 MMBtu/year represents a 50% reduction relative to the regional average household.

According to the latest survey of U.S. housing (U.S. Census Bureau 2013) the average size home in the region is 1,900 ft^2. Among the retrofit projects included in this analysis, the median conditioned floor area is 2,720 ft^2 and the average is 2,956 ft^2. This difference in conditioned floor area does not necessarily indicate a larger home per se, because almost all of the retrofit houses resulted in a conditioned basement and, therefore, include conditioned basement floor area in the total conditioned floor area of the home. For a simple volume two-story house with a basement, bringing the basement into conditioned space (typically a basement is excluded from conditioned space) would increase the conditioned floor area by roughly 50%. Therefore, the sample is understood to be reasonably representative of typical housing in the region and the regional average is taken to be an appropriate benchmark for per-household energy use.

In terms of site energy (Figure 13), the median post-retrofit per-household energy use for the comprehensive retrofits is 49.2 MMBtu/year while the mean is 52.8 MMBtu/year. Twenty-three of the comprehensive DER projects, representing 85% of the sample achieved a post-retrofit site energy use that is 30% less than the regional average. Fifteen of the projects use less than 50% of regional average per household site energy use.

In terms of source energy (Figure 14), the median post-retrofit per-household energy use is 95.3 MMBtu/year while the mean is 107.2 MMBtu/year. Eighteen of the comprehensive DER projects, representing 67% of the sample, achieved a post-retrofit site energy use that is 30% less than the regional average. Nine of the projects use less than 50% of regional average per household site energy use.

The Quincy and Westford retrofits, which are the two highest “per household” source energy users, are both single-family homes and are the largest in terms of conditioned square feet of the single-family homes in this community. This highlights one shortcoming of the “per household” performance metric—while it compensates for duplication of appliance and other miscellaneous use, it does not take into account the physical size of the home.

The Gloucester DER is one that involved a conversion to all electrical energy use, including water heating. The post-retrofit, per-household source energy usage of this DER is among the highest of the group while it is in the middle of the range for site energy use.

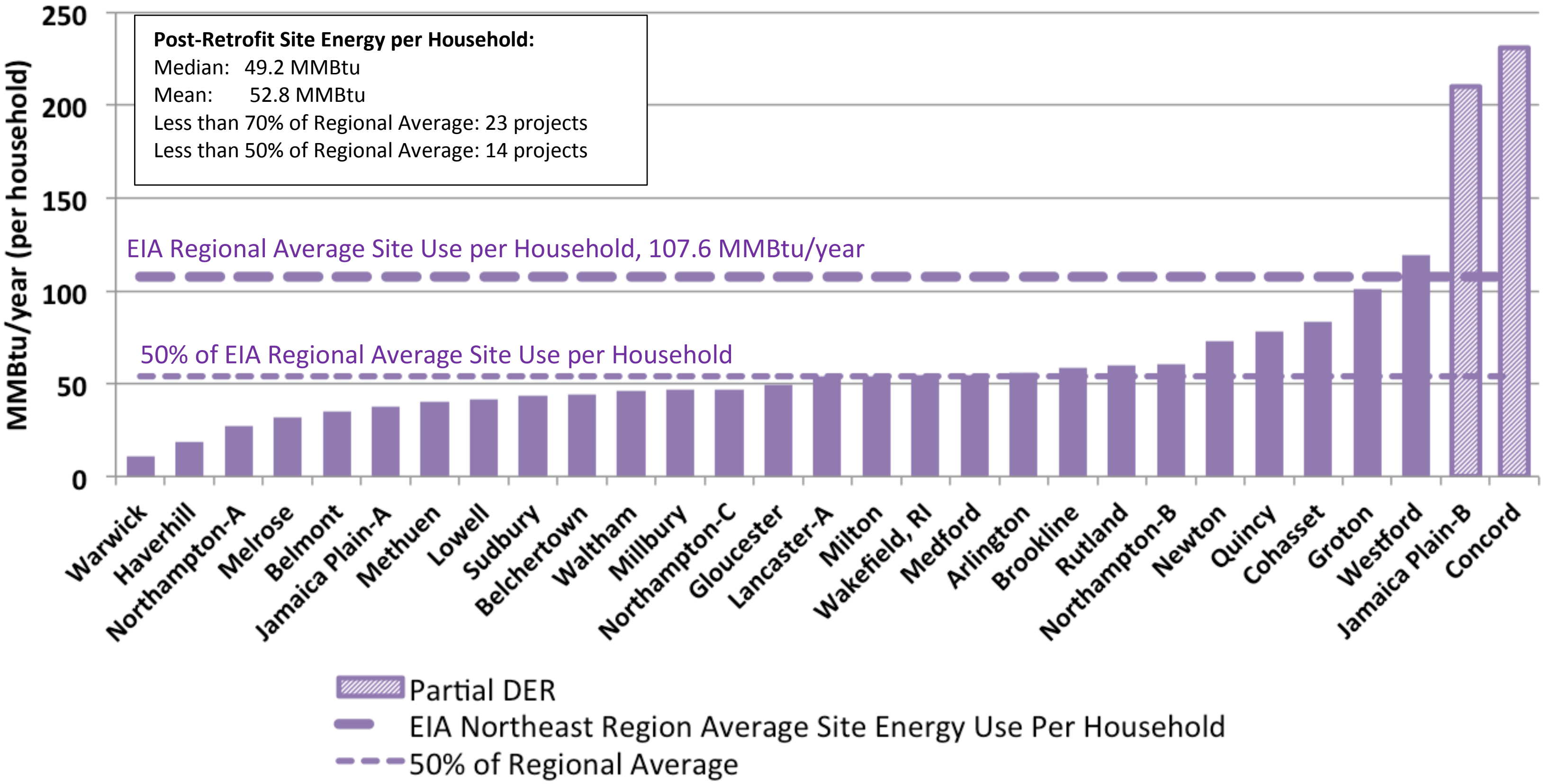


Figure 13. Post-retrofit site MMBtu/year per household

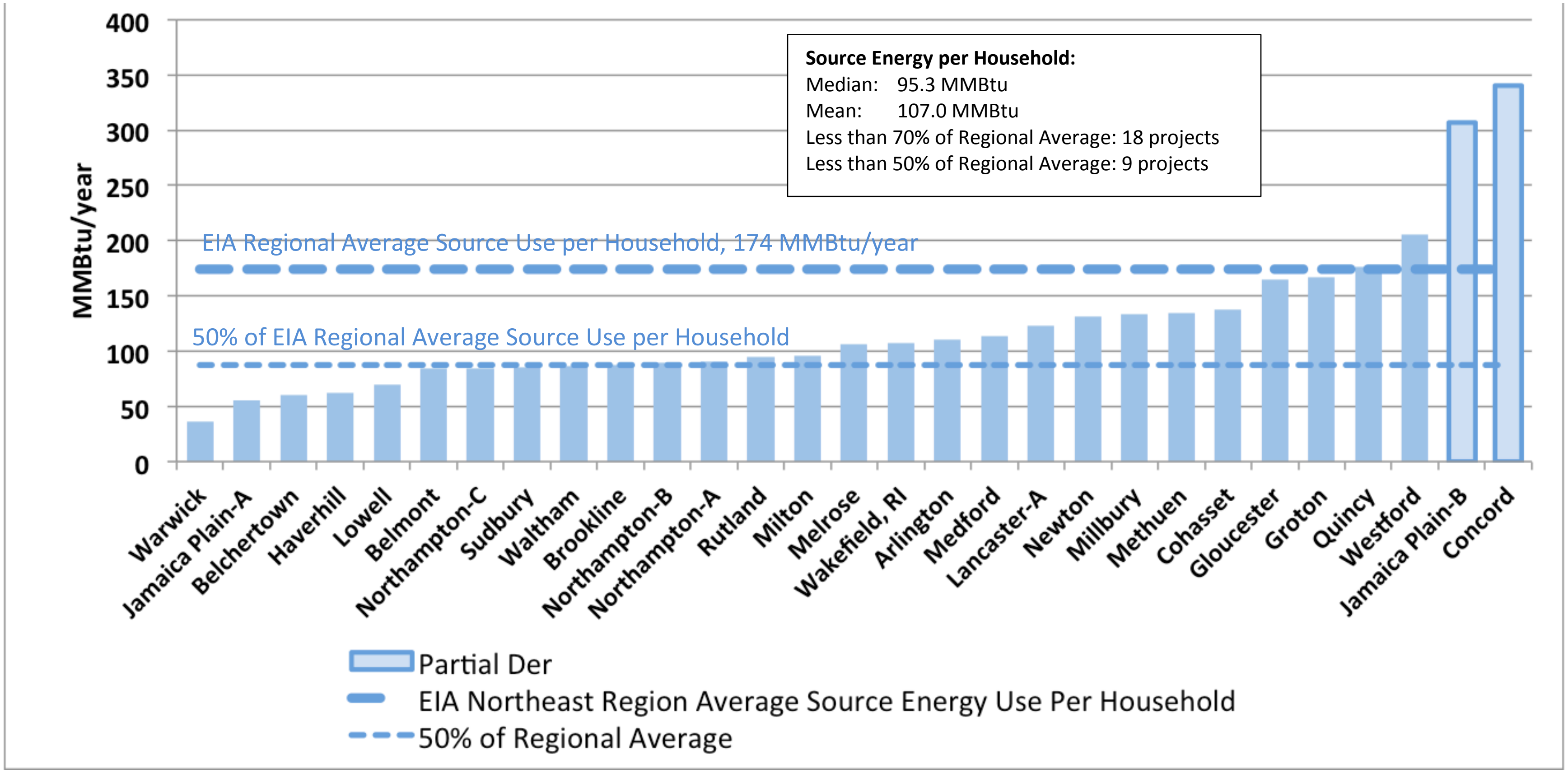


Figure 14. Post-retrofit source MMBtu/year per household

4.5.3 Post-Retrofit Energy Use Intensity

A common performance metric used for comparing energy consumption between buildings of various sizes is energy use intensity (EUI). This is the energy used per square foot of conditioned floor area, often expressed in terms of kBtu per square foot per year ($kBtu/ft^2 \cdot yr$). Performance targets of the 2030 Challenge and the Passive House program are expressed in terms of EUI. Since the EUI can refer to either source or site energy use, any EUI comparisons using must be source-to-source or site-to-site. Also, the calculation of "square footage of floor area" may vary. In this report, the conditioned space is determined by the interior dimensions of each floor and includes an insulated basement, but does not include insulated, unvented but unfinished attic space or crawlspaces.

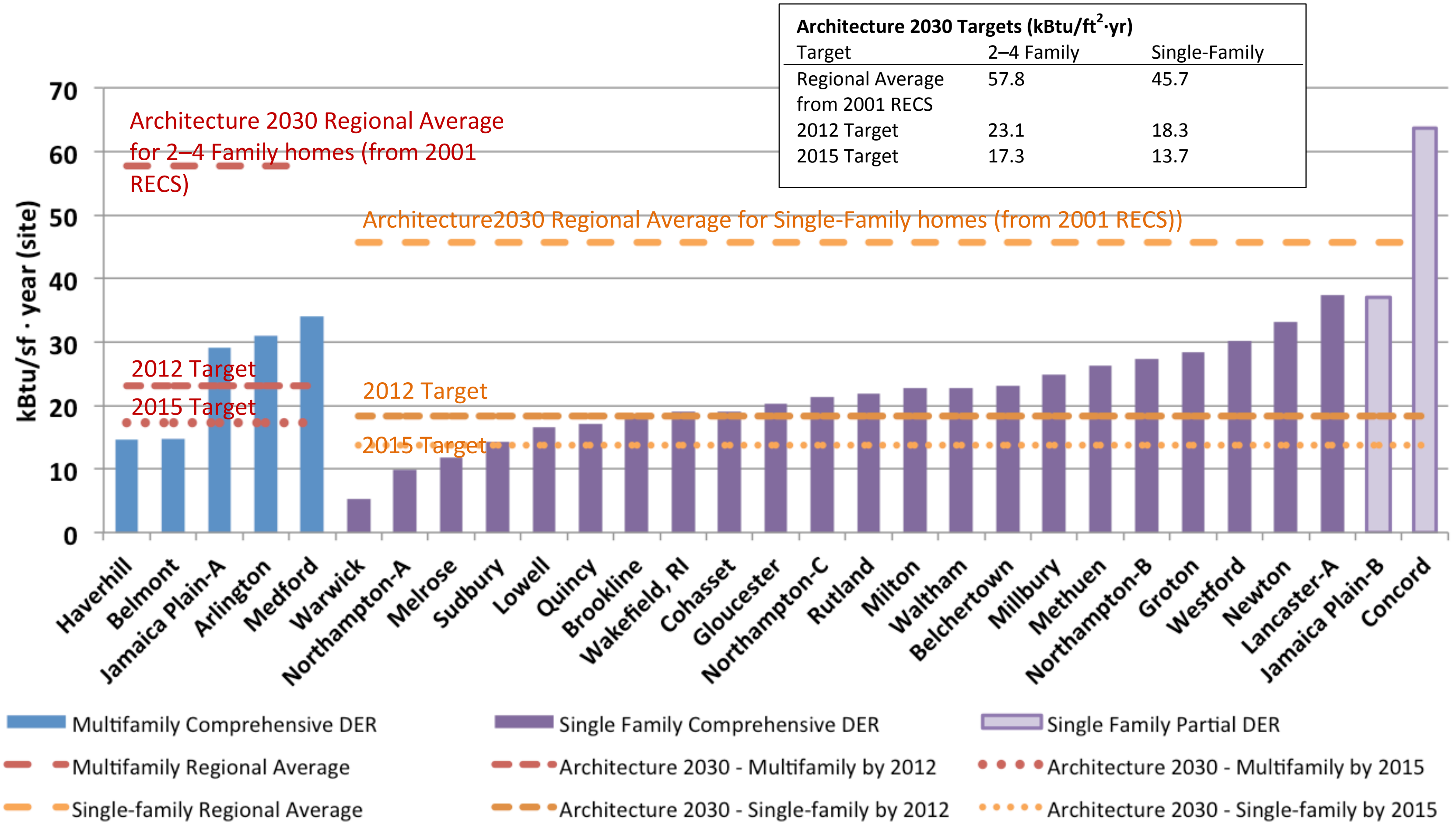
In 2002, Architecture 2030 established the 2030 Challenge with the ultimate goal of reducing fossil fuel, greenhouse-gas emitting energy consumption to zero by 2030, with intermediate goals provided along the way. These goals are stated in terms of fossil fuel-generated site energy. Therefore, this energy consumption includes all electricity use from the grid as well as natural gas and propane use on site. Intermediate reduction goals are stated relative to the building type regional average as determined by the 2001 RECS. The 2030 Challenge goal for 2012 is a 60% reduction of the average site energy for the particular building type in the region; the goal for 2015 is a 70% reduction.

Figure 15 shows the weather-normalized site energy use in site $kBtu/ft^2 \cdot yr$ for the retrofits. The figure also indicates the Northeast regional average EUI for 2-4 family and single-family houses from the 2001 RECS. The chart also shows the 2030 Challenge's 2012 and 2015 goals for Northeast multifamily (two- to four-unit multifamily houses) and single-family homes.

All of the comprehensive retrofits perform well below the respective 2001 RECS regional average EUI for multifamily and single-family homes. Even without subtracting the portion of energy used that is generated on site, three of the single-family retrofits (Warwick, Northampton, Melrose) as well as the Haverhill and Belmont two-family DERs meet the Northeast region 2015 goal of the 2030 Challenge. Six of the single-family DER projects meet the Northeast region 2012 goal.

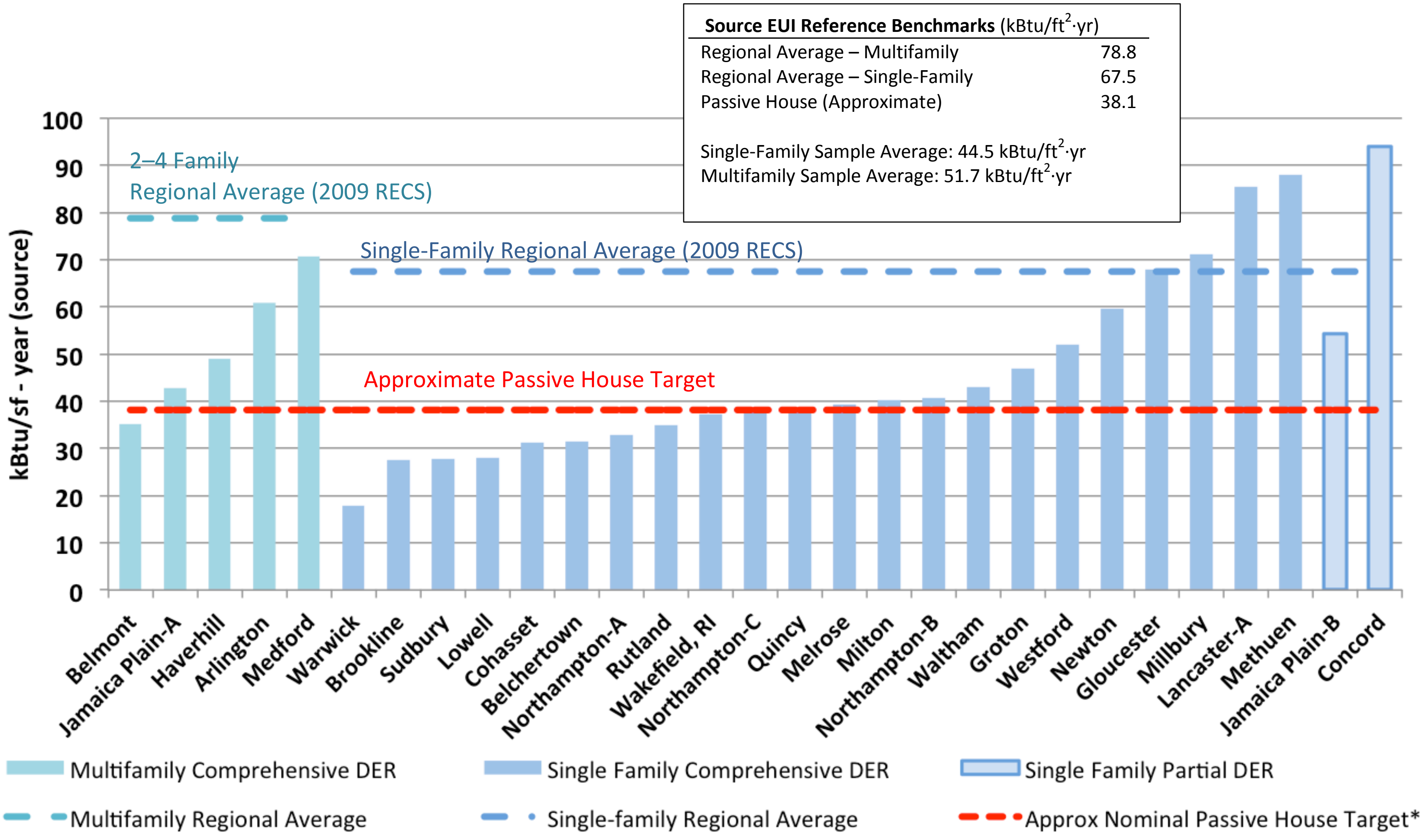
The mean site EUI for the entire group of comprehensive DER projects is less than half of the Northeast regional average determined by the 2001 RECS.

