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Bay Ridge Gardens—Mixed-Humid Affordable Multifamily Housing Deep Energy Retrofit

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Building America Partnership for Improved Residential Construction

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Definitions

A/C	Air conditioner
AFUE	Annual fuel utilization efficiency
CFM	Cubic feet per minute
CMU	Concrete masonry unit
DER	Deep energy retrofit
DOE	U.S. Department of Energy
ERV	Energy recovery or enthalpy recovery ventilator
ET	Environmental tobacco smoke
GC	General contractor
HERS	Home Energy Rating System
HSPF	Heating season performance factor
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
MEA	Maryland Energy Association
MEEHA	Multifamily Energy Efficiency and Housing Affordability Program
MF	Multifamily
PEG	Patuxent Environmental Group
Realization Rate	The ratio of actual energy savings to the predicted energy saving from the audit and modeling process
RH	Relative humidity
SEER	Seasonal energy efficiency ratio
SHGC	Soar heat gain coefficient
SIR	Savings to investment ratio
SPF	Spray polyurethane foam
Tenant-in-place remodel	An approach to building renovation in which residents vacate their dwellings during the daytime and return at night. Basic dwelling functionality is restored and health/safety risks are addressed at the end of each workday.

Executive Summary

Multifamily “deep” energy retrofits (DERs) on relatively common building types are valuable research efforts for the U.S. Department of Energy’s Building America research program. Such buildings represent great potential for energy savings, and the analysis of such projects provides valuable findings on efficiency measures, cost-effectiveness metrics, and risk factor mitigation strategies.

The Bay Ridge energy retrofit project comprised a “base scope” retrofit with a goal of achieving 30% savings (relative to pre-retrofit), and a “DER scope” with a goal of 50% savings (relative to pre-retrofit). The base scope has been applied to the entire complex except for one 12-unit building, which underwent the DER scope as well as energy monitoring for a one-year post-retrofit period. This report summarizes commissioning, short-term testing, utility bill data analysis, and results of on-site monitoring with a focus on the three-bedroom base scope and DER units.

Findings from the implementation, commissioning, and short-term testing include air infiltration reductions of greater than 60% in the DER building; a hybrid heat pump system with a savings to investment ratio > 1 (relative to a high efficiency furnace) which also provides the resident with added incentive for energy savings; and duct leakage reductions of > 60% using an aerosolized duct sealing approach.

The Bay Ridge DER was initially projected to achieve energy savings of approximately 52% compared to pre-retrofit conditions. Long-term analysis based on performance monitoring and utility bills revealed *actual* savings of about 43%. This savings level exceeds the current Building America goals for retrofits in mixed-humid climates of 30%. The long-term DER energy savings analysis focused on the three-bedroom unit, where occupancy was the most consistent across the pre- and post-retrofit periods.

The energy savings realization rate of 83% (= 43%/52%) was affected partially by an overestimation of energy consumption in the pre-retrofit computer model that was not apparent until monitoring data became available; a likely overestimation of the effectiveness of energy feedback devices; a specification change in the energy recovery ventilator installed during the retrofit; and higher-than-anticipated wintertime thermostat settings during the post-retrofit period. The energy savings realization rate of 83% for this project tracks favorably with the 61% fuel realization rate cited by others as typical of affordable multifamily energy retrofit projects (Steven Winter Associates and HR&A Advisors 2012). This research notes that fuel savings are easier to predict in multifamily buildings compared to electricity savings, yet fuel savings still fall significantly short of 100% realization. The complex nature of buildings and systems that are present render it difficult to closely predict actual savings. As was the case with the Bay Ridge project, occupancy frequently does not remain consistent, thereby adding another level of uncertainty.

The findings of the Bay Ridge retrofit project are significant in that they illustrate that substantial energy savings can be realized through implementation of fairly straightforward retrofit measures that can occur during ongoing occupancy, that also provide comfort and durability benefits. The efficiency measures included only those that were not severely invasive and did not require displacement of occupants during construction. Sealing major (but accessible) building envelope air leakage sites, duct sealing, replacement of aging space conditioning and water heating equipment, windows, and attic insulation are relatively standard energy improvements that reduced monthly utility bills for both the building owner and the tenants, increased comfort for the occupants, and likely provided a safer indoor environment.

Project findings are also significant in that they highlight opportunities to improve the energy savings realization rate in similar projects, including:

- Improving the characterization of pre-retrofit energy use via pre-retrofit monitoring and targeted diagnostics
- Increased emphasis on educating residents on their impact on energy use and costs
- Limiting or eliminating specification changes during construction
- Applying increased conservatism on the energy impact of efficiency measures that are not readily quantified.

Additional findings include those energy efficiency measures that that showed promising energy savings but that were ultimately rejected due to "risk factors." Risk factors covered various concerns, including occupant safety, potential unintended building failures, and possible regulatory/code issues. For instance, installing 1 in. of extruded polystyrene on the interior of the exterior walls would have provided a significant energy benefit. However, investigation of the wall assembly revealed a layer of polyethylene on the interior face of the masonry walls, presumably installed during initial construction as an air barrier. Hygrothermal analysis indicated potential risk of condensation and therefore, this measure was rejected. This research also reports on other rejected efficiency measures and the underlying reasons, which are valuable screening tools for similar projects.

1 Problem Statement

1.1 Introduction

Under this project, Newport Partners (as part of the BA-PIRC research team) evaluated the installation, measured performance, and cost effectiveness of efficiency upgrade measures for a tenant-in-place deep energy retrofit (DER) at the Bay Ridge multifamily (MF) development in Annapolis, Maryland. The design and construction phase of the Bay Ridge project was completed in August 2012. This report summarizes system commissioning, short-term test results, utility bill data analysis, and analysis of real-time data collected over a one-year period after the retrofit was complete.

Figure 1. Aerial view of Bay Ridge development

The Bay Ridge project comprised a "base scope" retrofit that was estimated to achieve a 30%+ savings (relative to pre-retrofit) on 186 apartments, and a "DER scope" which was estimated to achieve 50% savings (relative to pre-retrofit) on a 12-unit building (Figure 1 and Figure 2). The base scope was applied to the entire apartment complex except for one 12-unit building, which underwent the DER scope.

A wide range of efficiency measures was applied to pursue this savings target for the DER building, including improvements/replacements of mechanical equipment and distribution systems, appliances, lighting and lighting controls, the building envelope, hot water conservation measures, and resident education.

The results of this research build upon the current body of knowledge of MF retrofits. Toward this end, the research team has collected and generated data on the selection of measures, their estimated performance, their measured performance, and risk factors and their impact on potential measures.

Figure 2. Front view of three-story apartment building

1.2 Background

DERs can provide 30% or greater energy savings, and are much easier to implement when a building is undergoing a "substantial" remodel, in which case contractors can have greater access to walls, ceilings, duct systems, etc. For projects like Bay Ridge that are not undergoing substantial remodels—which is more often the case—the selection of DER measures during a renovation must balance the energy savings of upgrade measures against the ability to realistically apply the measures with residents still occupying the building during at least some part of the day. Simultaneously, these upgrade measures must also be evaluated for their potential to trigger code/regulatory issues, exacerbate pre-existing risk factors in the building, and the ability of contractors to reliably and successfully apply them.

The Bay Ridge DER research project builds upon this knowledge base by providing measured energy performance and cost data on a very common building type that underwent a moderate rehab.

1.3 Relevance to Building America's Goals

This research project is part of the U.S. Department of Energy's (DOE) Building America research program. Overall, the goal of the Building America program is to "reduce home energy use by 30-50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes)." Building America's energy savings goals are particular to individual climate zones. The project site is located in Annapolis, Maryland in a mixed-humid climate (Climate Zone 4A). As related to existing homes within mixed-humid climates, Building America has a goal of 30% energy savings from the pre-retrofit condition by 2013.

The most important merits of the research at the Bay Ridge complex are as follows:

- The project investigated a very common building type: a 1970s-era, three-story walk-up apartment building owned and operated by a major industry firm—Landex. Further, the renovation incorporated a retrofit model that property owners and affordable housing advocates support: tenant-in-place so the tenant may be inconvenienced for a short period of time but not displaced.
- The project investigated "risk factors" and regulatory issues, and their roles in determining what efficiency measures may not be viable because they would jeopardize building performance or occupant health, or trigger cascading regulatory requirements. Such risk factors are common and need effective identification and mitigation strategies for property owners to navigate them.
- Building owners and energy efficiency program managers both want the answer to the question: "How much energy did the project really save?" Under this effort, the research team investigated actual energy savings achieved compared to estimated energy savings, for the DER retrofit scope. The DER scope was initially estimated to result in a 50% energy savings.

Taken together, this research provides extremely valuable information to DOE and the MF building industry in understanding current capabilities in energy retrofits as well as remaining gaps.

The Bay Ridge DER research also maps directly to Building America program goals as they were expressed in 2010–2011 work scope descriptions, including:

- "Developing the combination of retrofit measures for evaluation in individual test homes that will contribute to achieving 15-30% or more energy savings while also meeting safety, risk minimization, durability, reliability and cost requirements to be implemented on a broad basis."
- "Determining the simplest and most reliable measures to reduce energy use by a minimum of 15-30% and be scalable for application to large numbers of houses. Longer-term opportunities for "deep retrofits" yielding savings of 30-50% should also be considered."
- "Performing field evaluations of indoor air quality/ventilation strategies."

1.4 Project Partners

This Building America project originally started as a project supported by the state of Maryland through both the Maryland Energy Administration (MEA) and the Department of Housing and Community Development, under the Multifamily Energy Efficiency and Housing Affordability Program (MEEHA) program. The purpose of MEEHA is to promote energy efficiency and affordability in the state's multifamily rental housing developments for low and moderate income households. Patuxent Environmental Group (PEG) was the lead auditor at Bay Ridge under the MEEHA phase of the project, while Newport Partners served as the energy consultant for the DER component, under contract to MEA. The owner of the Bay Ridge development, Landex, played a significant role in vetting and implementing efficiency measures.

After the project was underway, it was brought into the DOE Building America program. The project's inclusion in Building America leveraged the earlier efforts of the audit and DER consulting work, and provided additional resources for more analysis of the project results.

1.5 Cost Effectiveness

Newport Partners ("Newport") assessed and prioritized a wide range of potential efficiency measures, with the most effective and feasible measures combined into the DER scope. The following energy-related factors were assessed in the cost-effectiveness evaluation:

- Annual energy savings (modeled)
- Annual energy cost savings (modeled)
- Implementation costs (estimated)
- Cost effectiveness in the form of savings to investment ratio (SIR) (calculated).

Newport engineers and building analysts conducted energy modeling with REM/Rate software to project the cost effectiveness of various measures on the basis of SIR, which is highly relevant to MF projects that receive weatherization funding) and other metrics. BeOpt software was also evaluated for this work, but was ultimately bypassed due to lack of functionality in the following areas: modeling exterior wall orientations of varying construction type (e.g., common wall and exterior wall sharing the same orientation), and modeling hybrid (or “dual fuel”) heat pump systems. REM/Rate was also deemed acceptable for this project because energy upgrade analysis using REM/Rate was already underway for more than six months, under contract with MEA, when the retrofit project also became a Building America research effort.

While the modeling analysis provided a list of potential measures, additional “filters” were applied to ensure that efficiency measures accounted for existing conditions and the project’s moderate rehab model. These additional considerations were:

- Compatibility with a “tenant-in-place” rehab model (residents returned to the apartments in the evening for much of the retrofit project’s duration)
- Compatibility with a rehab scope, which did not include façade removal
- Sensitivity to creating cascading regulatory issues (e.g., exposing aluminum wiring as part of an air-sealing and insulation efficiency measure)
- Avoidance of unintended consequences (e.g., creating hygrothermal problems, negative indoor air quality [IAQ] impacts).

The vetting of potential measures against these factors involved extensive dialogue with the general contractor (GC), additional site inspections, hygrothermal modeling, and analysis of ventilation system options.

1.6 Tradeoffs and Other Benefits

Several types of tradeoffs were evaluated in the development and selection of the efficiency measures.

1.6.1 Energy Savings Versus Implementation Costs

The Newport research team conducted building energy modeling analysis along with cost estimating to compare energy cost savings versus implementation cost. Measures with a SIR > 1 generally passed this test, although this level is not a strict rule, and some measures with a SIR
< 1 were ultimately included in the DER scope. The magnitude of the implementation cost was also a consideration for marginal measures. For example, a solar electric array underwent initial screening but was not selected for further evaluation due to both the implementation cost and the SIR.

1.6.2 Regulatory and Constructability Tradeoffs

Given the tenant-in-place retrofit model being used at Bay Ridge, several measures under consideration were not selected due to complications with residents returning to their dwellings each night and underlying risk factors within the building.

Figure 3. Polyethylene layer on inside face of concrete masonry unit (CMU) wall assembly

One example included potential air sealing measures. Invasive air sealing efforts near the rim joist, which would require opening up drywall bulkheads, were not selected because the project team felt that "too much" of the existing aluminum wiring in walls and ceilings would be exposed. The local regulatory authority approved a copper-to-aluminum crimping retrofit approach because the aluminum wiring was otherwise not being exposed; however, if enough aluminum wiring was exposed, the authority would likely have required a full wiring replacement in the entire apartment. The crimping solution is an industry-recognized approach to existing aluminum wiring, and represents a practical solution for moderate rehabs. A secondary concern with invasive air sealing was the ability to safeguard the apartment at night in a way that prevented residents from being exposed to open building cavities, energized wiring, exposed nails, etc.

1.6.3 Building Science "Risk Factors"

Newport's moderately invasive investigations of the building revealed an exterior wall assembly of uninsulated CMU with a layer of polyethylene on the inner face of the block (see Figures 3 and 4).

Hygrothermal analysis of this assembly showed significant risk of wintertime condensation on the inner face of this polyethylene if insulation were added to the inner side of this assembly. As a result, laminating R-5 XPS insulation to the existing drywall on exterior walls—which had been a cost-effective measure based on initial analysis—was rejected as a potential efficiency measure.

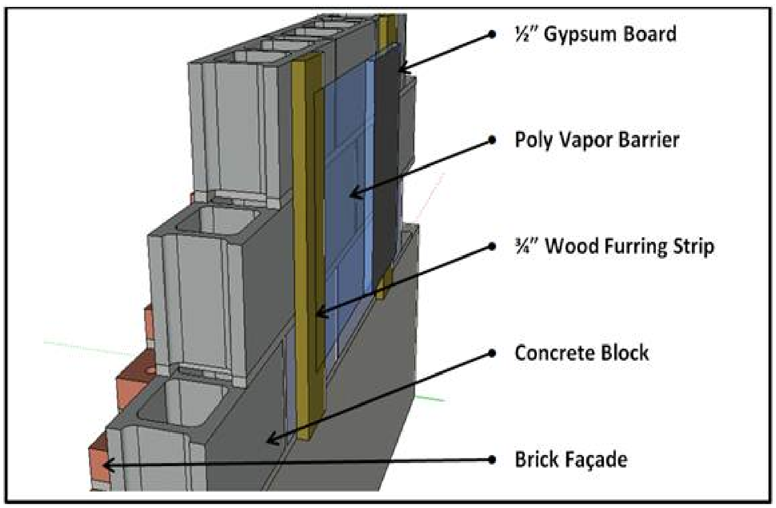

Figure 4. Exterior wall section showing limitted depth furring and polyethylene layer on inside face of CMUs

Table 1 provides a concise summary of numerous measures which were considered during the DER scope development but ultimately rejected due to the factors discussed above. While the specific conditions of a given project dictate viable energy upgrade measures, this summary serves as a primer for important factors to consider.