Figure 16 shows weather-normalized post-retrofit source EUI for each of the retrofits in the community. Source (or "primary energy") EUI is one of the metrics used in the Passive House program, a program that is universally acknowledged to represent a very rigorous standard for new construction building performance. In addition to indicating the regional average (based on the most current RECS survey date, 2009) source EUI for single-family and multifamily homes, the chart also indicates the nominal source EUI target for the Passive House program. Note that there is not a direct correspondence of the source EUI nominal target (38.1 $kBtu/ft^2 \cdot yr$) to the threshold indicated here, as the Passive House program uses different methodology to define conditioned floor area than the Residential Energy Services Network (RESNET 2009).



Architecture 2030 Targets (kBtu/ft²·yr)		
Target	2–4 Family	Single-Family
Regional Average from 2001 RECS	57.8	45.7
2012 Target	23.1	18.3
2015 Target	17.3	13.7

Figure 15. Post-retrofit site EUI (kBtu/ft^2·yr)



Source EUI Reference Benchmarks (kBtu/ft^2·yr)	
Regional Average – Multifamily	78.8
Regional Average – Single-Family	67.5
Passive House (Approximate)	38.1

Single-Family Sample Average: 44.5 kBtu/ft^2·yr
Multifamily Sample Average: 51.7 kBtu/ft^2·yr

Figure 16. **Post-retrofit source EUI (kBtu/ft^2·yr)**

Nine of the single-family projects and one of the multifamily projects achieved the nominal Passive House source EUI threshold. Passive House would count floor area differently including only the “net” usable floor area. Thus calculated EUI under Passive House methodology would be slightly higher. Still, it appears that at least half of the single-family comprehensive DER projects perform at a level close to this very rigorous performance standard. On average, the group of single-family DER projects achieved a source EUI of 44.5 kBtu/ft^2·yr while the group of multifamily DER projects achieved an average source EUI of 51.7 kBtu/ft^2·yr.

It is also apparent in Figure 16 that some of the single-family DER projects exceed the regional average source EUI and that some of the multifamily DERs in this group performed rather close to the regional average for source EUI. This may reflect the selection of low-performance options in the DER package, or implementation issues that detract from performance. For example, the Medford and Arlington projects excluded the basement from the thermal enclosure of the building. The analysis presented in Section 4.2 below, the strategy of excluding the basement from the thermal enclosure, results in less effective air leakage control. The Millbury and Westford projects are known to have performance problems associated with poorly functioning mechanical equipment (Gates and Neuhauser 2013).

The EUI measure has a bias that favors larger homes (Ueno 2010a). In general, one could think of the energy used in a home as representing two kinds of energy use: one is related to supporting residential function within the space and is not related to the size of the building (refrigeration, cooking, clothes washing). The other kind of energy use—heating for example—is related to factors that are tied to the size of the home. In a smaller home, the energy end uses related to people using the space (e.g., refrigeration, cooking, washing dishes) are allocated over a smaller conditioned floor area, when calculating EUI.

As shown in Figure 17, there appears to be poor correlation between house size and EUI ($R^2 = 0.17$). While there may not be a discernible correlation, it is notable that the two single-family comprehensive DER homes with the highest source EUI also have the smallest post-retrofit conditioned floor area (Figure 18).

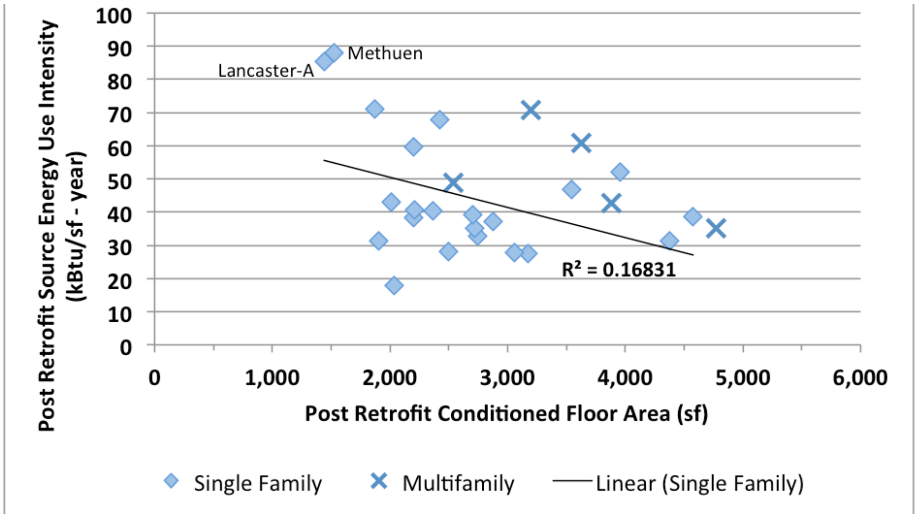


Figure 17. Source EUI relative to post-retrofit conditioned floor area for comprehensive DERs

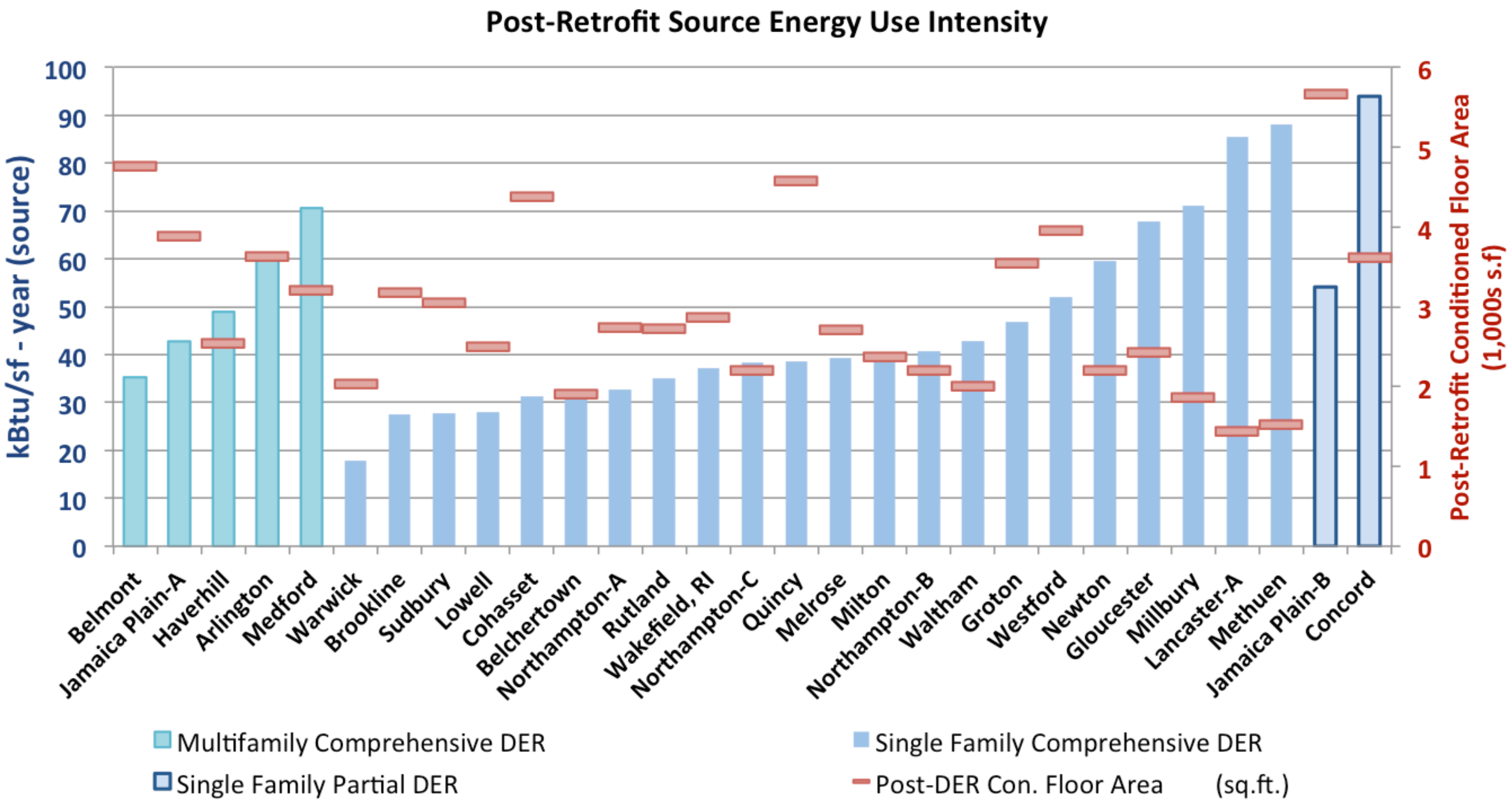


Figure 18**. Post-retrofit source EUI and post-retrofit conditioned floor area**

4.6 Impact of Retrofit Package Variations

In the following sections, the post-retrofit energy use is analyzed for the 27 comprehensive DER projects, examining trends associated with the aspects of the National Grid DER package. Given that the enclosure and mechanical system measures most directly affect heating and cooling energy use, the heating and cooling energy use disaggregated from total post-retrofit energy use is presented in this section.

4.6.1 Heating Fuel Source

Eight of the DER projects switched from primarily fossil fuel heating to electricity-fueled heating as part of the retrofit. This configuration of fuels appears to have been pursued as a means to reduce the externalities of energy use (e.g., carbon footprint) and also to control energy costs by avoiding the significant monthly fees associated with natural gas.

In high performance retrofit, the configuration of fuel or energy sources is not expected to have a significant impact on source energy use. A high efficiency heat pump system is expected to have comparable performance to a high efficiency fossil fuel heating system, when performance is measured in terms of source energy needed to satisfy the heating load. For a heat pump heating system, an overall coefficient of performance of 2.8 represents roughly the same source energy impact as a 90 AFUE boiler.[6] Table 10 and Figure 19 show the source EUI for the multifamily and single-family DER projects grouped by configuration of heating and water heating fuels. It shows that DER homes using a heat pump heating system exhibit the highest and among the lowest source EUI for the group.

Table 10. Heating Fuel and Source EUI

		Heating and Cooling EUI (kBtu/ft^2)			Total EUI (kBtu/ft^2)		
Heating Fuel	**No. Obs.**	**Range**	**Median**	**Mean**	**Range**	**Median**	**Mean**
Single-Family							
Electric Heating	7	8.6–32.8	17.1	20.2	17.8–88	67.8	57.5
Dual Fuel Heating	3	11.5–25.1	13.0	16.5	27.8–59.6	38.5	42.0
Fossil Fuel Heating	12	7.9–21.1	14.4	14.5	27.5–52	37.8	37.6
All Single-Family	22	7.9–32.8	15.0	16.6	17.8–88	38.9	44.5
Multifamily							
Electric Heating	1	23.1			48.9		
Dual Fuel Heating	1	28.9			70.7		
Fossil Fuel Heating	3	10.6–22.9	15.5	16.3	35.3–60.9	42.8	46.3
All Multifamily	5	10.6–28.9	22.9	20.2	35.3–70.7	48.9	51.7

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[6] This is a simple mathematical determination based on the relative efficiency of heating systems and the source-site ratio of the heating fuel used. For example, with a source-site ratio of 3.34 for electricity and 1.047 for gas, a heat pump system with a system efficiency or coefficient of performance of 2.86 will have nearly the same source energy impact as a gas furnace heating system with a system efficiency of 0.9 for a given heating load. This simple comparison is an approximation as a heat pump heating system will have an efficiency that varies with outdoor temperature and that tends to be lower with colder temperatures (i.e., when there are a greater number of heating load hours).

The comparatively large range in the heating and cooling source energy use for the single-family retrofits using electric heating may reflect that the effective system efficiency of these systems is highly variable between projects.

Use of a heat pump for heating or for both heating and DHW does not appear to result in noticeably higher source energy use. The three smallest single-family DER projects are among the DER projects with heat pump heating and higher source EUI. It has already been discussed how EUI has a bias against smaller homes. The multifamily building that used a heat pump for part of its heating energy use is also one that excluded the basement from the thermal enclosure.

Two of the single-family projects, Millbury and Gloucester, exhibit among the four highest source EUI measures and have ducted mini-split heat pump systems. BSC previously conducted a post-retrofit investigation of one of these projects, which concluded that the heat pump system was functioning poorly (Gates and Neuhauser 2013). The performance of ducted (as opposed to ductless) mini-split systems might be a topic for further research.

4.6.2 Included Versus Excluded Basement

One of the enclosure variants among the retrofits was the treatment of the basement. Through the project plan review process, BSC strongly advised projects against excluding the basement from the thermal enclosure, due to moisture and air quality risk. Some projects persisted with DER plans that excluded the basement from the thermal enclosure. In the sample of DER projects included in the energy use analysis, there are only two projects that excluded the basement from the thermal enclosure. Both of these retrofit projects involve multifamily (two-family) homes.

Figure 20 shows the heating and cooling source EUI for the projects and highlights the two projects that excluded the basement from the enclosure. The chart does show that the heating and cooling source EUI use for the DER projects that excluded the basement is considerably higher than for the other multifamily DERs in the peer group. However, the limited sample size and vast number of variables that affect post-retrofit energy use preclude suggesting a directly causal relationship. The air leakage analysis section below considers the impact of basement treatment on overall air leakage performance.

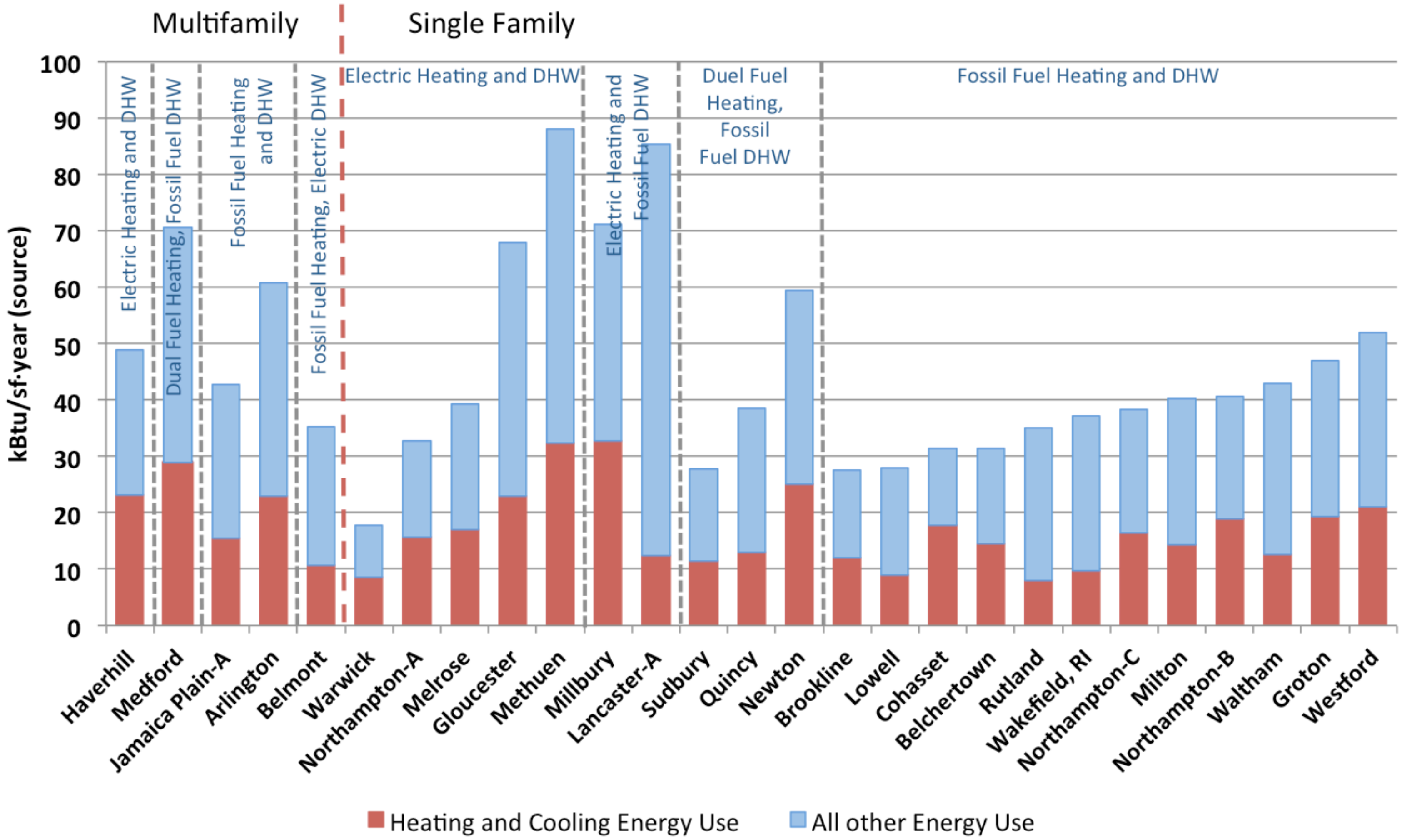


Figure 19. Post-retrofit source EUI grouped by heat and DHW fuel source with post-retrofit conditioned floor area

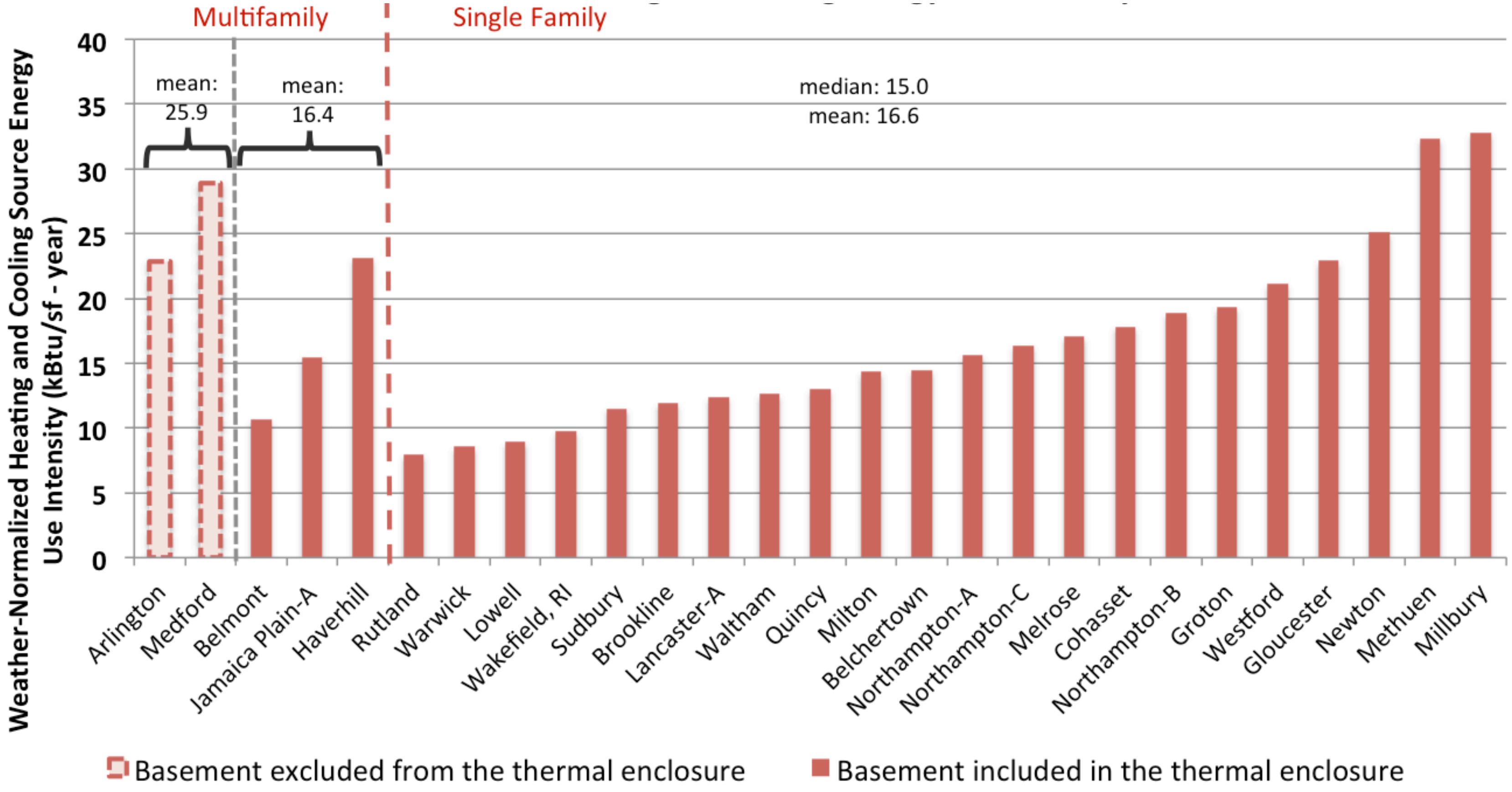


Figure 20. Post-retrofit heating and cooling source EUI by basement treatment

4.6.3 Unvented Versus Vented Attic

Another variant among the retrofit projects was treatment of the attic. The different approaches used were as follows:

- Vented attic with insulation at the attic floor
- Unvented attic with insulation under the roof deck
- Unvented attic with exterior insulation over (as well as under) the roof deck.

Vented attics and unvented attics with all insulation below the roof deck tend to have some heat loss at the wall/roof intersection due to the thermal bridging through the framing, and the limited insulation that can be installed above the wall top plate.

Figure 21 shows the post-retrofit heating and cooling source EUI for multifamily and single-family comprehensive DER projects grouped by attic and roof treatment. One of these projects includes both an unvented attic and a smaller vented attic; it is included in the unvented attic group but designated with a different bar in the chart. The mean EUIs for the vented attic DERs are appreciably higher than the mean EUIs for the unvented attic DERs. It is not clear that this difference is at all associated with the different attic/roof strategy.

The vented attic strategies applied in all of the vented attic single-family DER projects involved adding a completely new (including newly framed) roof and attic. Therefore, these vented attics are not representative of typical retrofit vented attic approaches.

When comparing the two unvented attic approaches, the group of single-family unvented attic DERs that applied insulation to the exterior and the underside of the roof deck had only a slightly lower mean heating and cooling energy use intensity than the group that employed insulation to the underside of the sheathing only.

A review of the post-retrofit performance for the first 13 DERs that completed projects through the pilot found that exterior insulation plus interior insulation appeared to have a slight edge (Gates and Neuhauser 2013). In that earlier analysis, the group of DER projects that implemented insulation to the exterior of the roof sheathing was the same set of projects that employed the so-called “chainsaw” retrofit technique at the roof-to-wall transition. In this set of DER projects, one project (Haverhill) was insulated to the exterior of the roof sheathing, but did not implement a chainsaw retrofit. Two other projects with insulation to the exterior of the roof sheathing (Lowell and Concord) implemented elements of the chainsaw technique.

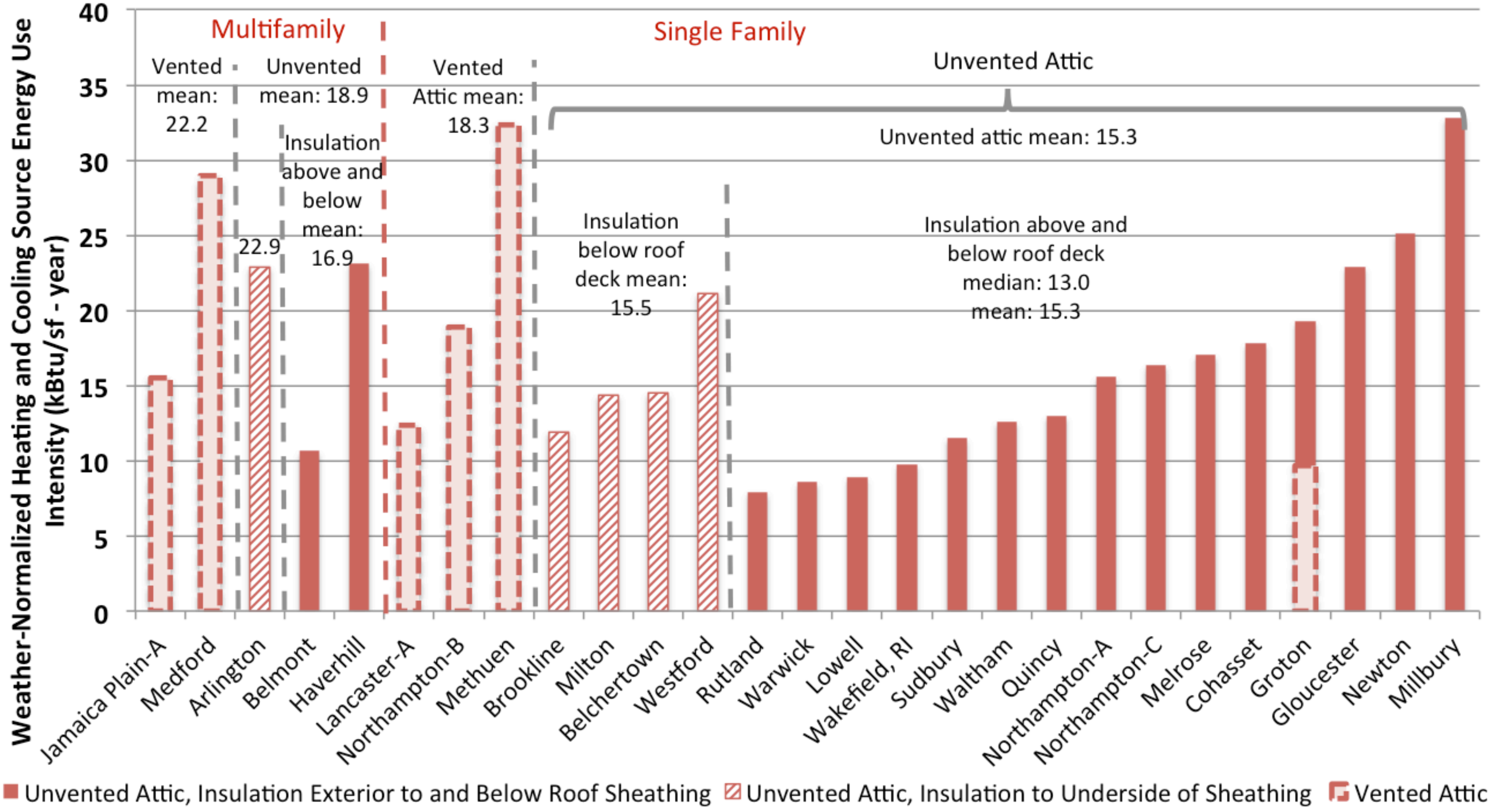


Figure 21. Post-retrofit heating and cooling source EUI grouped by attic and roof treatment

4.6.4 Airtightness Versus Post-Retrofit Energy Use

Air leakage is a major source of heat loss for homes in a cold climate. Figure 22 and Figure 23 show post-retrofit heating and cooling source EUI and heating and cooling source energy use per household (respectively), relative to the measured airtightness at the completion of the project for comprehensive DER projects.

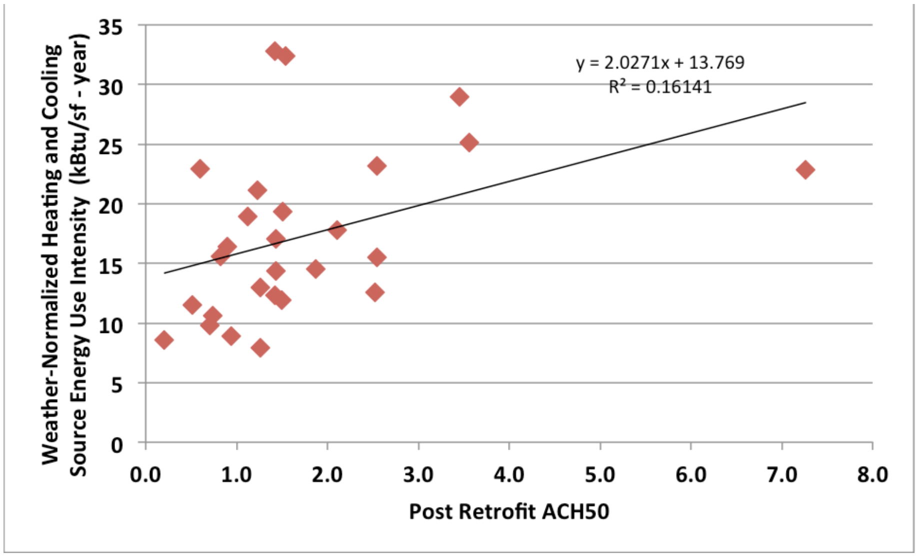


Figure 22. Post-retrofit heating and cooling EUIs relative to post-retrofit ACH50

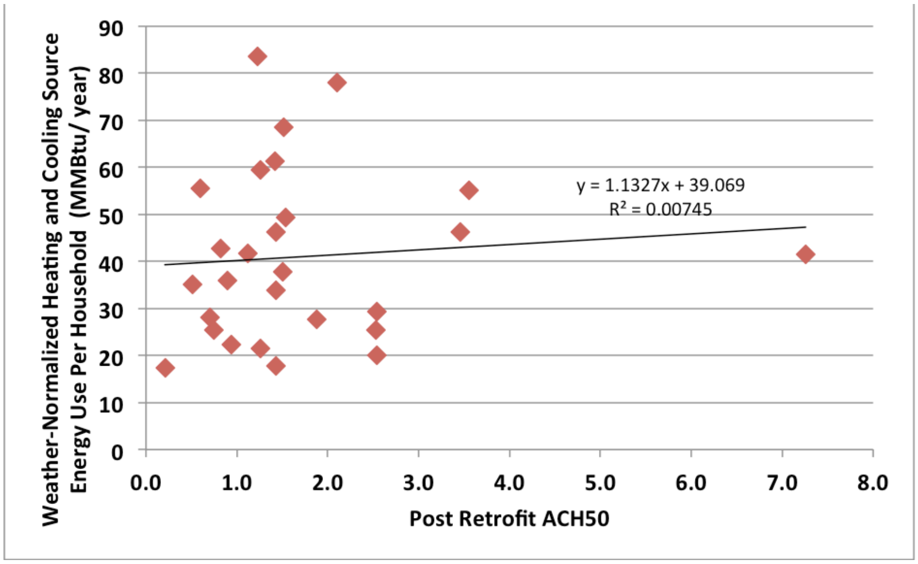


Figure 23. Post-retrofit heating and cooling energy use per household relative to post-retrofit ACH50

There is not a strong correlation between heating and cooling EUIs or per household and airtightness. There does appear to be a general trend of decreasing energy use with lower ACH50 (as one might expect).

Most of the projects with a post-retrofit measured ACH50 of 1.5 or less are in the lower energy use range, but there is also a noticeable grouping of projects in this airtightness range that exhibit post-retrofit energy use that is distinctly above the trendline for the group.

4.7 Conclusions of Energy Use Analysis

Research Question: *What measured savings does the population of DER projects demonstrate?*

For the 27 comprehensive DER projects for which sufficient post-retrofit energy use data were available, the mean reduction in total site energy use achieved is 58% with the site energy use reductions for individual projects ranging from 29% to 89%. On a source energy basis, the sample exhibits a mean reduction of 41% with a range of 10% to 74%. The authors maintain, however, that energy use reduction is not an appropriate metric for comprehensive retrofit. Because pre-retrofit conditions are highly variable, the relative reduction found in one sample of buildings is not necessarily applicable to another sample of buildings or to any one building. The post-retrofit performance achieved is a more reliable indicator of the potential benefit from the comprehensive DER package.

Research Question: *What level of post-retrofit energy performance does the population of DER projects demonstrate?*

The DER projects were compared to a variety of benchmarks (regional averages, etc.). This analysis used weather-normalized post-retrofit energy use for the 27 comprehensive DER projects for which sufficient post-retrofit energy use data were available:

- In terms of household site energy use, all but one project achieved performance that is below the EIA Northeast regional average; 14 of the comprehensive DER projects achieved performance that is below half of the regional average. The group of projects exhibits a mean per household site energy use of 52.8 MMBtu/year, which is slightly less than 50% of the regional household average.
- All but two of the comprehensive DER projects achieved household source energy use below the EIA Northeast regional household average; nine of the DER projects achieved performance that is less than 50% of the regional household average. The mean for the group is 107 MMBtu/year, or approximately 38% below the regional household average.
- In terms of site EUI, all of the comprehensive DER projects perform below the regional average with the mean for both the multifamily and single-family DER projects being below 50% of the respective Northeast region average. Two of the multifamily projects and three of the single-family projects meet the 2015 site EUI goal for the Architecture 2030 Challenge without taking any credit for on-site electricity generation.
- All but four of the of the single-family DER projects achieved source EUI that is below the Northeast regional multifamily and single-family average. Both the single-family and multifamily projects achieved a mean source EUI that is 34% lower than the respective regional average. One of the multifamily projects and nine of the single-family projects achieved a source EUI that is below the nominal primary energy use target in the Passive House program for new construction (albeit with different floor area calculations).

Based on this community, this DER package is expected to result in yearly source energy use on the order of 110 MMBtu/year or approximately 40% below the Northeast regional average. Larger and medium-sized homes that successfully implement these retrofits can be expected to achieve source EUI that is comparable to Passive House new construction.

Whether the National Grid pilot met the aspiration of demonstrating a 50% reduction in energy use relative to typical homes in the region depends upon whether the energy use is measured in terms of site energy or source energy. By both per-household and EUI metrics the sample of DER projects has a mean post-retrofit energy use that is more than 50% below the regional average on a site energy basis. On a source energy basis, the post-retrofit performance is less than 50% below the regional average.

Research Question: *Do energy performance data show discernible differences that may be attributable to variations in the approach to the overall DER package?*

No significant trends emerges from analysis of the post-retrofit energy use data. The following observations relative to heating and cooling source EUI may suggest topics for further study:

- DER projects that implemented a heat pump (electric) based heating system exhibited a wide range of performance relative to other DER projects. This may indicate significant variation in effective heat pump system efficiency.
- Projects in this sample that exclude the basement from the thermal enclosure exhibit higher heating and cooling EUIs than other DER projects in their peer group. With the limited number of observations for this variation among the sample, it is not possible to assert a direct causal relationship. The data from this study suggest a topic worth examining with a more targeted study.
- Among different approaches to attic and roof retrofit, the DER projects that implemented an unvented attic approach appear to have lower heating and cooling energy use on average.
- The data show only a vague trend of lower energy use with greater airtightness. The data also indicate significant variation in energy use associated with similar levels of airtightness. Controlling for some of the other variables in the package implementation, such as heating fuel, might reveal a stronger relationship between airtightness and heating and cooling energy use.

5 Airtightness Results and Analysis

One requirement for the participants in the National Grid DER pilot program was to provide a plan for airtightness, with a target of achieving 0.10 CFM/ft^2 of the building enclosure surface area (all six sides) at 50 Pascal air pressure differential (i.e., 0.10 CFM50/ft^2 enclosure). Toward meeting this goal, participants were asked to identify the air control system for the house and a means for ensuring that it was continuous.

The air control system is a system of materials designed and constructed to control airflow between conditioned space and unconditioned space. It is the primary boundary that separates indoor (conditioned) and outdoor (unconditioned) air (see Lstiburek 2005 for a primer on the subject). The air control system can be located anywhere in the building enclosure: at the exterior surface, the interior surface, or anywhere in between. However, it must be continuous over the entire enclosure, air impermeable, durable, and able to withstand forces acting on the building, both during and after construction.

The primary purpose of the air control system is to prevent energy loss through direct air exchange between the interior and exterior. Since this air exchange also includes air-transported moisture, it is also part of the vapor control system.