Table 1. Summary of Rejected Upgrade Measures

Energy Efficiency Retrofit Measure	Description	Primary Reason for Rejection
Interior Insulation on Exterior Walls	R-5 continuous, interior insulation adhered to inside gypsum face of all exterior walls. 1 in. rigid foam and sheetrock installed over existing wall surface. Extensions for windows, outlets, switches, etc.	Strong risk of winter season condensation within wall assembly, due to continuous layer of polyethylene vapor retarder within exterior wall assembly
Spray Foam Attic Insulation	Remove existing blown-in and batts; add 2 in. spray foam cap to floor of the attic; then re-apply blown-in to R-49	Spot air sealing deemed more cost effective
Solar Electric- Array	Multipanel photovoltaic array to generate electricity for all 12 apartment units	Capital cost too great for DER budget
Ground Source Heat Pump	Ground-source heat pump with central loop sized to meet building heating/cooling loads	Schedule delays for permitting; Site disturbance for loop
High Efficiency Furnace	95+ AFUE[a] furnace with electronically commutated motor blower motor (base scope used 92.5 AFUE 2-stage furnace)	Hybrid Heat Pump system more cost effective in terms of SIR
Upgraded Windows	U-0.29, SHGC[b]-0.27 windows (base scope used U-0.35 SHGC 0.35 units)	Limited energy savings (and SIR <1) relative to base scope, driven by relatively modest window area (14%–16% window to floor area ratio) and low design loads
Upgraded Cooling	Utilize 16 SEER[c] A/C[d] (base scope: 15 SEER, 1.5 ton)	Limited energy savings and SIR relative to base scope

Energy Efficiency Retrofit Measure	Description	Primary Reason for Rejection
Auxiliary Dehumidification	Auxiliary dehumidification considered as an IAQ measure, given limited, anecdotal reports of high indoor RH[e] levels and anticipated lower post-retrofit infiltration levels	ERV[f] whole-dwelling ventilation selected instead for balanced ventilation (which helps to limit unit-to-unit air infiltration) and moderate RH control
Venting Kitchen Range to Outdoors	IAQ upgrade for better kitchen ventilation	Construction team deemed too costly
Green Switch Switches and Outlets	Switch and outlet technology to allow residents to easily turn off electrical devices not in use with a remote switch	Reliance on regular, long-term resident intervention to realize energy savings

[a] Annual fuel utilization efficiency
[b] Solar heat gain coefficient
[c] Seasonal energy efficiency ratio
[d] Air conditioner
[e] Relative humidity
[f] Energy recovery ventilator

2 Research Questions

The key research questions for this project include:

- What level of energy savings did the DER retrofit package achieve? Did the actual savings meet the estimated savings?
- How did the hybrid heat pump performance compare to that of the high efficiency gas furnace?
- What do average indoor temperatures and RH indicate about occupant behavior?
- What do the average summer RH measurements indicate regarding the ability of the cooling system and the whole-house mechanical ventilation system to manage indoor humidity?

3 Retrofit Specifications

3.1 Selection and Cost Effectiveness of Final Deep Energy Retrofit Measures

To best understand the short-term test data, it is necessary to review the final selection of the DER scope efficiency measures. Newport's chief initial role in the Bay Ridge project, while serving under contract to the MEA and prior to the project becoming a Building America research project, was the development of the DER specifications.

The "base scope" for the project was mostly finalized at the point when Newport was tasked with developing additional cost effective specifications for the DER scope. In accordance with MEA's project goals, Newport used this base scope as the baseline for evaluating *additional* improvements that would form the DER scope. DER measures that replaced or altered a system within the base scope (e.g. using hybrid heat pump in the DER instead of the gas furnace and A/C in the base scope) were evaluated on the basis of their marginal energy savings and marginal implementation costs relative to the base scope. This analysis approach essentially asked the question: what can we cost-effectively implement beyond the base scope measures to reach 50% savings? It is also important to note that the "50% savings" metric compares the DER scope to the pre-retrofit building condition.

Given this background, Table 2 below relates the energy systems of the pre-retrofit building condition, the base scope, and the DER scope. The last row of Table 2 also highlights the *predicted* (modeled) energy savings of the base scope design (35%) and the DER design (52%). Above this row, the Home Energy Rating System (HERS) Index values for all three building conditions is also shown, with the base scope at 78 and the DER scope slightly better at 75. A primary reason for the relatively small spread in HERS Index (78 versus 75) but a much larger predicted energy savings reduction (35% versus 52%) is that a significant portion of the heating load is "fuel switched" from gas (furnace) to electric (heat pump) in the DER. This shift significantly reduces heating site energy usage, while the HERS Index is not impacted as significantly.

Note that SIR values in Table 2 are provided only for DER measures that went beyond the base scope. Some of these measures show SIR > 1, while others do not. In order to pursue the 50% savings level while also addressing ventilation and IAQ, MEA and the project team implemented some measures with SIR < 1.

The following components made up the SIR calculation:

- Useful lifetime for measures was based on sources such as NAHB/Bank of America's "Study of Life Expectancy of Home Components" Seiders et al. (2007) or estimated from industry data/experience.
- Implementation costs (equipment and labor) were based on quotes from the general contractor. In cases where a measure in the DER scope was replacing a system already included in the base scope, implementation cost was the net increase in cost for the DER measure.

Table 2. Energy Efficiency Retrofit Measures

Building System/ Component	Pre-Retrofit Condition	Base Scope	DER Scope	DER Scope Measure SIR (With Respect to Base Scope)
Attic Insulation	R-19	R-49 with sealing of duct bulkhead	Same as base scope	N/A
Attic Air Sealing	Leaky	Limited spot air sealing from within the top floor units where leakage sites were accessible (e.g. bath fan housing) as part of overall unit air sealing	Air sealing of attic floor penetrations from attic side with SPF[a]: including all mechanical, electrical, and plumbing penetrations; top plates of interior walls; This work was in addition to the limited spot air sealing in the base scope.	0.5
Windows	U-0.50 SHGC 0.40	U-0.35 SHGC 0.35	Same as base scope	N/A
Whole-House Mechanical Ventilation	None	Outside air duct in return air plenum; (no runtime controls or damper); not ASHRAE 62.2 compliant	ERV (66 W; 61% sensible recovery efficiency) to provide 60 cfm continuous; ASHRAE 62.2 compliant flow rates;	0.5
Bathroom Ventilation	Nominal 50 cfm fan > 6 sones	110 CFM, 6 in. bath exhaust with integrated humidity-sensing controls; 40 W	Same as base scope	N/A
Duct Air Sealing	Supply trunk not sealed; 3rd-floor units located in open-top bulkhead	Aerosolized duct sealing applied; open-top duct bulkhead in attic sealed and insulated	Same as base scope	N/A
Space Heating	80% AFUE gas furnace	92.5 AFUE, 2-stage gas furnace (36/60 kBtu)	Hybrid heat pump: 8.50 HSPF,[b] 92.5 AFUE 2-stage furnace back-up	1.3

Building System/ Component	Pre-Retrofit Condition	Base Scope	DER Scope	DER Scope Measure SIR (With Respect to Base Scope)
Space Cooling	10 SEER A/C unit	15 SEER, 1.5 ton	(36/60 kBtu), 40°F transition temp; cooling: 15 SEER, 1.5 ton.	
Domestic Water Heating	Central gas-fired storage, 100 gal, 0.54 EF (serving 12 dwellings)	100 gal, 95% thermal efficiency	Solar hot water with 3 flat panel collectors closed loop glycol; solar storage tank upstream of 100 gal, 95% thermal efficiency water heater	0.5
Lighting	100% Incandescents	100% compact fluorescent lamps for all permanent luminaires	In addition to 100% compact fluorescent lamps for permanent luminaires, supply resident with compact fluorescent lamps for all plug-in fixtures	13.0
Refrigerator	Non-ENERGY STAR®	ENERGY STAR	ENERGY STAR	N/A
Energy Feedback System	None	None	"Energy dashboard" to educate residents on electrical usage (assuming 10% electrical savings based in part on Parker et al. 2008). A 10% savings rate was estimated based on available literature and plans to train the residents on how to operate the retrofitted dwelling efficiently, given by the property manager.	1.8
HERS Index	127	78	75	N/A
Predicted Energy Use Reduction (Relative to Pre-Retrofit)		35%	52%	

[a] Spray polyurethane foam
[b] Heating season performance factor

- Estimated annual energy cost savings ($) were based on REM/Rate modeling (with additional analysis as needed for some measures not characterized within REM), combined with utility prices of $0.12/kWh and $1.50/therm. In cases where a measure in the DER scope was replacing a system already in the base scope, annual energy cost savings were the net difference between the DER measure and the base scope measure.

Initially, the pre-retrofit energy model was based on building audit data and diagnostic tests. When the energy use of this pre-retrofit model was compared with limited historical utility data for several apartments, it was within 5%–15% (depending on which apartment it was compared against). This was deemed acceptable given uncertain occupancy densities and behavior trends, and a well-documented audit of the pre-retrofit building condition.

In subsequent analysis of post-retrofit utility bill and monitoring data, issues with the pre-retrofit model were identified that had the affect of over estimating pre-retrofit energy use, and thus, also over estimating energy savings. These issues are discussed below in Section 4 "Long Term Monitoring Results and Utility Bill Analysis."

- Life cycle energy savings were reduced by 15% to estimate degradation of performance over time (MEA policy).
- No assumed utility rate escalation.