Post-retrofit air leakage testing results were obtained for each of the projects participating in the pilot therefore the DER project sample in this section includes all 42 DER projects participating in the pilot. Table 12 and Table 13 provide airtightness testing results for the full and partial DERs, respectively. Results are given for pre-retrofit tests (available in all but three cases), and post-retrofit tests. The results are also normalized in terms of air changes per hour at a 50 Pascal air pressure differential (ACH50), based on the volume of the house post-retrofit. The materials used to create the air barrier at the roof/attic, above-grade wall, and basement ceiling (where applicable) were called out per project; the key is shown in Table 11. The final column in Table 12 and Table 13 shows whether the “chainsaw” retrofit was used at the roof-wall junction (Yes/No/Partial).

Table 11. Air Barrier Material/Air Control Layer Key for Data Tables Below

Abbreviation	Air Barrier Material/Air Control Layer
CB	Taped/sealed ceiling board
DW	Drain wrap (corrugated house wrap)
FA	Fully adhered membrane
HW	House wrap
SPF	Spray polyurethane foam insulation
TI	Taped rigid insulation
TP	Taped panel
TPly	Taped plywood
n/a	Not applicable

Table 12. DER Community Test Results and Air Control System Properties–Full DERs

House Location	Pre-Retrofit CFM50	Post-Retrofit CFM50	Pre-Retrofit ACH50	Post-Retrofit ACH50	Roof/Attic Air Control Material (See Key Above)	Above-Grade Wall Air Control Material (See Key Above)	Basement Ceiling Air Control Material (See Key Above)	Chainsaw? Yes/No/ Partial
Belchertown, MA	9,097	468	57.7	1.88	SPF	SPF	n/a	N
Belmont, MA	5,700	590	9.3	0.74	FA	HW+TI	n/a	Y
Millbury, MA	2,860	402	10.4	1.42	FA	HW	n/a	Y
Milton, MA	1,695	584	4.5	1.43	SPF	HW	n/a	N
Quincy, MA	5,050	762	18.5	1.26	HW	HW	n/a	Y
Arlington, MA	8,730	3,586	30.0	7.26	SPF	HW old/TP new	TI	N
Newton, MA	3,199	1,299	10.2	3.56	HW	HW	n/a	Y
Jamaica Plain-A, MA	7,729	1,802	10.9	2.54	SPF sloped/CB flat	HW + TI	n/a	N
Northampton-A, MA	6,155	473	Pre-retrofit volume not available	0.82	FA	TP	n/a	Y
Lancaster-A, MA	4,254	293	36.1	1.43	SPF	HW	n/a	N
Brookline, MA	1,640	655	3.8	1.50	SPF	HW + TI	n/a	N
Westford, MA	2,592	930	4.8	1.22	SPF	TPly old/SPF new	n/a	N
Gloucester, MA	2,258	235	6.6	0.60	FA	HW	n/a	Y
Medford, MA	5,296	1,922	9.9	3.46	SPF sloped/CB flat	HW	TI	N
Northampton-B, MA	1,315	556	4.1	1.12	Poly sheet	TPly	n/a	N
Haverhill, MA	6,970	1,085	18.0	2.54	SPF	HW	n/a	N
Dorchester, MA	13,779	5,084	19.9	7.10	SPF sloped/CB flat	HW	TI	N
Rutland, MA	1,658	493	6.6	1.26	FA	HW+TI	n/a	Y
Methuen, MA	2,452	504	11.6	1.54	CB	Nail base insul.	n/a	N
Wakefield, RI	4,665	222	14.8	0.70	FA	FA	n/a	Y
Groton, MA	2,644	830	4.8	1.51	SPF	HW + TI	n/a	Y
Williamstown, MA		556		2.30	TI	HW	n/a	N
North Kingstown, RI	2,800	1,358	5.6	2.25	SPF	SPF	n/a	N
Cohasset, MA	4,455	1,664	7.4	2.10	TPly	HW	n/a	Y
Sudbury, MA	2,095	224	Pre-retrofit volume not available	0.51	FA	HW	n/a	Y
Worcester, MA	9,779	464	19.5	0.88	FA	HW + TI	n/a	Y
Northampton-C, MA	2,800	453	Pre-retrofit	0.90	FA old/TP new	TI old/TP new	n/a	Y

House Location	Pre-Retrofit CFM50	Post-Retrofit CFM50	Pre-Retrofit ACH50	Post-Retrofit ACH50	Roof/Attic Air Control Material (See Key Above)	Above-Grade Wall Air Control Material (See Key Above)	Basement Ceiling Air Control Material (See Key Above)	Chainsaw? Yes/No/ Partial
			volume not available					
Warwick, MA	1,689	60	5.9	0.21	FA	HW	n/a	Y
Lexington, MA	4,658	536	18.8	1.26	TP	TI	n/a	Y
Melrose, MA	2,798	434	10.3	1.43	FA	DW	n/a	Y
Providence-A, RI		1,429		1.94	FA	HW	SPF	Y
Roslindale, MA	2.700	1,213	6.4	2.48	FA	DW	n/a	P
Lowell, MA	3.547	340	13.2	0.94	HW old/TP new	HW	n/a	P
Waltham, MA	3,005	677	17.6	2.53	FA	HW + TI	n/a	Y
Northampton-D, MA	7,635	476	11.3	0.70	TP	HW	n/a	Y
Lancaster-B, MA	5,709	1,886	Pre-retrofit volume not available	3.00	FA	DW	SPF	Y
Providence-B, RI		1,134		2.02	FA	HW	n/a	Y

Table 13. DER Community Test Results and Air Control System Properties–Partial DERs

House Location	Pre-Retrofit CFM50	Post-Retrofit CFM50	Pre-Retrofit ACH50	Post-Retrofit ACH50	Roof/Attic Air Control Material (See Key Above)	Above-Grade Wall Air Control Material (See Key Above)	Basement Ceiling Air Control Material (See Key Above)	Chainsaw? Yes/No/ Partial
Jamaica Plain-B, MA	8,000	4,539	9.9	5.29	SPF	n/a	n/a	N
Florence, MA	4,094	1,902	6.5	3.07	CB	n/a	n/a	N
Concord, MA	3,376	1,907	5.9	3.33	FA	n/a	n/a	N
Watertown, MA	4,988	2,440	6.3+	3.04	HW	n/a	n/a	Y

5.1 Airtightness Test Results

Blower door tests were performed on the homes prior to the beginning of the DER construction and again after the DER construction was complete. Pre-DER and post-DER total CFM50 blower door test results are shown in Figure 24. No pre-DER results are shown for three projects (Williamstown, Providence RI-A and Providence RI-B), because demolition work had begun prior to engagement with the National Grid program and thus testing could not provide meaningful results.

The percent of total CFM50 reduction between the pre-DER and post-DER is shown in Figure 25. For all of the full DER projects, the reduction in total CFM50 was greater than 50%. For the partial DER projects, all of which included treatment of the roof or attic but not the exterior walls, the reduction in total CFM50 was from 40% to 55%.

The CFM50 measure represents an absolute measure of air leakage not normalized to building geometry. This metric is useful, for example, to gauge the impact on air leakage of a particular renovation project regardless of how or whether the renovation might have changed the area of the enclosure or the volume of space enclosed.

The National Grid pilot program established an enclosure airtightness target in terms of CFM50 per enclosure area. This metric provides a standard of airtightness performance for the enclosure components retrofit as well as those components for which the retrofit is incentivized.

Air changes per hour induced by a 50 Pascal pressure difference (ACH50) is a more common measure for building airtightness. It is used in the ENERGY STAR and Passive House programs, for example. Because the measured air leakage rate at an induced pressure difference is expressed relative to the volume of enclosed space, the ACH50 measure can be thought of as normalized to building size.

When the airtightness results are normalized to ACH50 (air changes per hour at a differential of 50 Pascals), more than half of the full-DER projects achieve an airtightness of 1.5 ACH50 or better (see Figure 26).

All but two projects among the full-DER projects have airtightness results meeting that required for ENERGY STAR v3 homes. These two projects, Dorchester and Arlington, which are obvious outliers in terms of airtightness for the DER community, established the lower air control layer at the basement ceiling rather than including the basement within the air control enclosure. It has been observed in the past that this often results in significant air leakage through the basement ceiling (Ueno and Lstiburek 2012).

In order to assess how variations in the DER package might impact airtightness performance, it is important to first check whether other significant factors such as size, age, and pre-retrofit condition of the building impact post-retrofit performance. As can be seen by the scatter graphs in Figure 27, there is no apparent relationship between the post-DER airtightness results achieved and the size, the age/vintage, or the pre-DER airtightness conditions of the house.

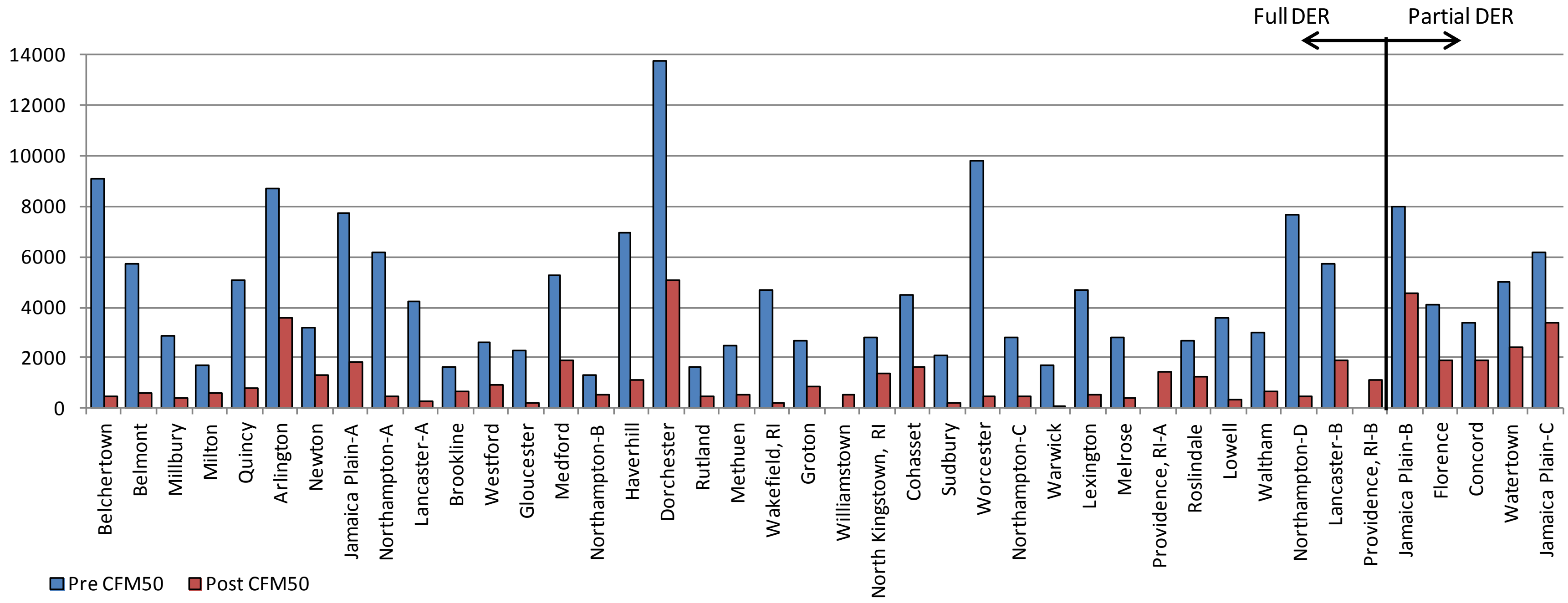


Figure 24. Pre-DER and post-DER total CFM50 results

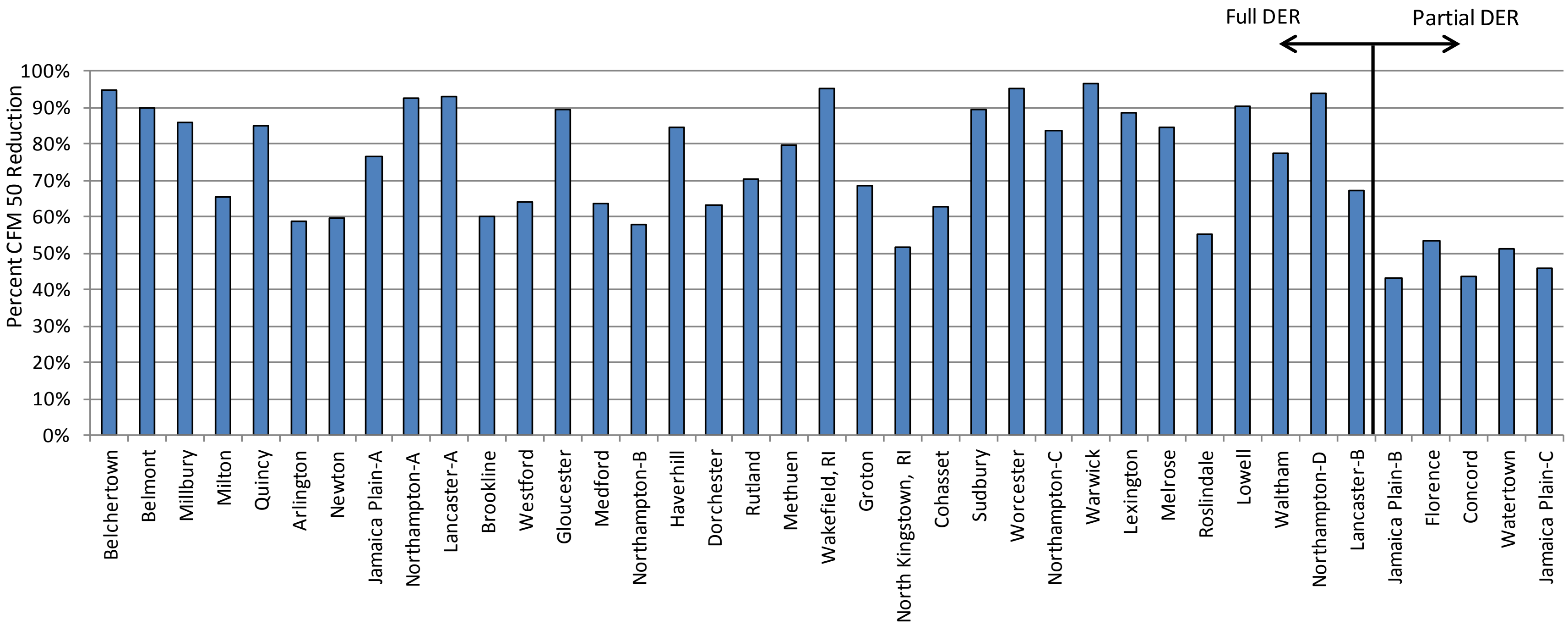


Figure 25. Percent reduction from pre-DER to post-DER total CFM50

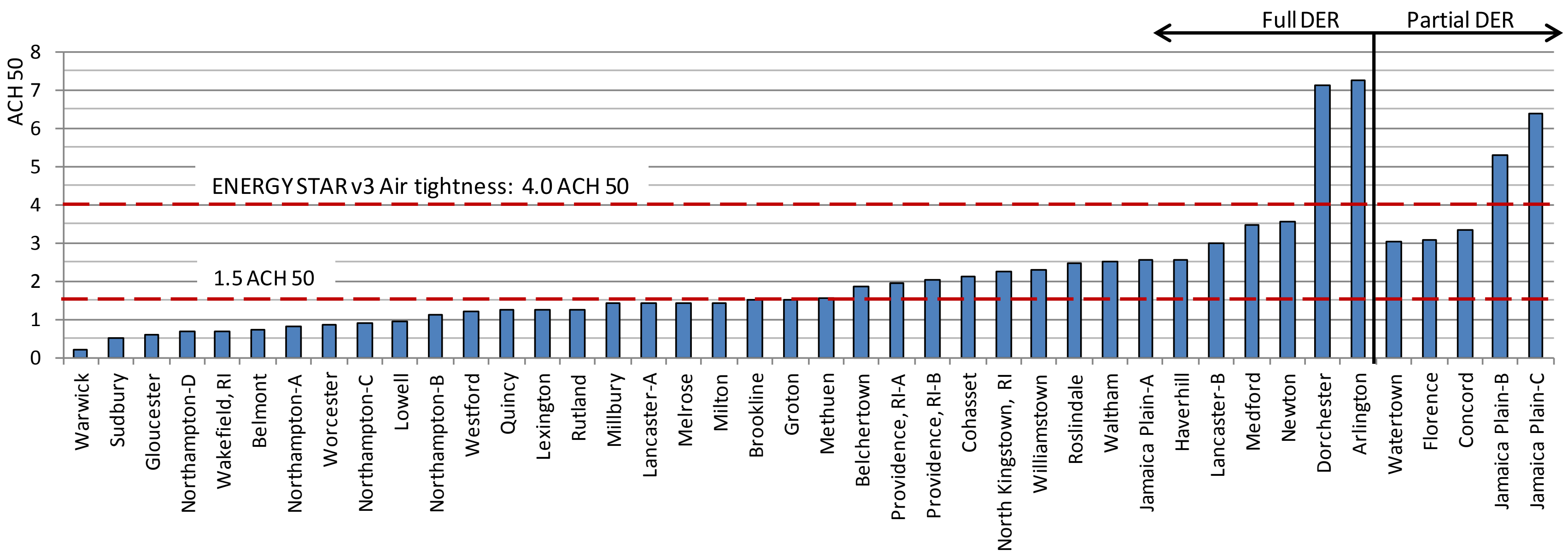
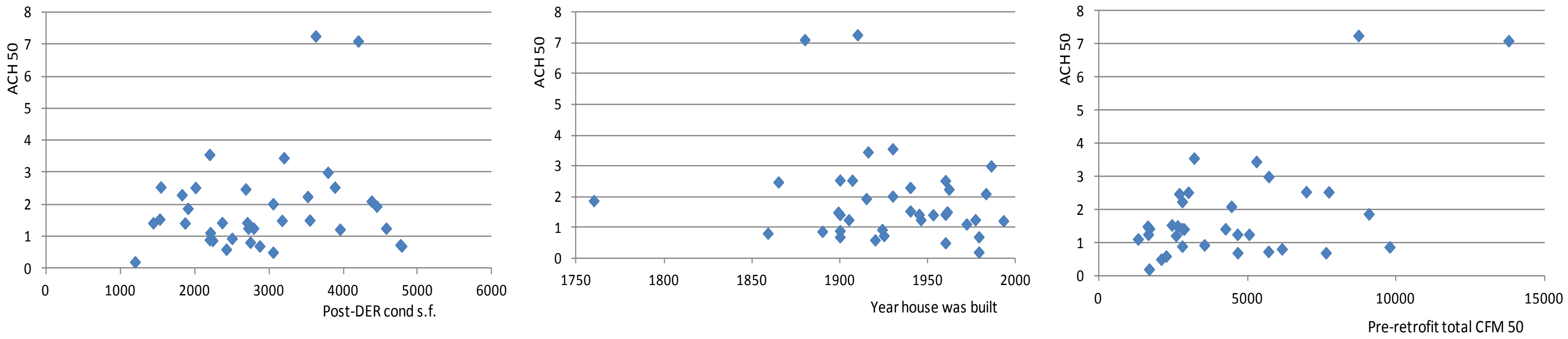


Figure 26. Post-DER ACH50 results



Post-DER Conditioned Square Feet | **Year House Built** | **Pre-retrofit total CFM50**

Figure 27. Post-DER ACH50 versus size of house, year house was built, and pre-DER total CFM50

5.2 Analysis of Airtightness and DER Package Variations

In the following subsections, the airtightness results for the full DERs are analyzed with respect to several variations within the implementation of the DER measures that may be expected to have an impact on the airtightness results. These variables include inclusion/exclusion of basement in air control enclosure, vented/unvented attic, and air control materials.