These factors were used in the following calculation of SIR:

$$SIR = (\text{Useful Life} * \text{Annual Energy Cost Savings} * 0.85) / \text{Implementation Cost}$$

3.2 Implementation, Commissioning, and Short-Term Testing of Final Deep Energy Retrofit Measures

The following sections discuss key findings gained during the implementation, commissioning, and short-term testing of specific DER energy upgrade measures.

3.3 Building Envelope Infiltration Reduction

Reducing natural infiltration was a primary strategy for the DER. The base scope included significant air sealing measures as they could be applied from within the apartment units (e.g., SPF around duct boot/drywall junction). Given typical pre-retrofit infiltration rates of 17 ACH50 (guarded) based on a sample of three representative buildings, the cost effectiveness of air sealing in the base scope was very attractive (SIR ~5).

The DER scope built upon this to also include additional air sealing in the attic. In the attics above the third-floor apartments, existing insulation was temporarily moved, and spray foam was applied to all mechanical, electrical, and plumbing MEP penetrations and the drywall/top plate joint of interior partitions. While the implementation cost and estimated energy savings for this measure were more modest (SIR ~ 0.5), it was deemed as an acceptable step to further reduce air infiltration.

Figure 5. Air sealing opportunity at corners of duct boot where it meets ceiling drywall

In terms of implementation, the GC's scope included detailed prescriptive requirements for air sealing which established what locations to seal, what sealing materials to apply, and how much sealant to apply. Additionally, the GC lead integrated coordination meetings among the trades, and conducted multiple on-site walk-thrus with the insulation contractor. Newport and PEG, the auditor for the base scope, also provided frequent on-site inspections.

Despite these efforts, the implementation of air sealing measures was inconsistent. This was partly due to frequent turnover in the insulation contractor crew. The prescriptive nature of the air sealing requirements also had a role in this inconsistency, as workers would sometimes adopt the perspective of "What is the minimum step I have to apply at this location?" instead of "How can I reasonably achieve significant air sealing in conducting my work scope?".

As a result, Newport has recommended to the property owner a performance-based air sealing approach for future projects. Such an approach would incorporate:

- Testing-in on a sample of units to establish a baseline
- Establishing a reasonable air infiltration reduction target (e.g., 30%–40% for moderate rehab). This target should be attainable, on average, with reasonable additions to the contractor's typical work scope.
- Specifying best opportunities for reductions as guidance.
- Implementing measures, and then testing-out.

Given the energy savings that are commonly attributed to air sealing in retrofits, validating these savings and linking contractor performance to tested reductions is a reasonable approach to consider.

Despite the inconsistency of the air sealing and a limited amount of rework, the average infiltration reduction in the DER units compared to the pre-retrofit condition was about 63% as shown in Table 3.

Table 3. Building Leakage: Blower Door Test Results

	Maximum ACH50*	Minimum ACH50*	Average ACH50*	Average ACH50 Reduction (Compared to Pre-Retrofit Condition)	Average ACH50 of 3rd-Floor Dwellings (n = 4)*	Ratio of Outdoor to "Total" Leakage**
Pre-Retrofit Condition	19.4	14.8	17.1			
Post-Retrofit Base Scope Dwellings (n = 18)	8.4	5.1	7.0	61%	7.3 (n = 6)	82%
Post-Retrofit DER Dwellings (n = 11)	8.3	5.2	6.4	63%	6.4 (n = 4)	81%

* Leakage to outdoors only, based on guarded blower door testing. This value was used in calculating energy savings from air sealing, not total (or unguarded) blower door leakage.
** Value determined by comparing guarded blower door results to unguarded blower door results

The additional attic air sealing efforts in the DER apartments also showed a marginal improvement relative to a tested sample of the base scope apartments, which had identical air sealing with the exception of work in the attic. The researchers predicted that the effectiveness of the attic air sealing would be most prominent in the third (top) floor apartments. This is illustrated above in Table 3, which shows about a 12% leakage reduction in third-floor DER apartments (n = 4) compared to third-floor base scope apartments (n = 6).

Both guarded and unguarded blower door tests were performed. For the base scope and DER scope apartments, both groups showed that about 82% of all leakage through the apartment envelope was leakage to outdoors (as opposed to neighboring units). This ratio does not mirror the ratio of apartment envelope surface area that is between conditioned space/outdoors and between conditioned space/neighboring units. Top-floor apartments have the highest percentage of envelope area between conditioned space and outdoors, at about 66% of their total shell area. Middle-floor apartments have the lowest percentage at about 24% (see floor plans in Figure 7).

In neither case does the surface area proportion align with the measured distribution of air leakage, however. This suggests that the distribution of air leakage sites was not evenly distributed across the building envelope, with a greater concentration of leakage sites in the assemblies separating conditioned space from outdoor air.

Figure 6. Air sealing of duct register boot and an HVAC penetration

Referring to Figures 2 and 7, the guarded blower door tests were conducted on a stairwell basis. In other words, all six apartments accessed from a given stairwell, and that were “connected” through the shared mechanical room on each floor, were simultaneously depressurized to –50 Pascals and maintained at this level while a CFM50 reading was recorded for each. Arranging access for this level of testing, in addition to having enough technicians and equipment, was a very significant effort. Thus, only a sample of apartments and stairwells were tested pre- and post-retrofit as noted in Table 3.

In examining the lack of correlation between building envelope surface area distribution (with 24%–66% of total shell between living space and outdoors) and the measured leakage rates (with ~82% of leakage to outdoors), the researchers examined whether it was possible that the guarded test was not completely guarded. This could occur if the guarded apartment was still in communication, via a floor assembly, wall assembly, or chase, to some other apartment which was not being simultaneously depressurized. The result would be an overestimate of the proportion of shell leakage to outdoors (as opposed to neighboring units).

In reviewing the guarded blower door test results and protocol (which was established in the initial audit), it was possible that there was some communication from guarded apartments to “unguarded” apartments. This was a reality of the testing that required extensive equipment, staff, and full apartment access to all surrounding units. In the guarded blower door tests, tests were run by the stairwell. Thus, the “interior” units sandwiched between the stairwells had no guarding across the firewall assembly in the very middle of the building, which joined them to the neighboring interior units (e.g., the interior two-bedroom and three-bedroom units in the floor plan in Figure 7). This points to the potential complicated nature of many MF buildings and the difficulties that can be encountered when performing energy audits, conducting and interpreting diagnostic test results, and implementing retrofit measures. It can be very easy to miss air leakage pathways to the outdoors and/or to other units in the building.

Newport’s researchers separated out guarded versus unguarded blower door results for the “exterior” apartments (those with three exterior walls plus the wall adjacent to the stairwell) versus the “interior” units. The results indicated that 79% of total leakage was to outdoors for the exterior units, versus 86% for interior units. This difference supports the concept that some unit-to-unit leakage was occurring during the guarded tests for interior units—most likely across the firewall to the adjacent interior unit. However, the rough magnitude of the difference is reasonable given the costs and logistical challenges of guarded testing in this type of MF building where depressurizing nine apartments would have been the ideal setup. Further, other factors such as more extensive leakage paths to outdoors may also have contributed to this difference.

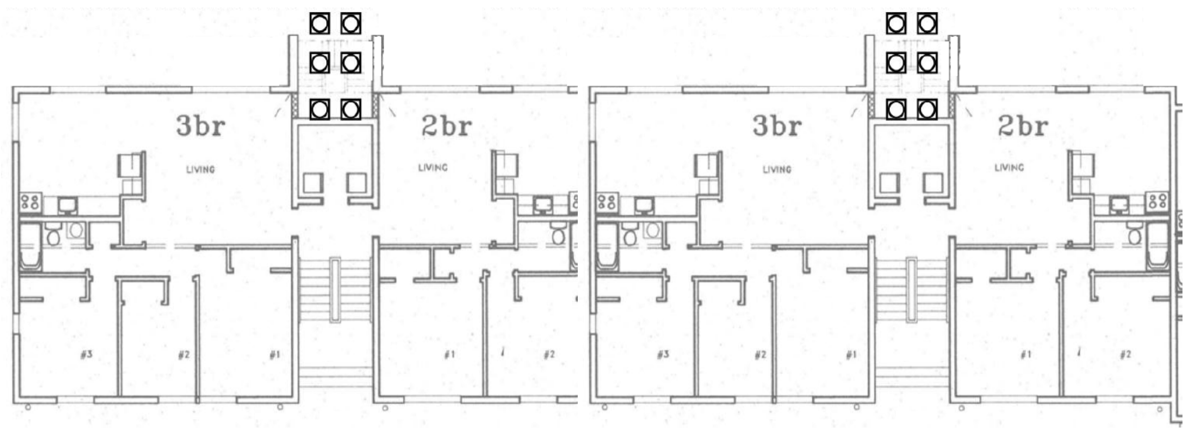

Figure 7. Floor plans for three-bedroom and two-bedroom apartments (same on all three floors)

3.4 Duct Air Leakage Reduction

The DER involved sealing the ducts with an aerosolized duct sealing system (also part of the base scope), which facilitated leakage reduction even though most ducts were inaccessible. All ducts were also cleaned using a brush-based system with vacuum to collect and expel dust, prior to aerosolized sealing. Duct cleaning prior to aerosolized duct sealing is recommended if the ducts are extremely dirty. Given this recommendation and the general conditions of the ducts and the old plywood plenums (see Figure 9 below), duct cleaning was part of the retrofit base scope for all apartments.