5.2.1 Inclusion/Exclusion of Basement in Air Control Enclosure

The DER measures did not specify whether the basement was to be included in the thermal and air control enclosures. In general, it is better to include the basement in the thermal and air control enclosures because (1) mechanical equipment and ductwork is typically located there (resulting in regain of duct/pipe thermal losses); (2) this approach reduces the dampness commonly associated with a basement if executed correctly; and (3) it is very difficult to establish an effective air separation between the basement and the rest of the house due to the many penetrations and framing connections in the basement ceiling (Ueno and Lstiburek 2012).

As shown in Figure 28, five of the projects chose to exclude the basement from the thermal and air control enclosure. The results from this group support the previous argument that air separation is difficult to achieve at the basement ceiling. During the blower door testing of the Arlington project, it was noted that roughly half of the total air leakage from the building was occurring through the basement ceiling (Neuhauser 2011).

As indicated in Figure 28, two of the projects for which the basement was excluded used SPF insulation in the basement ceiling framing for the air control layer, while the other three used taped rigid insulation panels for the air control layer. The two retrofits with SPF insulation in the basement ceiling have better airtightness results than those that used taped rigid insulation, but these are still significantly leakier than the mean for the group of projects that included the basements.

Garages and unconditioned crawlspaces with living space above can create similar difficulties in establishing an air separation as basement ceilings, though generally there are fewer (if any) penetrations to be accommodated. The projects that included the basement but also have these other conditions are shown as subgroup in Figure 28.

Since exclusion of the basement appears to be a significant factor in air leakage results, these projects are distinguished in the analysis charts in the remainder of this section.

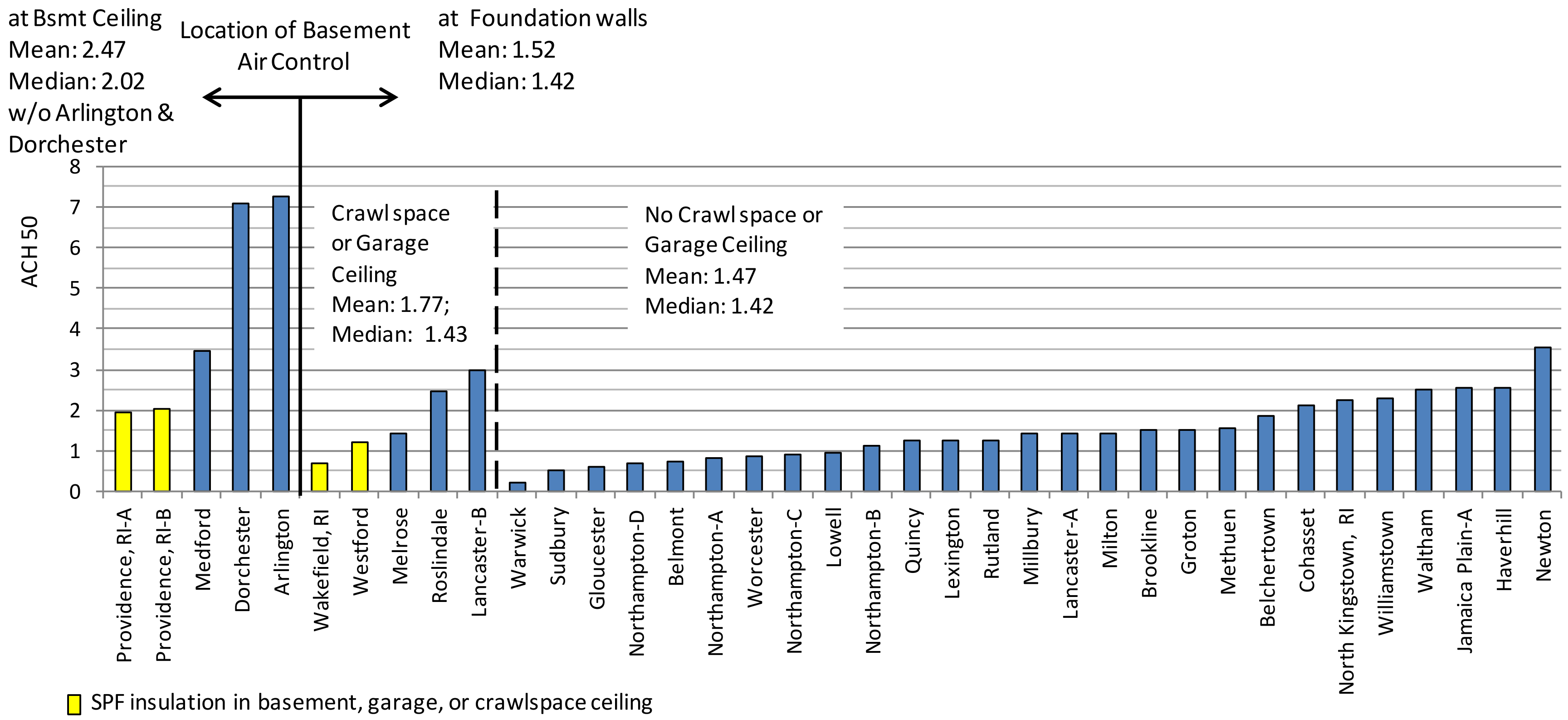


Figure 28. Post-DER ACH50 results grouped by treatment of basement

5.2.2 Vented/Unvented Attic

The DER measures did not specify whether the upper thermal and air control layers were to be at the attic floor (vented attic) or at the roof plane (unvented attic). Seven of the DER projects established the thermal and air control layers at the attic floor (or top floor ceiling). The air control layer was at the roof plane for all of the other full-DER projects.

For a retrofit, establishing an air barrier between the attic and the conditioned space below can be hindered by the ceiling and roof framing, knee walls, or partition walls in the floor below. However, the more difficult air control problem is to create a continuous connection between the air control layer at the attic floor and the air control layer of the exterior wall. This is particularly difficult when the air control layer for the wall is on the exterior of the wall, as is the case for all except one of the DER projects: the air barrier must be transitioned across the thickness of the built-out wall.

A similar continuity problem may exist with an unvented attic when the air control layer is to the interior side of the roof, but is to the exterior side of the wall. If there is discontinuity of air control across this transition, there will be air leakage at the intersection of the roof and the exterior wall. On the other hand, if the air control layers for the roof and for the wall are both to the exterior, the connection between the two is straightforward if the rafter tails and rake overhangs are cut off before the air control layers are applied. The roof air control layer can then lap over (and be sealed to) the wall air control layer, thus eliminating the air leakage at the intersection. This technique is commonly referred to as the “chainsaw” approach (Orr and Dumont 1987; Holladay 2009).

Figure 29 groups the DERs by vented and unvented attics, and then the unvented attics by chainsaw, partial chainsaw, or non-chainsaw air control. The partial chainsaw retrofits are those that used the chainsaw approach for only part of the house. While the Dorchester and Arlington projects are shown in their appropriate groups, these projects are not included in computing the means and medians for the groups because of their outlier status.

The results for the vented attic group show that very good airtightness results can be obtained when a new attic or roof is being built as part of the overall project. While this may not be typical for a retrofit, it can occur when the retrofit project is combined with the addition of space (as was the case for Northampton-B, Lancaster-A and Methuen). With careful sequencing of the construction, the air control continuity at the intersection of the wall and the attic can be established before the new rafters or trusses are put in place. The Williamstown project also included a new space over one portion of the existing house, but parts of the existing attic were retained.

The mean and medians for the full chainsaw group were better than those of the partial chainsaw and the non-chainsaw group, as well as those of the vented attic group. In addition, the chainsaw group includes the nine best airtightness results of all of the DERs.

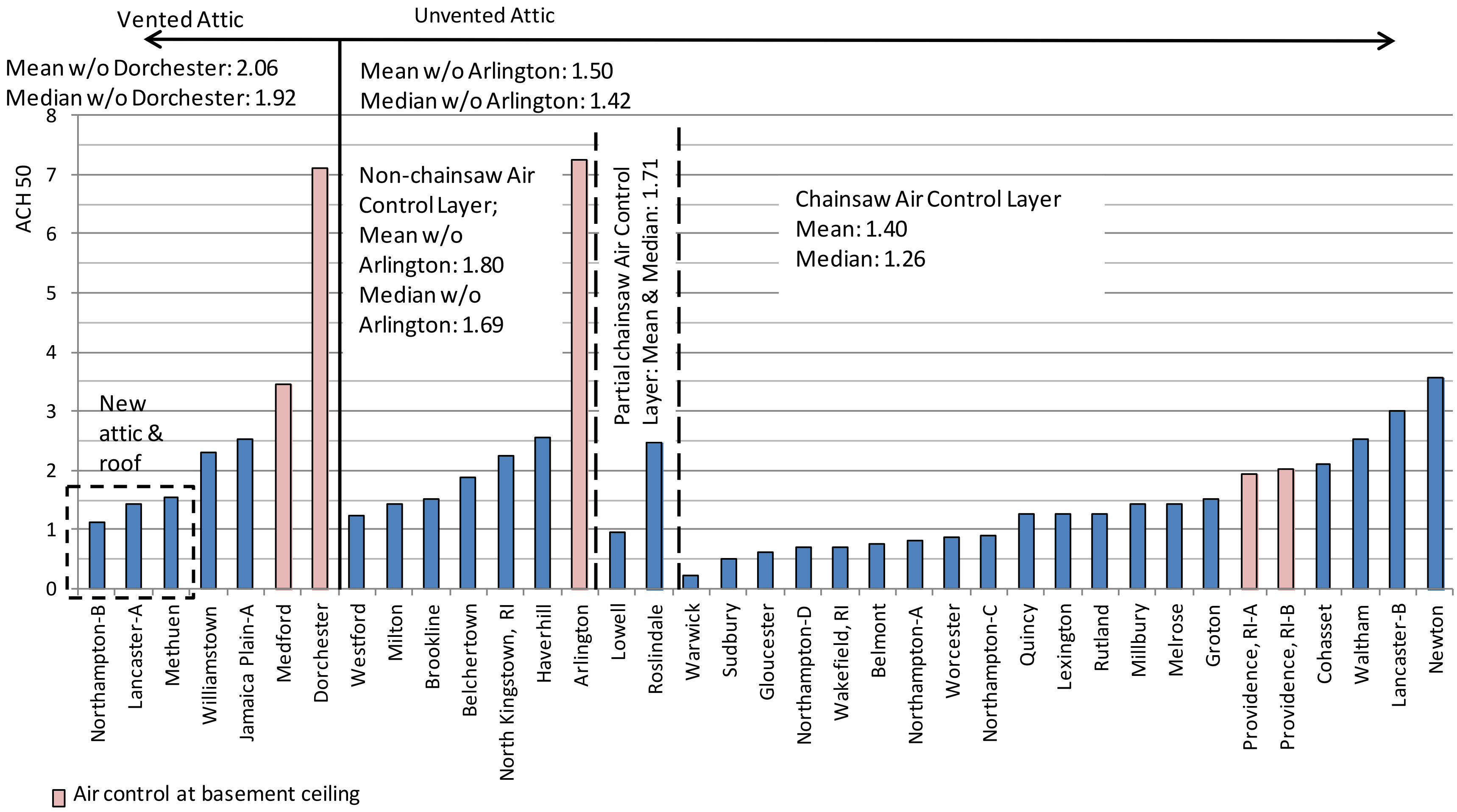


Figure 29. Post-DER ACH50 results grouped by treatment of attic/roof treatment

5.2.3 Air Control Materials

The airtightness results are primarily a function of the following factors and sub-factors:

- Roof/attic and above-grade wall air control layers
    - Material
    - Location
    - Installation
- Effectiveness of the connection between the air control layers of different components
    - Roof/attic to exterior wall
    - Exterior wall to window/door
    - Exterior wall to foundation wall/basement ceiling.

In the previous sections, the location and some aspects of the installation and connections have been compared. In this section, the comparisons are based primarily on air control materials for the roof/attic and for the above-grade walls.

The materials and approaches used for above grade wall air control in these projects included:

- Taped and sealed house wrap or drain wrap (corrugated house wrap) applied over the existing sheathing (majority of projects)
- Taped oriented strand board (OSB) panels
- Taped plywood panels
- Taped rigid insulation
- Fully adhered membrane over the existing sheathing (one project)
- SPF insulation on the interior (one project).

All of the projects with an exterior wall air control layer also applied insulation to the exterior of the walls: most projects used taped foil-faced polyisocyanurate, while other choices included semi-rigid mineral wool and nail base insulation panels. Several of the projects that used taped and sealed house wrap also incorporated the exterior insulating sheathing into the wall air control layer by sealing all of the layers together at the assembly perimeter and at openings.

For the vented attic air control layer, most projects used a layer of SPF insulation, taped ceiling board, or a combination of SPF insulation and taped ceiling board. One project used a continuous polyethylene sheet between the attic and the living space below.

The unvented attic approaches can be divided into interior- and exterior-side air barriers. The projects that used an interior air control layer under the roof deck used SPF insulation. The projects that used exterior air control used taped and sealed house wrap, taped OSB panels, or fully adhered roof membrane. In most (but not all) cases with an exterior air control roof layer, exterior insulation in the form of taped foil-faced polyisocyanurate was applied over the air control layer. The exceptions were Lexington, Providence RI-A and Providence RI-B: they all used an exterior air control layer on the roof, but all insulation is on the interior side of the roof deck.

In Figure 30, the projects are grouped first according to the type of roof/attic air control material and then according to the type of wall air control material. The term *panel* includes OSB panels, plywood panels, rigid insulation panels, or ceiling board panels; house wrap includes drain wrap. As outliers, the Dorchester and Arlington projects are not included in the computation of any of the means.

Among the four groupings based on roof air control material, the group that used fully adhered membrane for the roof air control is the largest group, has the second best airtightness result, and contains many of the best individual airtightness results. The best group airtightness result is for the “Others” group. This group is not well characterized by the roof air control material: it includes two projects that use different air control materials on different sections of the roof and the vented attic project that uses a sheet of polyethylene on the attic floor.

When the wall air control material subgrouping is also included, there is a marginally consistent pattern within each of the roof groups of taped panels for walls having the best results, then taped house wrap plus insulating sheathing, and then taped house wrap.

Many of these projects used SPF insulation in either the wall or the roof/attic component, though this was not always relied upon as the air control material. SPF insulation is air impermeable, creates a seal with the framing elements when applied per manufacturer’s instructions, and is relatively easy to apply as a continuous layer even where there is limited access. Therefore, its use could be expected to improve the robustness of the air control system.

The normalized airtightness results grouped by SPF and non-SPF (in roof and walls) are shown in Figure 31. As a group, use of SPF insulation for both the walls and the roof has better ACH50 results than when the SPF insulation is used only for one or the other (or for only parts of the walls or roof). But the group with the best ACH50 result is the group that does not use SPF insulation at all in the walls or roof. These projects used cellulose or batt insulation for the cavity insulation, and did not rely on cavity insulation for air control.