The third-floor apartments were also targeted for duct leakage reduction and improved insulation through an additional measure: sealing the top side of a bulkhead that housed the supply trunk. This bulkhead was open to the attic space in terms of air movement, and had inconsistent levels of insulation (ranging from R-19 to no insulation) placed on top of the supply trunk (see Figure 8).

Figure 8. Supply trunk for third-floor apartment exposed to attic (pre-retrofit condition)

The results of pre- and post-retrofit duct blaster testing are shown in Table 4. Overall, the duct sealing efforts resulted in a significant reduction in total duct leakage (63%). The return plenums, originally constructed from plywood and in very poor condition including signs of past water damage (Figure 9), were also replaced with sheet metal plenums.

Table 4. Duct Leakage Test Results

	Total Duct Leakage (CFM@25 Pa)
Pre-Retrofit Condition	481
Post-Retrofit Base and DER Scope Dwellings	180
% Reduction	63%

Figure 9. Pre-retrofit furnace and HVAC return plenum

Insulating and air sealing the open-top bulkhead shown in Figures 8 (above) and 10 (below) involved a two-step process specified by the base scope auditor PEG. It involved (1) removing insulation from the bulkhead area and laying down a membrane to serve as a substrate; and then (2) applying a layer of SPF to bond the membrane to the ceiling drywall as well as cap off the ends of the bulkhead. These two steps are shown below in Figure 11. This process proved to be effective when properly implemented; however, in some cases site inspections revealed that the insulation contractors would cover the top of the bulkhead with SPF but fail to block off the ends, which would still allow significant air leakage to the attic.

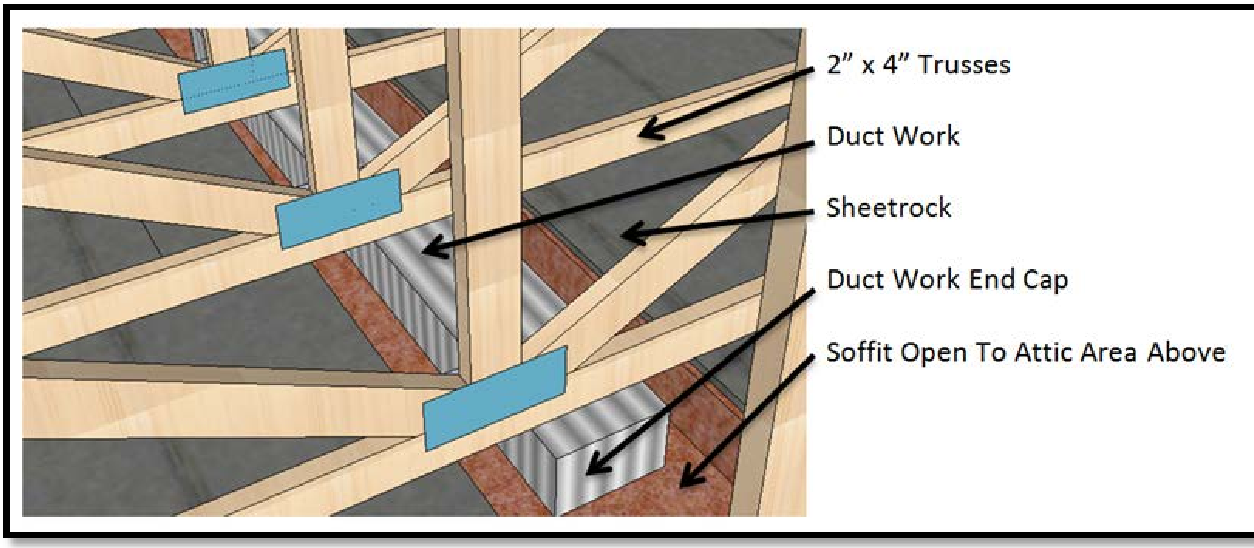

Figure 10. Diagram of duct bulkhead open to the attic space

Figure 11. Membrane application followed by SPF application to seal off top of duct bulkhead from attic

Sealing off this bulkhead also contributed to the whole-dwelling air leakage reductions for the third-floor apartments noted above in Table 3.

3.5 Heating, Ventilation, and Air Conditioning Equipment Efficiency Upgrade

The pre-retrofit heating, ventilation, and air conditioning (HVAC) systems were ~15-year-old furnaces and split system A/C units. Labeled efficiency levels were 80 AFUE and 10 SEER, respectively. The base retrofit scope upgraded these systems to a two-stage, 92.5 AFUE condensing furnace and a 15 SEER split A/C system. Given the mixed climate zone location (~4700 HDD; 17 F heating design temp) and the utility rates, Newport investigated hybrid heating options involving both electricity and natural gas. A heat pump-only approach was ruled out early in the process, because the electrical service to the units could not accommodate the required capacity for electric resistance backup heating.

The research team's energy modeling and cost analysis concluded changing from the base scope's 92.5 AFUE, two-stage gas furnace with 15 SEER A/C to a hybrid heat pump (15 SEER, 8.50 HSPF with 92.5 AFUE furnace backup) was a cost-effective, energy-saving measure with a SIR of 1.3. Given that the base scope already utilized a 15 SEER split A/C system and a high efficiency furnace, the marginal cost to upgrade to the hybrid heat pump system was reasonable at $975.

Residents at the Bay Ridge development are responsible for paying for electricity, which is metered at the apartment level. Natural gas is paid for by the property management, and is metered at the building level. Therefore, the researchers conducted additional analysis to estimate the impact of shifting a portion of the space heating load and cost to the residents in the form of heat pump heating.

Table 5. Energy Savings and Costs Analysis of Hybrid Heat Pump System

Scope	HVAC	Total Annual Heating Energy (MBtu)	Total Annual Heating Energy Cost (MBtu)	Total Electric Cost ($/Resident)	Total Natural Gas Cost ($/Property Owner)
Base	92.5 AFUE, 36/60 kBtu furnace 15 SEER, 1.5 ton A/C	30.4	$512	$20	$492
DER	15 SEER, 8.5 HSPF 1.5 ton heat pump with 92.5 AFUE 36/60 kBtu furnace	22.1	$401	$122	$279
DER Savings for Resident		8.3	$111	($102)*	$213

While the shift from furnace-only heating (base scope) to the hybrid heat pump was estimated to result in added electricity costs of $102, the measure was deemed acceptable because even with these added electricity costs for heating, the DER residents gained a net heating energy cost savings of about $100/year when compared to the pre-retrofit building condition. When considering the application of hybrid heating systems on a larger basis in retrofits, the issue of increased utility payments (and the potential impact on allowable rents in affordable housing developments) is a key issue.

Along with the shift to combined heat pump/furnace space heating, the researchers integrated whole-dwelling ventilation based on ASHRAE 62.2 rates. Key factors that lead to the specification of an ERV included the following:

- The base scope system, which was a 3-in. outside air duct routed into the return air plenum with no motorized damper or runtime controls on the central air handling unit, was deemed insufficient by the research team in terms of energy performance and IAQ.
- Due to frequently cited IAQ concerns caused by apartment-to-apartment air leakage (such as environmental tobacco smoke), balanced ventilation was preferred over supply- or exhaust-based.
- Reports and observations of poor IAQ conditions (strong smoking odors) in the pre-retrofit buildings made a continuous system, located in the mechanical room, attractive.

In terms of humidity removal, after consulting with maintenance staff, Newport's researchers determined that controlling indoor summertime RH (via the ERV's ability to reduce the moisture load in incoming fresh air) was more critical than specifying a system based on pre-supposed high indoor winter RH levels (which would have indicated a heat recovery ventilator).

Also, given the reported and observed IAQ in several apartments, an airflow rate of 60 cfm was specified. This rate is at least 25% higher than the minimum flow rated permitted under ASHRAE 62.2.

During the implementation and commissioning of the HVAC and ERV systems, Newport's research team noted these findings:

- The hybrid heat pump systems did not cycle into furnace operation at the agreed-upon transition temperature.
- Due to miscommunications from the GC to the HVAC contractor, the HVAC contractor did not initially install the correct thermostat for the hybrid heat pump system. After this was corrected, Newport closely monitored the hybrid heat pump system using the long-term energy monitoring system in December 2011. Due to the mild winter, there were limited nights with ambient temperatures < 40°F, which was the transition temperature for the system. Below this temperature the heat pump is cycled off and the furnace assumes 100% of the heating load.
- After two or three sub-40°F nights without furnace operation, Newport alerted the GC and HVAC contractor that the furnace was still not operating when it should. The

underlying problem was that the thermostats were not wired correctly to the furnace. We also learned that the outdoor temperature sensor relies on wireless communication to communicate with the unit, and that this wireless sensor is battery powered. While this wireless sensor did not cause the initial problem, battery change-outs will be a long-term maintenance issue. If furnace operation fails in this system because the system does not sense outdoor temperature, the resident will pay for 100% of space heating and will rely on a heat pump without a backup heat source. It is recommended that a reminder be posted on the equipment to replace the battery as part of the annual maintenance protocol.

DER apartment residents were provided with limited education on the hybrid heat pump system. The property manager did provide a basic overview of the features of the DER apartments to residents. However, the session was poorly attended and it is unclear how much information was given on the hybrid heat pump (e.g., who pays for the different operating modes). While the residents now have an aligned incentive for heating energy conservation (modest set points; keeping windows closed), there appeared to be some reluctance to highlight the fact that residents now pay for part of their own heating.

This challenge is likely common in MF developments where fuel switching occurs, and the end result can be lost energy savings.

4 Long-Term Monitoring Results and Utility Bill Analysis

Once the retrofits were complete monitoring equipment was installed in two base scope apartments and two DER apartments. All four apartments faced the same cardinal direction and were located on the third floor of the buildings; two apartments were two-bedroom units (713 ft^2) and two were three-bedroom units (909 ft^2). Occupancy was not equivalent across units of the same size, and in some cases, it was also not consistent in the pre- and post-retrofit periods in the same unit despite efforts to obtain apartments with the same residents. Thus, resident-neutral comparisons of pre- and post-retrofit energy use and of post-retrofit energy use in the base scope versus DER apartments are difficult to make. The variability in occupancy was not controllable, and thus the monitoring plan was developed based on the best available information at the time.

Monitoring including the following data:

- Indoor and outdoor temperature and RH
- Hybrid heat pump runtime and natural gas consumption
- Heat pump blower and compressor electricity consumption
- Gas furnace runtime and natural gas consumption
- Apartment-level hot water consumption.

Newport used the data collected over an 11-month period along with utility billing data to answer the following questions:

- What energy savings did the DER units show compared to the pre-retrofit condition? Did the actual savings meet the estimated savings?
- How did the energy performance of the high efficiency hybrid heat pump compare to the 95 AFUE furnace?
- What do the average summer and winter indoor temperatures measurements indicate regarding occupant preference and behavior?
- What do the average summer RH measurements indicate regarding the ability of the cooling system and the whole-house mechanical ventilation system to manage indoor humidity?

4.1 Post-Retrofit Energy Savings in the Deep Energy Retrofit Units

Apartment 4, a three-bedroom, 909-ft^2 unit in the DER apartment building, offered the best opportunity for pre- and post-comparison due to the fact that it had the greatest consistency in occupancy as well as the greatest availability of utility bill history. (Generally, utility bill availability was inconsistent due to frequent resident turnover, along with the need to obtain resident permission to access bills.) Therefore, the comparison of pre- and post-retrofit energy use concentrated on Unit 4. Figure 12 below illustrates the total pre- and post-retrofit energy use of Apartment 4 as a function of average monthly temperature.

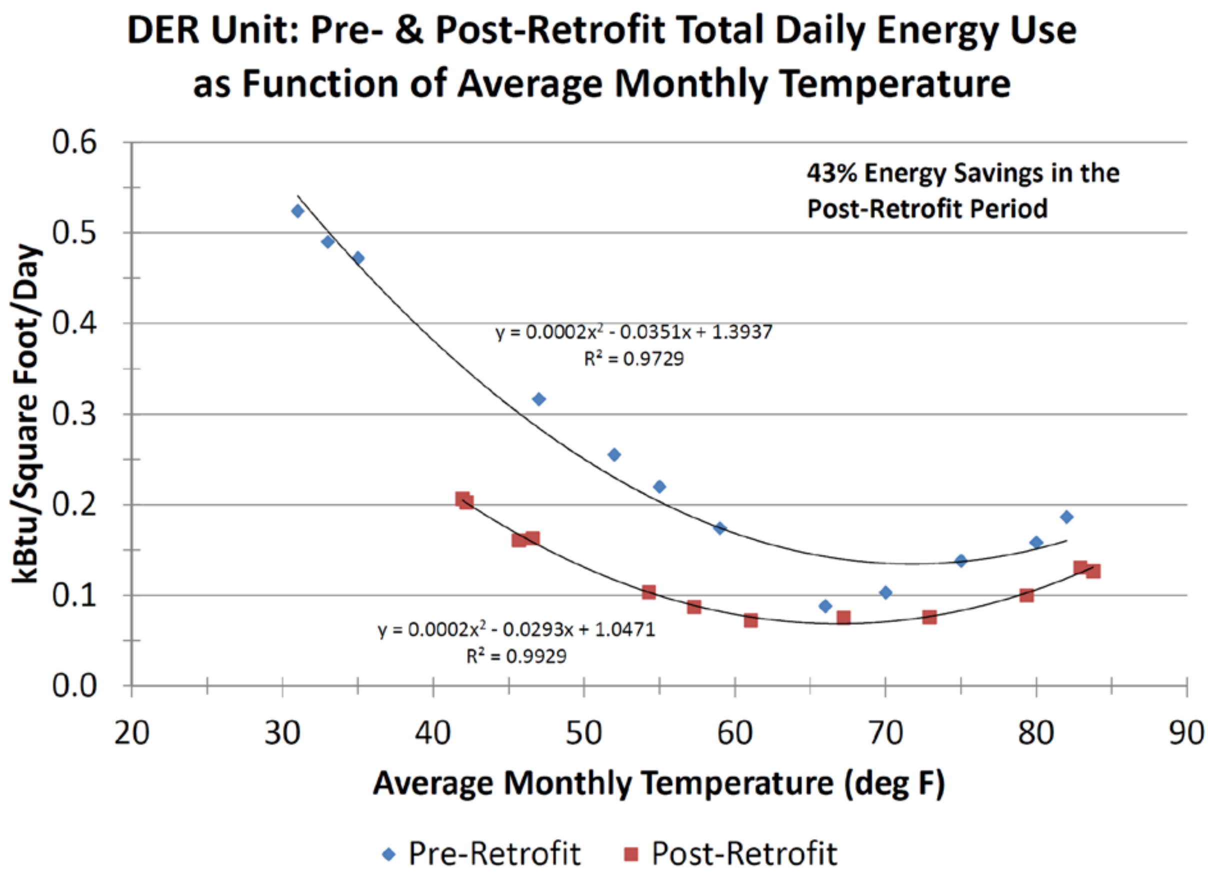

Figure 12. Pre- and post-retrofit energy use in DER Apartment 4

The savings in total energy use resulting from the DER measures was 43% relative to the pre-retrofit condition. The percentage savings was calculated by:

1. Regressing pre- and post-retrofit monthly energy use as a function of monthly average outdoor temperature.
2. Applying the resulting equations for each period to an annual set of average monthly temperatures based on a 30-year dataset from the National Oceanic and Atmospheric Administration.
3. Summing the monthly energy consumption values to achieve annual totals
4. Calculating the percent savings.

The 43% reduction in pre- versus post-retrofit energy savings is lower than the original projection of 52% energy savings which was based on modeling in REMRate. However, the 43% realized energy savings do exceed the Building America goals for the mixed-humid climate.