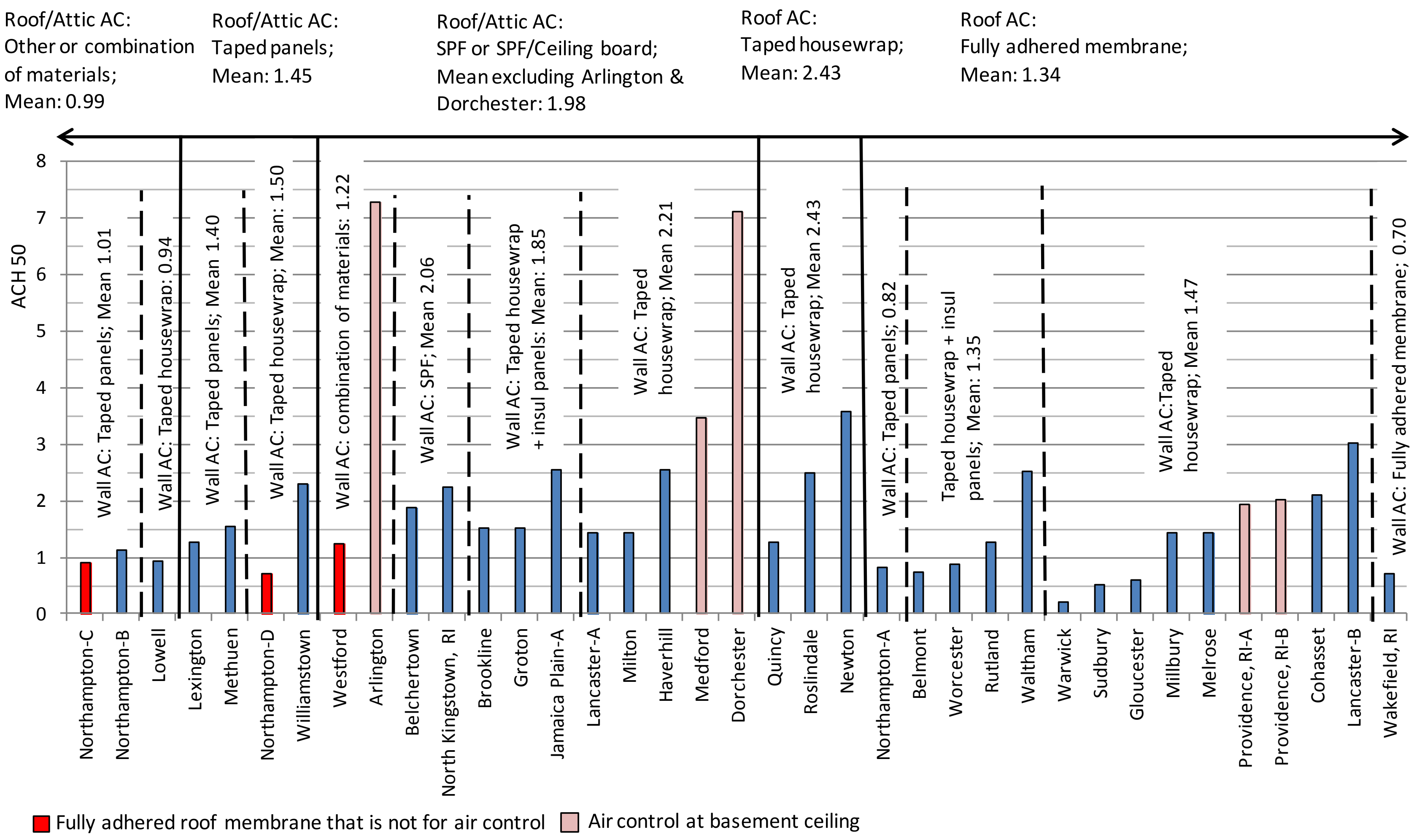


Figure 30. Post-DER ACH50 results grouped roof and wall air control material

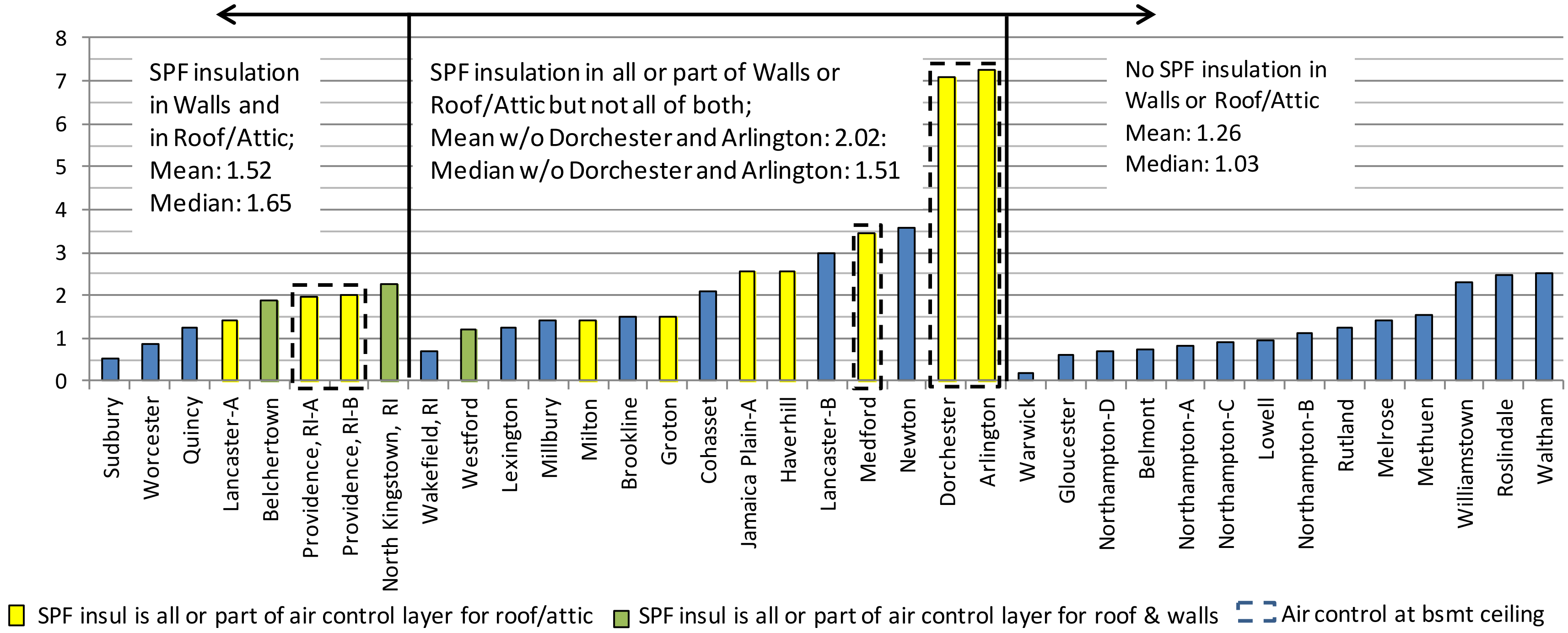


Figure 31. Post-DER ACH50 results grouped use of SPF insulation in walls and roof

In the previous sections where air control material was not included in the information, the group of projects that used a chainsaw air control approach had the best overall result. Figure 32 combines the use of fully adhered membrane on the roof as the air control layer (or simply as an underlayment) with the chainsaw technique. The projects that used taped panels for the wall air control layer are also highlighted. Only DERs with unvented attics are shown in Figure 32.

In the group with the fully adhered roof membrane, the mean of projects that used the chainsaw technique is 5% less than the mean of the full group that used a fully adhered roof membrane; the median of the chainsaw subgroup is about 25% less. The nine DERs with the best individual airtightness results in the DER community are in this subgroup. For the group without a fully adhered roof membrane, the mean is slightly greater for the chainsaw subgroup, and the median is slightly less. It is likely that both the fully adhered material and the chainsaw technique play a role in achieving the better airtightness results.

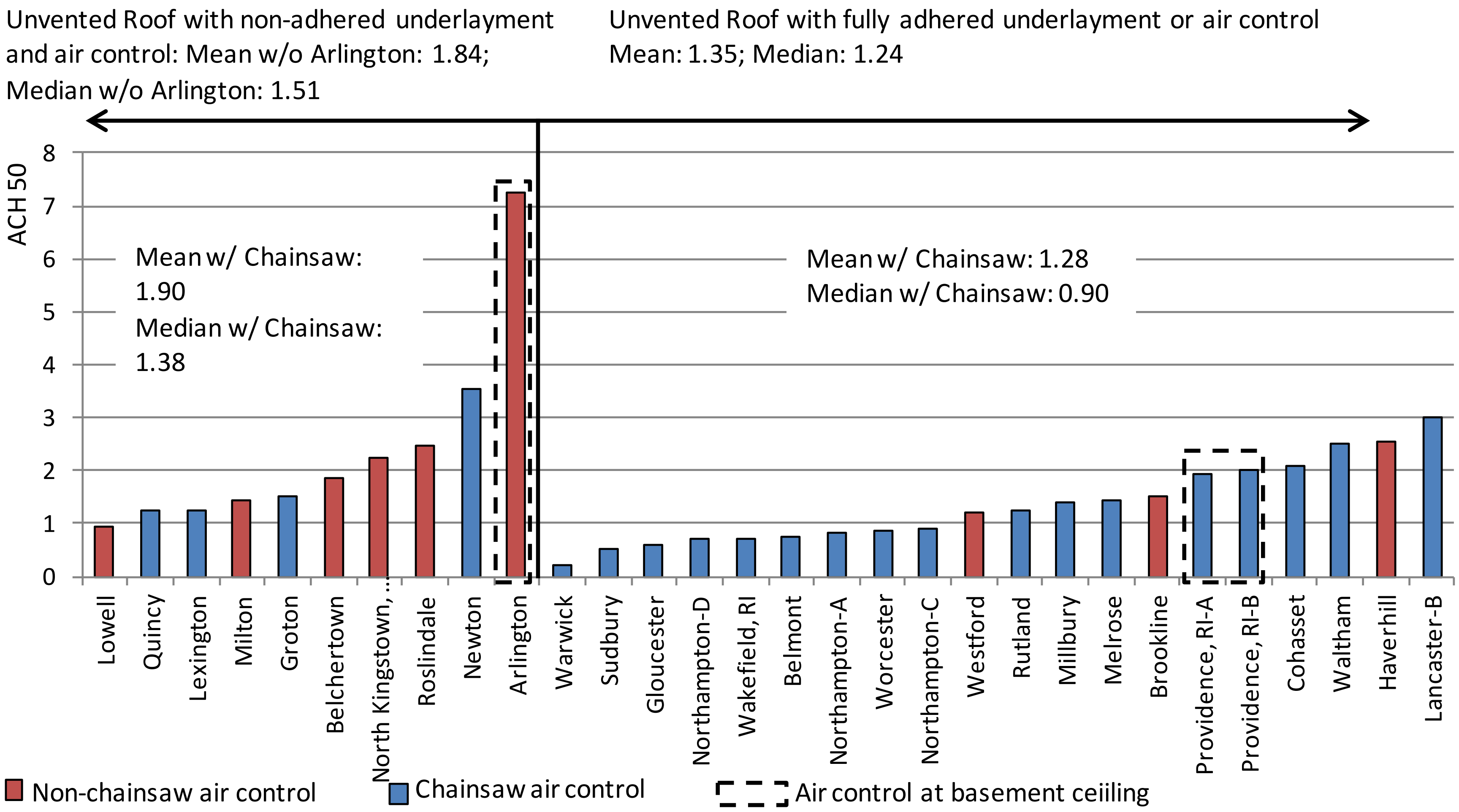


Figure 32. Post-DER ACH50 results grouped by non-adhered/fully adhered roof underlayment

5.3 Airtightness Trends Observed in the DER Community

The following trends were observed in the National Grid Pilot DER community that consists of 37 full DERs and five partial DERs.

Research Question: *What level of post-retrofit airtightness performance does the population of DER projects demonstrate?*

- All full DER projects achieved better than 50% reduction in total CFM50; all partial DER projects achieved better than 40% reduction in total CFM50.
- All but two of the full DER projects achieved a post-retrofit ACH50 below the ENERGY STAR threshold for climate zones 5–7. For over half of the full DER projects, the post-DER ACH50 results are 1.5 ACH50 or better. The mean post-DER ACH50 for the group of full DER projects is 1.9 ACH50.

Research Question: *Do post-retrofit airtightness data show discernible differences that may be attributable to variations in the approach to the overall DER package?*

- The group of DER projects that included the basement in the air control enclosure had a better overall airtightness result than the group that excluded the basement (i.e., insulation and air control at basement ceiling).
- The group of DER projects with unvented attics had a better overall airtightness result than the group with vented attic.
- The group of DER projects with unvented attics that used the chainsaw approach for the wall to roof air control layer connection had a better overall airtightness result than the group with unvented attic that did not use the chainsaw approach.
- The group of DER projects with unvented attic that used a fully adhered roof membrane had a better overall airtightness result than the group with unvented attic that did not use a fully adhered roof membrane. The airtightness result for the subgroup that used a fully adhered roof membrane and used the chainsaw approach was slightly better and included the nine best individual airtightness results for the DER community.

6 Construction Cost Analysis

Prior to participating in the National Grid DER pilot, prospective participants completed a series of application forms that provided information about the planned DER project. Among the information required was projected cost information for the specific DER measures. These measures correspond to the enclosure components, air sealing (if provided as a separate cost item), and heating, cooling, and ventilation costs. The contractor for the prospective team provided the measure cost information that is included in the application. The cost information in the application typically reflects the contractual cost for implementation of these measures. Therefore the cost reported is the cost to the homeowner, as opposed to the contractor's cost to implement the measure. The costs in the contract may not reflect the final cost to the homeowner where changes were pursued after the start of the project. Also, contractors are likely to exhibit significant variations in how total project costs are apportioned to various measures.

As part of the cost information provided in the application, a distinction was made between "allowable" and "non-allowable" costs. The "allowable" costs are items that are specifically implemented for reducing energy use (e.g., additional insulation or replacing an old inefficient boiler with a 95%-rated AFUE boiler), while the "non-allowable" costs are for items that are not related to reducing energy use (e.g., replacing roofing or siding). The *Deep Energy Retrofit Multifamily and Single-family Pilot Guidelines* (National Grid 2011) provide the following guidance relative to distinguishing allowable from non-allowable costs:

> Allowable project costs eligible for incentives are limited to net incremental costs, of implementing the DER measures. For example; for super insulation on wall exterior, the customers' costs of the insulation material, its installation, special attachments and trim modifications required to accommodate the super insulation would be eligible for incentives, whereas costs for the new siding (or cladding such as stucco) and its installation would not.

This breakdown was intended primarily to determine the costs eligible for incentive payments, but is also useful to break down costs into energy-related and non-energy (e.g., aesthetic) related costs. It should be noted that reported project costs relate to the retrofit project only. If, for example, the larger project between the contractor and the homeowner included such items as new kitchens cabinets and countertops, costs for such items are not included in the project cost considered in this analysis.

6.1 Summary of Energy-Related Construction Costs

Table 14 shows the total project costs and the total energy-related project costs for each of the DER projects as reported in the applications. In addition, the energy-related portion of the project costs are divided into enclosure measure costs and HVAC measure costs.

Table 15 provides shows project costs for the partial DERs and indicates what measures were implemented.

Table 14. Summary of National Grid DER Project Costs as Derived From Program Application Forms—Full DERs

House Location	Total DER Project Cost	Total Energy-Related DER Measures Cost	Projected Energy-Related DER Enclosure Measures Cost	Projected Energy-Related DER HVAC Measures Cost (With Some DHW)
Belchertown, MA	$64,629	$51,642	$35,045	$16,597 (no cooling in cost)
Belmont, MA (2 units)[a]	$212,357	$174,762	$142,094	$32,668
Millbury, MA	$82,719	$71569	$49,894	$21,675
Milton, MA	$77,651	$66,236	$51,236	$15,000
Quincy, MA	$127,197	$108,515	$68,915	$39,600
Arlington, MA (2 units)	$125,240	$95,163	$69,537	$25,626 (cooling coil; no condenser)
Newton, MA	$148,039	$97,039	$65,539	$31,500
Jamaica Plain-A, MA (3 units)	$214,313	$180,678	$165,528	$15,150 (ventilation only in cost)
Northampton-A, MA	$237,791	$119,701	$85,061	$34,640
Lancaster-A, MA[b]	$76,510	$57,446	$47,408	$10,038
Westford, MA	$117,712	$107,464	$94,080	$13,384 (no heating in cost)
Gloucester, MA	$142,317	$89,165	$70,665	$18,500
Medford, MA (2 units)	$114,153	$88,767	$66,167	$22,600
Northampton-B, MA	$79,350	$56,350	$46,350	$10,000 (heating only in cost)
Haverhill, MA (2 units)	$131,200	$104,200	$83,200	$21,000
Dorchester, MA (3 units)	$158,701	$113,951	$81,650	$32,301
Rutland, MA	$99,905	$79,490	$56,820	$22,670 (no cooling in cost)
Methuen, MA	$113,340	$73,340	$56,340	$17,000
Wakefield, RI	$78,953	$77,953	$70,953	$7,000 (ventilation only in cost)
Groton, MA[c]	$167,980	$167,980	$128,030	$38,950
Williamstown, MA**	$36,181	$31,564	$21,564	$10,000 (no cooling in cost)
North Kingston, RI (2 units)	$130,412	$95,860	$61,860	$34,000
Cohasset, MA	$132,564	$70,814	$59,921	$10,893
Sudbury, MA	$157,506	$105,611	$88,861	$16,750
Worcester, MA (3 units)	$143,207	$108,307	$84,307	$24,000
Northampton-C, MA	$228,902	$112,971	$108,771	$4,200 (ventilation only in cost)
Warwick, MA[b]	$100,210	$88,762	$80,070	$8,692
Lexington, MA	$79,151	$66,161	$49,861	$16,300 (no cooling in cost)
Melrose, MA	$165,284	$124,184	$116,544	$17,000
Providence-A, RI (3 units)	$251,806	$194,352	$148,728	$45,624 (no cooling in cost)
Roslindale, MA	$146,235	$145,085	$141,885	$3,200 (ventilation only in cost)

House Location	Total DER Project Cost	Total Energy-Related DER Measures Cost	Projected Energy-Related DER Enclosure Measures Cost	Projected Energy-Related DER HVAC Measures Cost (With Some DHW)
Lowell, MA	$81,605	$56,555	$53,555	$3,000 (ventilation only in cost)
Waltham, MA	$74480	$59,729	$47,449	$12,280
Northampton-D, MA (2 units)	$255,581	$111,387	$84,722	$15,000
Lancaster-B, MA (2 units)	$177,450	$103,210	$88,210	$15,000
Providence-B, RI (3 units)	$210,988	$139,465	$99,965	$39,500 (no cooling in cost)

[a] DER measure costs for this project are taken from a post-project analysis produced by the homeowner with input from the contractor.

[b] Volunteer labor was used in this project.

[c] Total project costs for this project did not include non-energy-related items.

Table 15. Summary of National Grid DER Project Costs as Derived from Program Application Forms—Partial DERs

House Location	DER Measures	Total Project Cost	Total Energy-Related DER Measures Cost	Projected Energy-Related DER Enclosure Measures Cost	Projected Energy-Related DER HVAC Measures Cost
Brookline	Walls, windows, HVAC	$135,774	$73,055	$58,850	$14,205 (no cooling in cost)
Jamaica Plain-B, MA*	Roof, HVAC	$52,410	$52,410	$50,010	$2,400 (ventilation only in cost)
Florence, MA	Attic, basement, HVAC	$83,446	$82,665	$55,815	$26,850 (no cooling in cost)
Concord, MA	Roof	$45,555	$31,201	$31,201	$0
Watertown, MA (2 units)	Roof, basement, HVAC (1 unit)	$134,516	$67,128	$51,128	$16,000
Jamaica Plain-C, MA (3 units)	Roof, HVAC	$102,154	$49,980	$9,978	$40,002 (heating only in cost)

* Total project costs for this project did not include non-energy-related items.

There is considerable variation between projects in the DER measure costs. While many factors will affect variation in project cost, the size of the project will have a very significant impact. Therefore, total and energy-related DER measure costs are shown normalized by post-retrofit conditioned floor area (Figure 33) and by post-retrofit six-sided enclosure area (Figure 34), for the full DER projects.

When normalized by conditioned floor area, the total energy-related costs for the full DER projects range from \$16.17/ft^2 to \$54.04/ft^2, with an average of \$34.59/ft^2 of post-retrofit conditioned floor area.