One key reason for the initial, higher estimate of energy savings (52%) was an overestimate of pre-retrofit energy use in the REMRate model, specifically for water heating and space heating. The REM model initially assumed a volume of hot water consumption that was approximately 10% greater than that revealed in the post-retrofit monitored data. In addition, pre-retrofit space heating energy use was perhaps exaggerated due to an overly conservative derating of equipment performance based on age and an assumed maintenance factor. Actual combustion efficiency test results were not available from the initial energy audit performed prior to the project's inclusion in Building America.

Another likely overestimation in the energy savings calculation was an assumed 10% electrical energy savings resulting from the energy dashboard system in each DER apartment (Table 2). A study released after this initial estimate arrived at an average electricity savings of 3.8% based on nine pilot programs (Foster and Mazur-Stommen 2012). In the case of the Bay Ridge occupants, it is unknown to what extent they actually paid attention to the energy dashboards. Relatively high winter indoor temperatures and low summer indoor temperatures observed in the post-retrofit data indicated that these devices did not encourage occupants to moderate thermostat set points.

Another contributing factor was a lower-than-actual energy use estimate for the ERV. The specified ERV was not installed after initial approval, due to product availability delays for the HVAC contractor. As a result, the energy consumption for the whole-dwelling ventilation system more than doubled, and added an additional 1 MBtu/yr in energy consumption beyond the originally specified ERV.

Finally, a recent study by Steven Winter Associates and HR&A Advisors (2012) cited actual fuel savings realization rates substantially lower than initial projections in affordable MF building energy retrofits. Whereas savings between 25% and 50% were originally predicted, *actual* fuel savings proved to be only between 10% and 40%. The fuel savings realization rate was 61% with a 90% confidence level ± 14%. This savings realization rate is for space and water heating only.

The study notes that electricity savings in MF buildings are even more difficult to predict. Thus, the total energy savings realization rate of 83% (= 43/52) for the Bay Ridge project compares favorably with these findings. Because MF buildings (and occupant behavior) are complex with multiple factors impacting one another, empirical studies and modeling do not always prove fully reliable, despite being critical inputs to the audit and retrofit process. The authors of the aforementioned study recommended "capping" overly optimistic predictions to maintain more conservative projections and improve realization rates.

4.2 Energy Performance of the High Performance Hybrid Heat Pump and the 95 Annual Fuel Utilization Efficiency Gas Furnace

As discussed previously, the 92.5 AFUE two-stage furnace that was installed as part of the base scope energy package was upgraded to a hybrid heat pump for the DER scope due to the estimated SIR of 1.3 relative to the base scope. Like the mechanical equipment in the base scope units, the backup furnace that was part of the hybrid system had an AFUE of 92.5. The heat pump, however, had ratings of 8.5 HSPF in heating mode and 15 SEER in cooling mode. When correctly commissioned, the system was set to transition to furnace operation at an outdoor temperature of 40°F.

Figure 13 shows the daily energy consumption of each of the systems as a function of indoor-outdoor temperature difference over a three-month winter period from January through March.

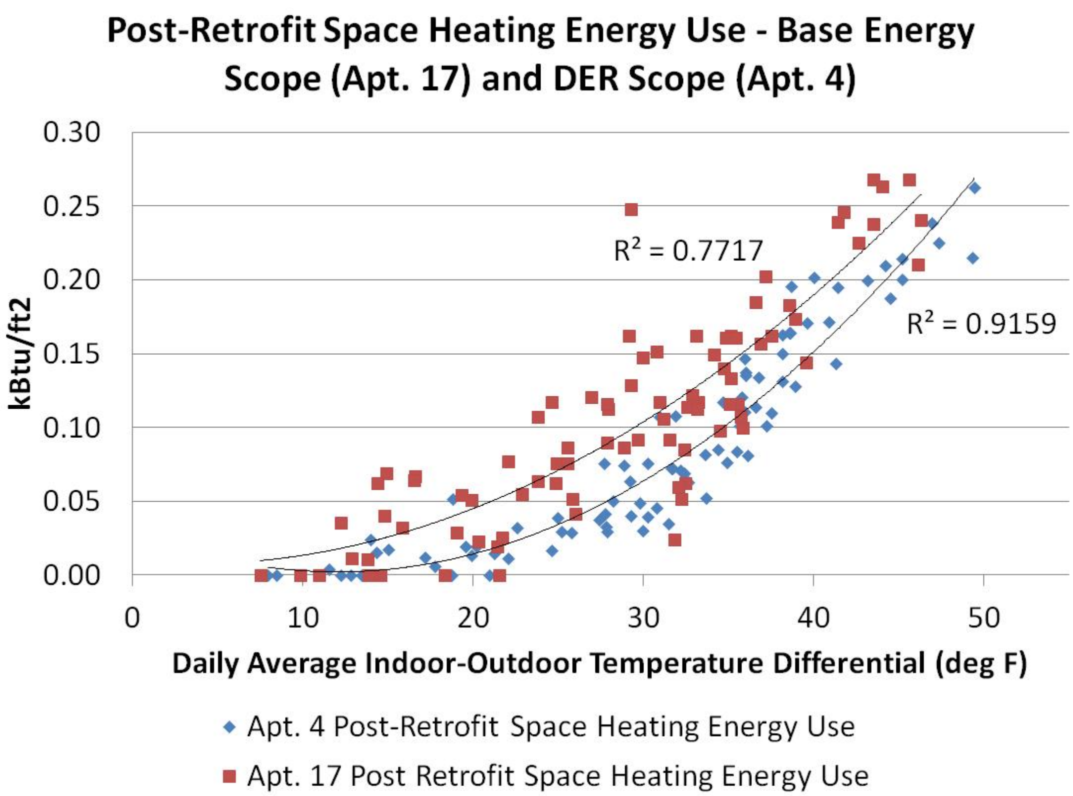

Figure 13. Post-retrofit space heating energy use

The measured data do show that the DER Apartment 4 consumed 17.6% less energy for space heating than did the base scope apartment (17) over the three-month period (6.69 MBtu versus 8.12 MBtu). However, potential complicating factors that could influence these results include different mechanical ventilation systems (see Table 2); differences in window operation; differences in ventilation fan use; differences in envelope tightness (although blower door testing across several base scope and DER units showed similar average results); and duct tightness (results on these specific units were not available from the audit contractor).

The chart in Figure 13 also indicates some interesting trends. Under warmer outdoor temperature conditions, e.g., lower indoor-outdoor temperature difference, the energy consumption of the two systems converges. This makes sense because calls for heat will be more intermittent and runtimes are likely to be shorter, dampening out compromising equipment and operating efficiencies. As outdoor temperatures become colder and demand increases, the energy consumption of the two systems begins to diverge, indicating possible differences in furnace versus heat pump operation and performance. Then as outdoor temperatures get very cold ≥ 40°F temperature differential—energy consumption again converges as both units are operating under the natural gas furnace, which has similar AFUE ratings.

The BA-PIRC team also reviewed the data to characterize heat pump operation versus furnace operation over a three-month period of space heating. The controls were set such that the furnace would assume all heating operation when the outdoor temperature dropped below 40°F . Supply plenum average temperatures generally remained between 85°– 95°F under heat pump operation. Figure 14 shows heat pump versus furnace operation as a function of outdoor temperature difference. The gas furnace satisfied the majority of the space heating demand constituting 76% of the space heating energy. The reason for the furnace operation during a period with temperatures in the upper 50s and low 60s is uncertain.