When normalized to total enclosure area, the energy-related costs for the full DER projects range from \$7.83/ft^2 of enclosure to \$26.47/ft^2 of enclosure with an average of \$16.51/ft^2 of enclosure. Since most of the DER measures involve the enclosure, the full DER cost metric in terms of enclosure area may be more meaningful.

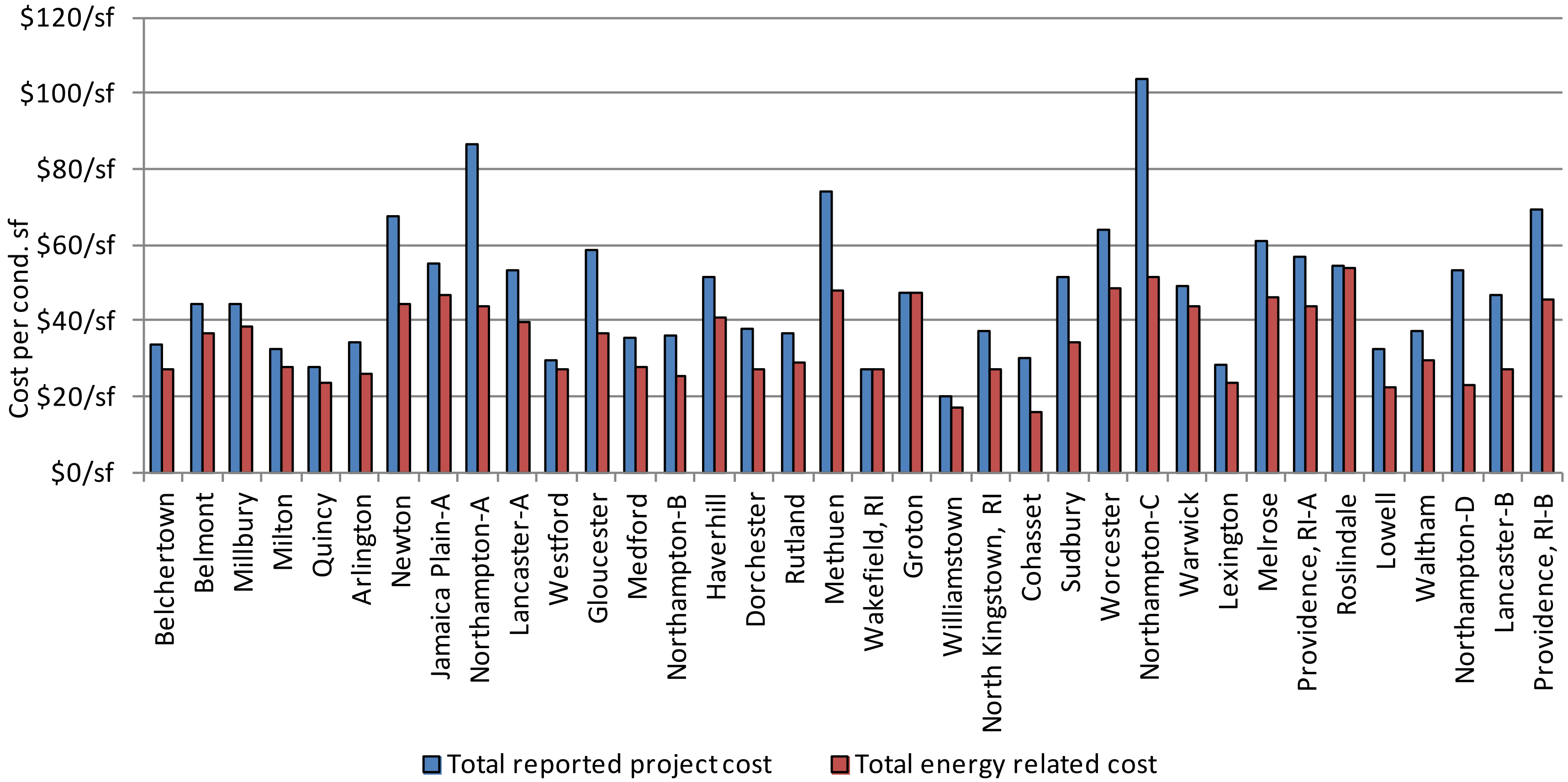


Figure 33. Total project and total energy-related costs normalized by conditioned floor area for full DER projects

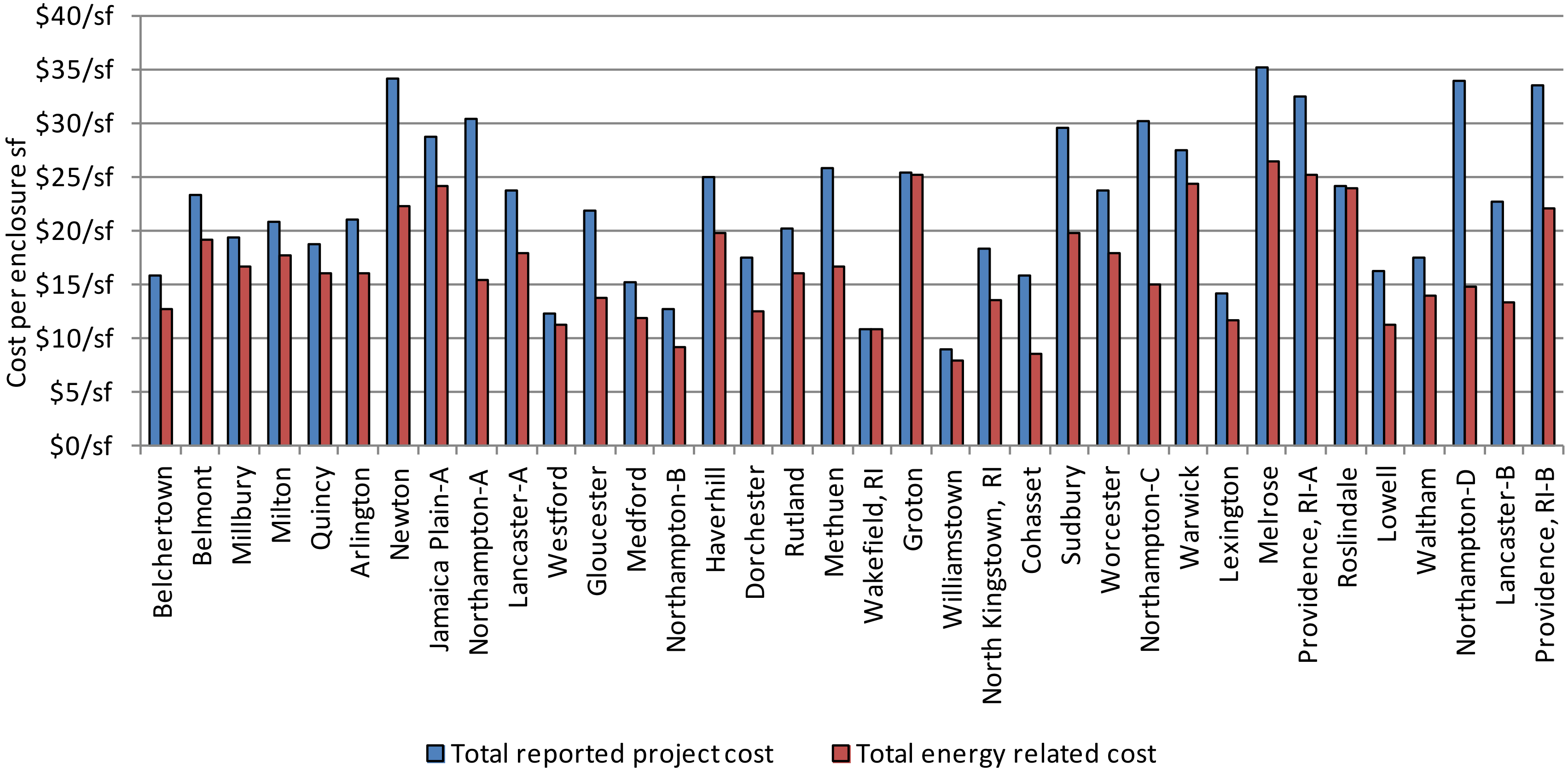


Figure 34. Total project and total energy-related costs normalized by enclosure area for full DER project

The scope of the DER also impacts the cost. For the full DERs, the scope of work on the enclosure is not dramatically different between projects, but with the introduction of partial DERs, only the treated part of the enclosure is relevant. Figure 35 shows the total energy-related enclosure measures cost (excluding the HVAC measure), normalized by the treated enclosure area for full and partial DER projects.

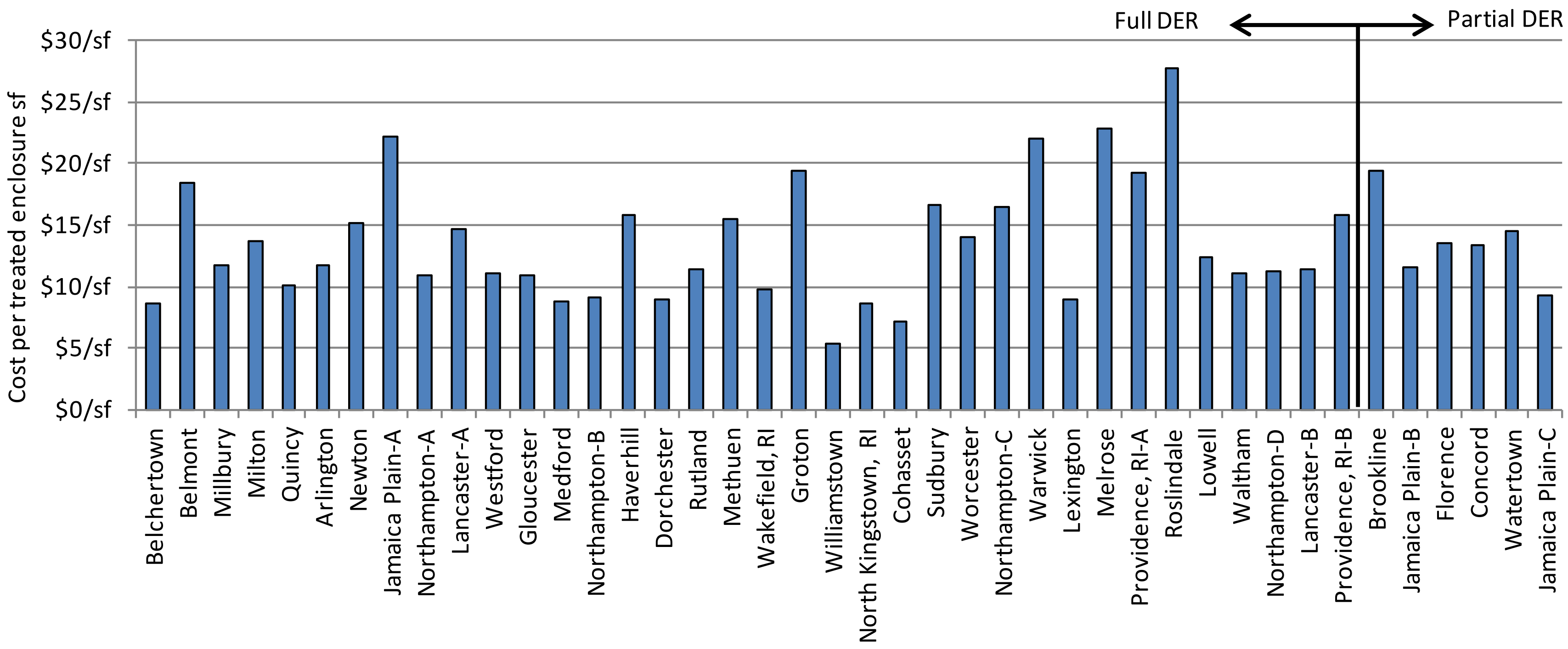
The range of energy-related enclosure costs per treated enclosure area for all DER projects is \$5.35/ft^2 of treated enclosure to \$27.65/ft^2 of treated enclosure with an average of \$13.57/ft^2 of treated enclosure.

For both full and partial DERs, the scope of the HVAC measure depends primarily on the number of separate living units in the building, the condition of the existing mechanical equipment, health and combustion safety issues, and the homeowner’s goals. The energy-related HVAC measure cost includes those costs in the HVAC measure which directly or indirectly reduce energy use for the home. For example, exhaust only ventilation is acceptable for the HVAC measure to meet the air quality and health requirements of the DER, but it is not related to energy reduction. So while these contribute to the total HVAC measure cost, they are not included in the energy-related part of the HVAC measure cost. Figure 36 normalizes the total energy-related HVAC measure costs by number of living units, and then groups them according to the functions of the equipment installed for the HVAC measure.

For projects that installed HVAC equipment (all of which directly or indirectly reduce energy use), the HVAC measure cost ranged from \$7,500 to \$39,600 per living unit, with an average of \$16,560.

For projects that installed energy-reducing heating and ventilation only, or cooling and ventilation only, the range was from \$10,000 to \$38,950 per living unit with an average of \$18,195.

The two projects that provided heating only averaged \$11,670 per living unit. Those that provided ventilation only (HRV or ERV) ranged from \$7,000 to \$2,400 per living unit with an average of \$4,140.



▨ Energy-related enclosure cost

Figure 35. Total energy-related enclosure costs normalized by treated enclosure area for all DER projects

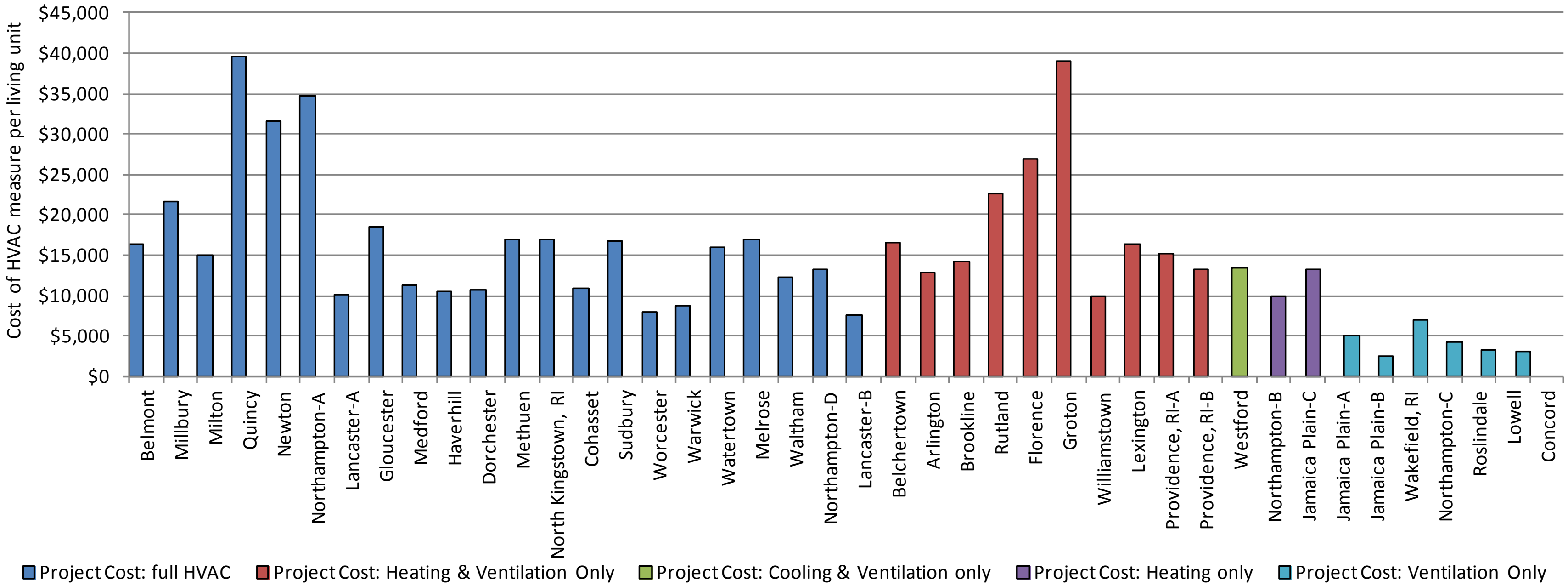


Figure 36. Total energy-related HVAC costs normalized by living units in building and grouped by function

6.2 Energy-Related Construction Costs per DER Measure

In the following sections, the energy-related construction costs are broken up into the individual DER measures as provided in the application.

6.2.1 Attic/Roof DER Measure

Figure 37 shows the cost per attic/roof sf for all of the full DER projects, and the partial DER projects that implemented this measure. The projects are grouped according to the approach taken for the implementation.

For those projects that provided attic floor insulation, the costs range from \$4.21/ft^2 to \$16.00/ft^2 with an average of \$8.40/ft^2. For those projects that provided roof cavity insulation, the range is from \$6.24/ft^2 to \$18.39/ft^2 with an average of \$11.59/ft^2.

The energy-related costs for roof exterior and rafter cavity insulation do not include the cost of new roofing. In this group, there are five outlier projects—three with extremely low costs and two with significantly higher costs than the other projects. Excluding these outliers, the range is from \$10.05/ft^2 to \$21.84/ft^2 with an average of \$14.21/ft^2.

The last group (labeled “Other”) is projects that have vented attics but also sloped ceilings on portions of the upper floor, which is a combination of attic floor insulation and rafter cavity insulation. The costs for this group range from \$6.66/ft^2 to \$10.25/ft^2 with an average of \$8.50/ft^2.

6.2.2 Exterior Wall DER Measure

Figure 38 shows the energy-related costs for implementing the above-grade exterior wall DER measure.

One of the DER projects implemented the exterior wall DER measure by constructing a stud wall to the interior of the wall framing and filling the widened wall cavity with insulation. All of the other projects added insulation to the exterior of the existing wall. Where there was no existing wall cavity insulation, it was installed. If there was existing wall cavity insulation, it was upgraded (generally from the exterior) as needed.

For the projects with exterior insulation, there are three outlier projects–two with extremely low costs and one with significantly higher costs. Excluding these outlier projects, the energy-related costs for exterior walls range from \$4.67 to \$19.15 per wall square foot with an average cost of \$10.51/ft^2. The cost of re-siding is not included in the energy-related cost for those projects with exterior insulation, nor is the cost of the additional framing included for the double wall implementation.

These figures are higher than the cost presented by Ueno (2010b) of \$4/ft^2. However, that figure was from early work before the development of mature contractor pricing. The same contractor who provided the original pricing later updated this figure to the \$7/ft^2 to 15/ft^2 range, depending on access, complexity of detailing, and other secondary factors.

The range of unit costs reported for this measure is somewhat surprising given that the scope for this measure is similar across the projects.

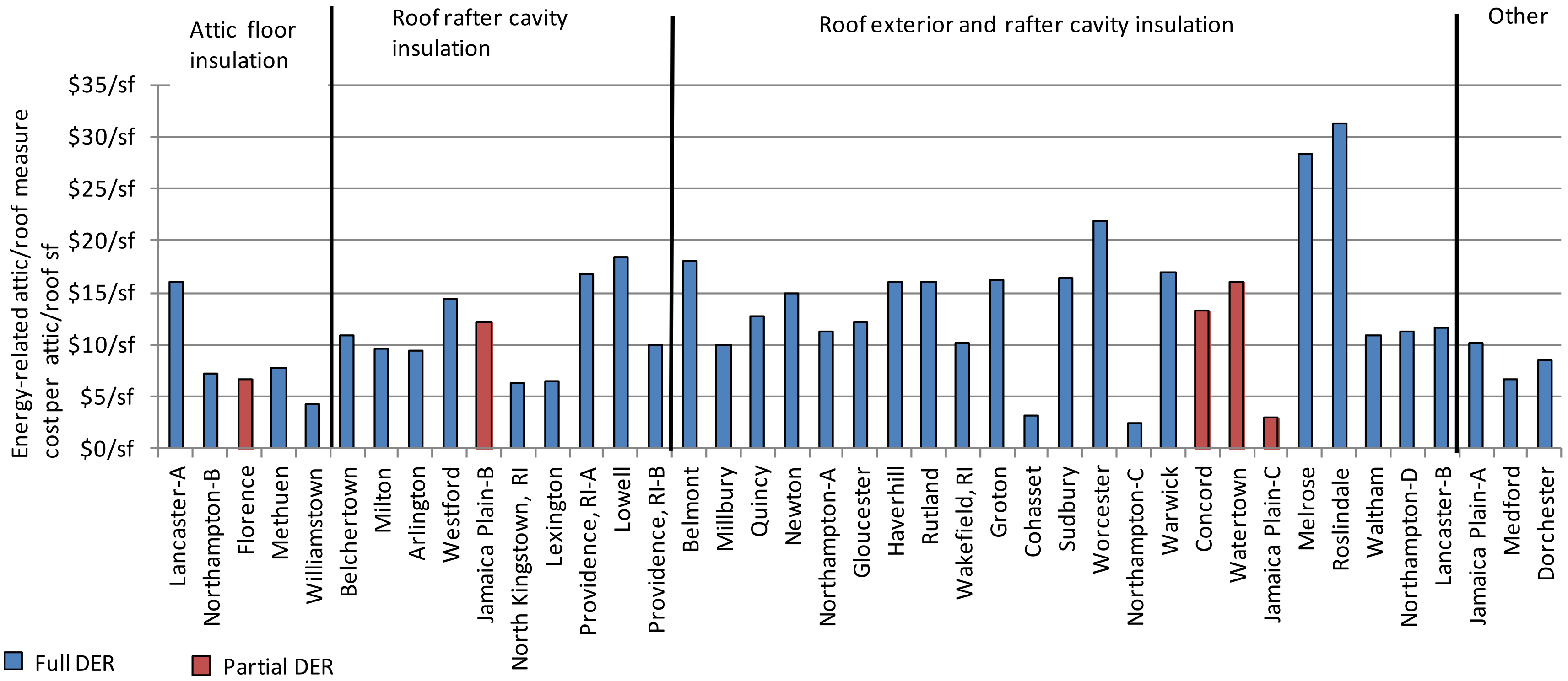


Figure 37. Total energy-related attic roof costs per attic/roof square foot

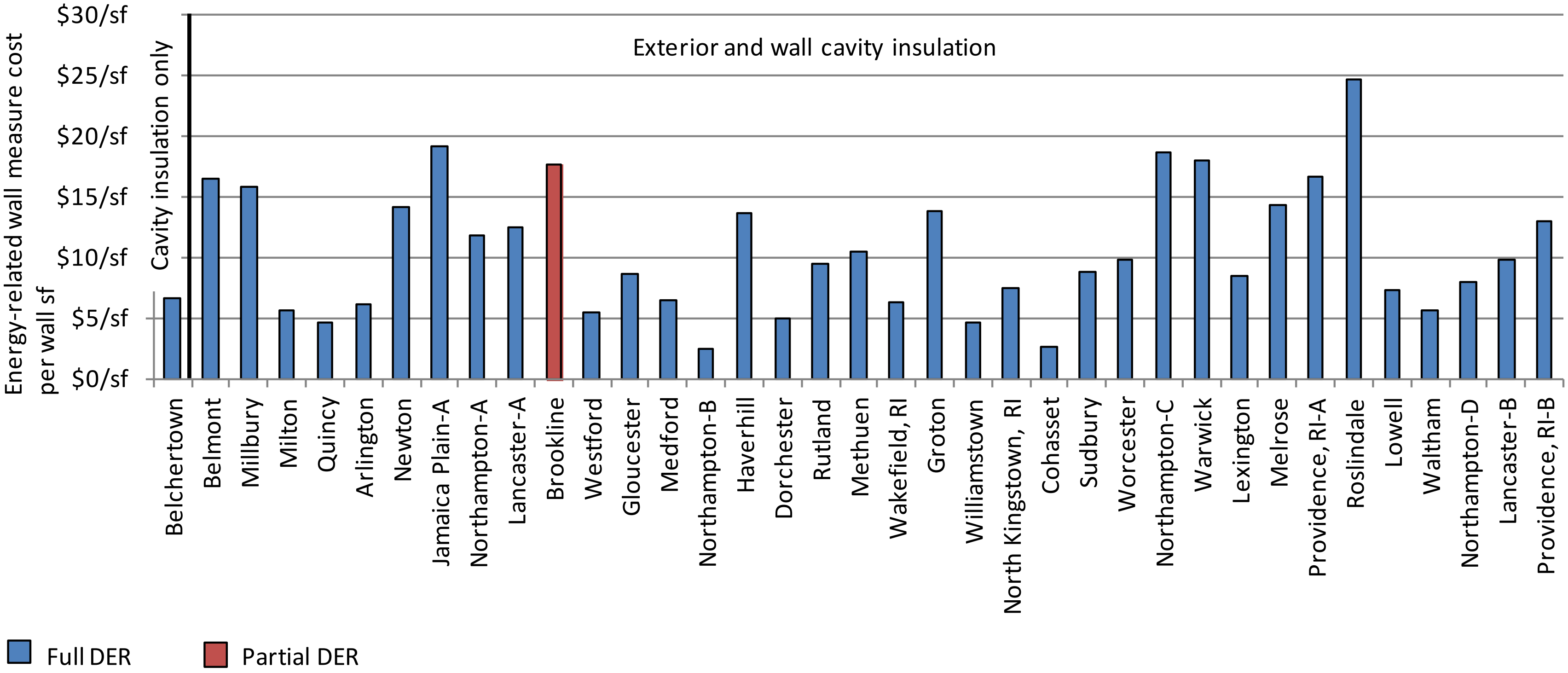


Figure 38. Total energy-related exterior wall costs per wall square foot

7 Homeowner Satisfaction

A survey was sent to all participants 6 months after the close of the pilot; 12 homeowner responses were received. The survey requested information on the homeowner's objectives in deciding to undertake a DER, the benefits of the DER after completion, the challenges of the project, any detrimental consequences of the DER, and additional comments not addressed elsewhere. A blank survey is included in the Appendix.

The majority of the respondents noted energy savings (in general or as reduced fossil fuel consumption or reduced carbon footprint) and improved comfort as some of their initial reasons for considering a DER; four noted additional living space and two noted they wished to be examples of how to complete a DER successfully.

In the post-DER responses, cost was noted in a number of the surveys—from cost overruns to equipment costs and estimating. Because of the cost, two projects would reconsider doing the below-grade insulation and sub-slab work, which they eventually did complete.

Complaints on the general contractor and subcontractor were noted in the Milton, Sudbury, Lowell, and Northampton-C responses. Scheduling, uncooperative building inspectors, and lead time for ordering equipment/windows were other issues noted in several projects.

The Sudbury, Warwick, and Medford homes noted they would not use spray foam again due to the environmental concerns of the blowing agents and off-gassing. The Medford house would consider alternatives to rigid foam board as well.

A number of projects (the Williamstown, Arlington, Lowell, and Concord homes) would either upgrade the HRV equipment or rework the ductwork and placement of the HRV. A few projects noted they were impressed with the improved air quality of their homes post-DER.

The Milton project was the only home to note considerable detrimental post-DER consequences, which included insect infestation in the closed-cell attic foam, issues of cell phone reception due to interference from the foil-faced exterior foam, and additional home maintenance (cleaning the HRV filter and cleaning the exterior foam insect barrier).

Aside from the Milton project, the majority of the responses were very positive with respect to the work that was completed under the National Grid program and meeting their expectations for comfort and energy reduction. However, there were some issues with the complexity of the program (i.e., deciphering the program and how to meet the requirements almost always required additional help), how to better coordinate the subcontractors (i.e., including the subs much earlier in the process) and how to disseminate the accumulated knowledge from each project going forward to improve the National Grid program and to encourage others to participate.

8 Conclusions

Research Question: *What measured savings does the population of DER projects demonstrate?*

For the 27 comprehensive DER projects for which sufficient post-retrofit energy use data were available, the mean reduction in total site energy use achieved is 58% with the site energy use reductions for individual projects ranging from 29% to 89%. On a source energy basis, the sample exhibits a mean reduction of 41% with a range of 10% to 74%. The authors maintain, however, that energy use reduction is not an appropriate metric for comprehensive retrofit. Because pre-retrofit conditions are highly variable, the relative reduction found in one sample of buildings is not necessarily applicable to another sample of buildings or to any one building.

Research Question: *What level of post-retrofit energy performance does the population of DER projects demonstrate?*

The DER projects were compared to a variety of benchmarks (regional averages, etc.). This analysis used weather-normalized post-retrofit energy use for the 27 comprehensive DER projects for which sufficient post-retrofit energy use data were available:

- In terms of household site energy use, all but one project achieved performance that is below the EIA Northeast regional average; 14 of the comprehensive DER projects achieved performance that is below half of the regional average. The group of projects exhibits a mean per household site energy use of 52.8 MMBtu/year, which is slightly less than 50% of the regional household average.
- All but two of the comprehensive DER projects achieved household source energy use below the EIA Northeast regional household average; nine of the DER projects achieved performance that is below half of the regional household average. The mean for the group is 107 MMBtu/year, or approximately 38% below the regional household average.
- In terms of site EUI, all of the comprehensive DER projects perform below the regional average with the mean for both the multifamily and single-family DER projects being below 50% of the respective Northeast region average. Two of the multifamily projects and three of the single-family projects meet the 2015 site EUI goal for the Architecture 2030 Challenge without taking any credit for on-site electricity generation.
- All but four of the single-family DER projects achieved source EUI that is below the Northeast regional single-family average. Both the single-family and multifamily projects achieved a mean source EUI that is 34% lower than the respective regional average. One of the multifamily projects and nine of the single-family projects achieve a source EUI that is below the nominal primary energy use target in the Passive House program for new construction (albeit with different floor area calculations).

Based on this community, this DER package is expected to result in yearly source energy use on the order of 110 MMBtu/year or approximately 40% below the Northeast regional average. Larger to medium sized homes that successfully implement these retrofits can be expected to achieve source EUI that is comparable to Passive House new construction.

Whether the National Grid Pilot met the aspiration of demonstrating a 50% reduction in energy use relative to typical homes in the region depends upon whether the energy use is measured in terms of site energy or source energy. By both per-household and EUI metrics the sample of DER projects has a mean post-retrofit energy use that is more than 50% below the regional average on a site energy basis. On a source energy basis, the mean post-retrofit performance is between 35% and 40% below the regional average.

Research Question: *Do energy performance data show discernible differences that may be attributable to variations in the approach to the overall DER package?*

No significant trends emerges from analysis of the post-retrofit energy use data. One plausible interpretation of this is that the heating and cooling energy use has been reduced to the point where relatively minor variations to an otherwise consistent package have little discernible impact. The following observations relative to heating and cooling source EUI may suggest topics for further study:

- DER projects that implemented a heat pump (electric) based heating system exhibited a wide range of performance relative to other DER projects. This may indicate significant variation in effective heat pump system efficiency.
- Projects in this sample that exclude the basement from the thermal enclosure exhibit higher heating and cooling EUI than other DER projects in their peer group. With the limited number of observations for this variation among the sample, it is not possible to assert a direct causal relationship. The data from this study suggest a topic worth examining with a more targeted study.
- Among different approaches to attic and roof retrofit, the DER projects that implemented an unvented attic approach appear to have lower heating and cooling energy use on average.
- The data show only a vague trend of lower energy use with greater airtightness. The data also indicate significant variation in energy use associated with similar levels of airtightness. Controlling for some of the other variables in the package implementation, such as heating fuel, might reveal a stronger relationship between airtightness and heating and cooling energy use.

BSC conducted analysis of airtightness achieved by projects in the National Grid pilot DER community based on pre- and post-retrofit measurements for 37 full DERs and five partial DERs.

Research Question: *What level of post-retrofit airtightness performance does the population of DER projects demonstrate?*

- All but two of the full DER projects achieved a post-retrofit ACH50 below the ENERGY STAR threshold for climate zones 5–7.
- For over half of the full DER projects, the post-DER ACH50 results are 1.5 ACH50 or better.
- The mean post-DER ACH50 for the group of full DER projects is 1.9 ACH50.

- All full DER projects achieved better than 50% reduction in total CFM50; all partial DER projects achieved better than 40% reduction in total CFM50.

Research Question: *Do post-retrofit airtightness data show discernible differences that may be attributable to variations in the approach to the overall DER package?*

- The group of DER projects that included the basement in the air control enclosure had a better overall airtightness result than the group that excluded the basement (i.e., insulation and air control at basement ceiling).
- The group of DER projects with unvented attics had a better overall airtightness result than the group with vented attics.
- The group of DER projects with unvented attics that used the chainsaw approach for the wall to roof air control layer connection had a better overall airtightness result than the group with unvented attic that did not use the chainsaw approach.
- The group of DER projects with unvented attic that used a fully adhered roof membrane had a better overall airtightness result than the group with unvented attic that did not use a fully adhered roof membrane. The airtightness result for the subgroup that used a fully adhered roof membrane and used the chainsaw approach was slightly better and included the nine best individual airtightness results for the DER community.

Research Question: *What are the total DER project costs?*

There is no question that high performance retrofit—especially a comprehensive high performance retrofit—represents a significant cost. In this DER community, reported project costs ranged from slightly more than \$36,000 to almost \$255,600. The reported energy-related portion of the project costs ranged from slightly more than \$31,500 to approximately \$194,350. Further analysis of the reported project costs yields some interesting observations.

- Relative to post-retrofit conditioned floor area, the reported energy-related costs average \$34.59/ft^2 for the DER community. This is well below a reasonable cost for attaining a similar level of performance in new construction. Even the upper level of the range at \$54.04/ft^2 compares favorably to the cost of high performance new construction.

Research Question: *What are the unit costs of major retrofit measures?*

- The cost of HVAC measures varied significantly with the maximum observation of \$39,600 being more than five times the lower observation of \$7,500. The variations in HVAC measure costs appear to relate to homeowner preferences and to not appear to be correlated with a noticeable difference in performance with the possible exception of one project that installed a ground-source heat pump. But with this single observation it is not possible to assert a causal relationship.
- The energy-related portion of roof/attic measures show some trends for different approaches where the reported cost for a vented attic approach with insulation at the attic floor averaged \$8.40/ft^2, the unvented attic approach with rather cavity insulation only averaged \$11.59/ft^2, and the unvented attic with insulation both exterior to the roof sheathing and between roof framing averaging \$14.21/ft^2.

- Excluding some noted outliers, the reported energy-related cost for the most typical wall retrofit approach ranged from \$4.67/ft^2 to \$19.15/ft^2 with an average of \$10.51/ft^2. This range is surprising given the relatively uniform scope of work for this measure. The range may be indicative of variations in how contractors allocate project costs to various measures.

Research Question: *What benefits do participating homeowners associate with DER projects implemented through this pilot program?*

- Twelve of the homeowner participants in the DER pilot responded directly to a request for feedback through a survey distributed by National Grid. The majority of the respondents noted energy savings and improved comfort among their initial reasons for considering a DER. It is interesting to note that in some cases the survey responses indicated the energy reduction goal in general terms and in other cases, energy reduction was expressed in terms of reduced fossil fuel consumption (several projects switched to all-electric site energy use) and reduced carbon footprint.

The paucity of survey respondents and difficulties encountered in obtaining useful energy use data are noteworthy given that provision of such information was a contractual obligation associated with the generous utility program incentives. This portends difficulties in obtaining useful post-retrofit data from similar communities of retrofit projects. Direct metering of energy use with direct access to the metering data for monitors/research may resolve the issue with energy use data. As for the qualitative feedback, direct interviews with participants may prove more useful than a survey.

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Appendix: Homeowner Survey

Deep Energy Retrofit (DER) Homeowner Experience Survey

Before you started this project, what were your top 5 (or so) objectives when you set out to undertake the DER? (examples–Energy savings, additional livable space, improved comfort, etc…) If you can, list or number these in order of importance to you (at the time).

If energy savings appears on your list, please tell us more. Can you further prioritize objectives relative to energy savings?
Examples–
Reduce energy costs
“Hedge” against potential energy cost increases in the future
Reduce environmental impact (e.g. climate change)
Reduce social/geopolitical impact (e.g. national security)

Now that the project is complete, what are the top 5 (or so) benefits that you think your project accomplished? If you can, list or number these in order of importance to you. Examples–energy savings, additional livable space, improved comfort, passive survivability (in case of power outage or heating equipment failure), reduced noise from outdoors, basement water and moisture management, confidence that pre-existing structural and envelope problems have been corrected, confidence that major exterior upgrade should not be necessary in the next 30 years, improved indoor air quality, improved durability, radon mitigation

What challenges did you encounter in implementing the DER project?

What would you do differently if you were to do this project again?

Are there any detrimental consequences of the DER project?

We welcome any additional thoughts you would like to share:

Thank you for participating in the National Grid DER Homeowner Experience Survey!

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