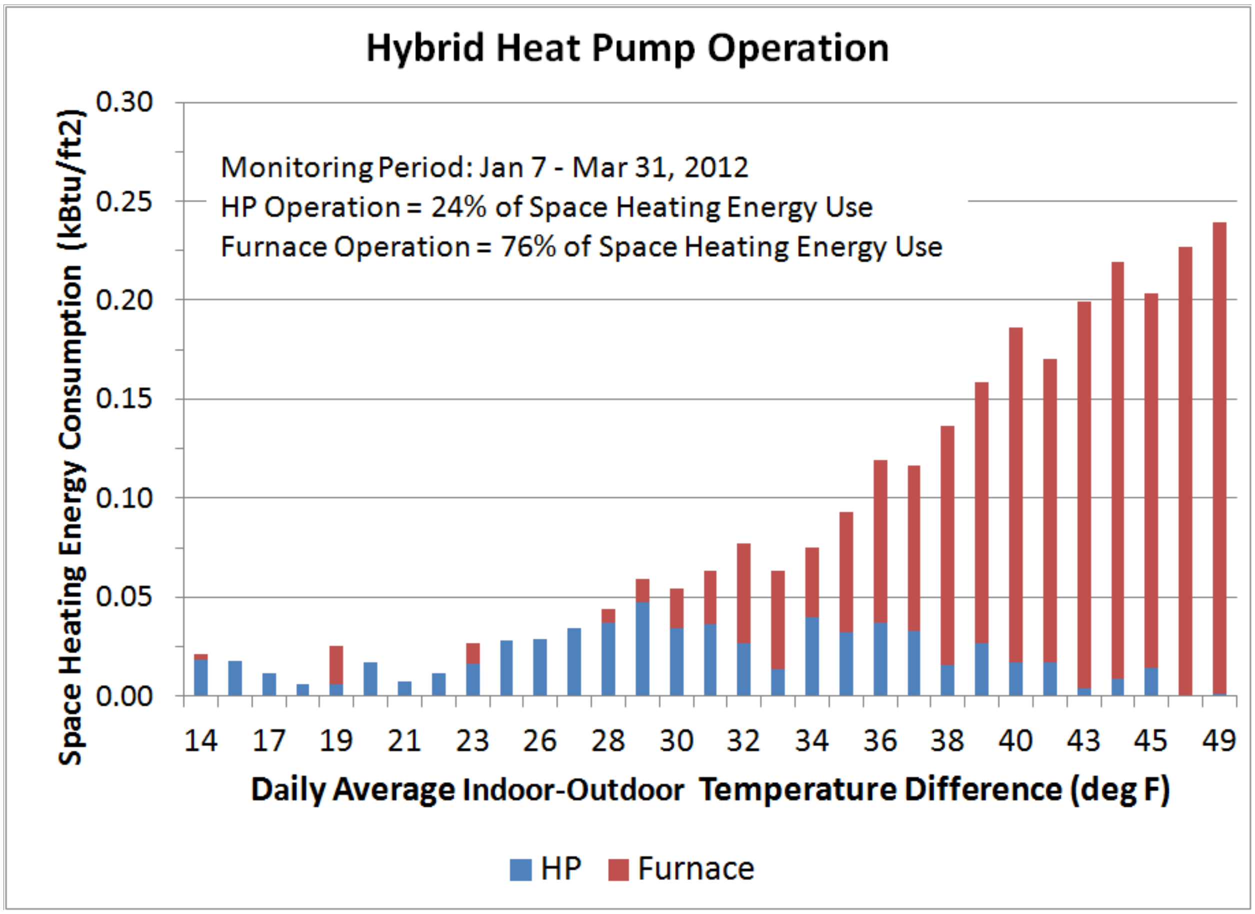

Figure 14. Heat pump versus furnace operation average indoor temperature and RH measurements

Temperature and RH sensors were placed near the ceiling in the living rooms of all four apartments, post-retrofit. Table 6 below shows the average winter and summer indoor temperatures and the average indoor RH in each of the apartments.

Table 6. Average Indoor Winter/Summer Temperature and RH

Unit	Average Temperature December–February (°F)	Average Temperature June–August (°F)	Average RH June–August (%)
Apartment 4	75.6	75.7	58.7
Apartment 4-2	77.6	74.7	58.5
Apartment 17	75.9	76.1	56.5
Apartment 17-2	77.2	69.3	63.8

Heating season indoor temperatures indicate fairly high heating system thermostat set points, even in the DER apartments (4 and 4-2) where the tenants shifted from not paying for *any* portion of their heating (pre-retrofit gas furnace) to paying a substantial portion of their space heating energy costs (post-retrofit hybrid heat pump system where residents paid for electricity). Hourly data for at least one of the apartments also show some winter indoor temperatures > 80°F. This indicates that the seasonal averages likely mask even higher intermittent set points for the system.

The summer season indoor average temperatures indicate that at least one apartment (17-2) had an extremely low thermostat set point. In addition, the average indoor RH in this apartment during the June through August period was clearly the highest at almost 64%. At least part of this difference can be attributed to the whole-dwelling ventilation system in the base scope apartments. This ventilation system (specified by an outside consultant who was not part of the BA-PIRC research team) was simply an outside air duct routed into the return plenum with no control logic or damper. Thus, in unit 17F, a very low cooling thermostat set point would result in greater A/C system runtime and consequently, a greater latent load introduced from the outdoor ventilation air.

Initially, the programmable thermostats were set at 68°F and 75°F, respectively, for winter and summer months when the retrofit was completed and the occupants were given some instruction how to use them. Likewise, they were introduced to the "energy dashboards" and shown how they could use these devices to monitor their energy consumption relative to certain actions such as raising and lowering thermostat temperatures. However, from the measured average indoor temperatures and RH levels, it is apparent that more effective resident education could result in greater energy savings in any of the post-retrofit apartments.

5 Conclusions

The DER project at Bay Ridge has provided numerous findings related to the selection of the DER scope; the ability of the retrofit to achieve more than 30% energy savings and possibly as high as 50% savings; and the implementation, commissioning, short-term testing, and long-term monitoring of the efficiency upgrade measures. Because the building type at Bay Ridge is quite common in many parts of the country, many of these findings will also apply to other MF retrofit projects. Key conclusions are noted below.

5.1 Developing a Deep Energy Retrofit Scope

In the evaluation of potential energy upgrades to include in a retrofit of this type, several types of tradeoffs must be considered. The most obvious is the balance between energy savings and implementation cost. This decision should also factor in the expected life cycle of an upgrade measure. The SIR is a widely recognized metric for addressing these factors. An efficiency upgrade with an SIR value > 1 is generally considered a good efficiency investment that will pay for itself over the course of its life cycle. Several of the DER measures had SIRs > 1, although lower SIR measures such as whole-dwelling ventilation were also included in the DER scope, given the importance of adequate ventilation in post-retrofit, air-sealed apartments. It is important to note that SIR values in this program were developed in a very conservative manner: energy savings estimates were made relative to the base rehab scope, plus a 15% performance degradation factor was applied to all measures.

Beyond the question of energy savings versus implementation cost, there are several other critical tradeoffs to consider in developing a retrofit work scope. These factors can greatly affect the cost, complexity, and effectiveness of energy upgrades, and include:

- **Regulatory tradeoffs**. Within this project, the presence of aluminum wiring in the building was addressed through an industry-recognized copper-aluminum crimping system. However, if a large amount of aluminum wiring were to be exposed—as part of an air sealing effort, for example—the local regulatory authority would require a more extensive replacement of the aluminum wiring. Other types of potential regulatory issues that could be triggered by an energy upgrade measure include fire safety (especially in MF), combustion safety, and even environmental impacts (e.g., related to ground source heat pump loop installation).
- **Constructability tradeoffs**. Within this project the residents returned to the apartments at night for most of the project, which required the dwelling to be safe and habitable at the end of each workday. This ruled out the possibility of some energy upgrade measures due to constructability—the contractors simply could not complete the work scope within these parameters. Residency issues, as well as scheduling constraints, may rule out some measures in this way.
- **Building science "risk factors."** This is a broad category of "pitfalls" to be aware of when evaluating different energy upgrade measures, covering thermal and moisture considerations, along with other factors such as radon and combustion safety. Within this

project, the presence of polyethylene sheeting within the exterior wall assembly posed a significant condensation risk if interior insulation were added.

5.2 Energy Savings Realization Rate

The Bay Ridge DER achieved a 43% energy use reduction compared to the pre-retrofit building by incorporating efficiency measures mostly with SIR values > 1 compared to the base scope. Compared to the initial savings estimate of a 52% reduction, the validated energy savings represent a realization rate of 83%. Relative to other affordable MF retrofit projects, this is a favorable result. Opportunities to improve the realization rate further include:

- Improving the characterization of pre-retrofit energy use via pre-retrofit monitoring and targeted diagnostics
- Increased emphasis on educating residents on their impact on energy use and costs
- Limiting or eliminating specification changes during construction
- Applying increased conservatism on the energy impact of efficiency measures that are not readily quantified.

5.3 Implementation, Commissioning, and Testing of Efficiency Upgrade Measures

Air sealing in a tenant-in-place retrofit model, where the envelope assemblies generally could not be opened up, was constrained. Despite this limitation, very significant infiltration reductions (63%) were realized by applying an “inside-out” air sealing strategy that re-established the drywall as the unit’s air barrier. Caulk and spray foam sealant were used at most leakage locations accessible from within the apartments during construction, including HVAC boot/drywall joints, floor/wall intersections, framing joints around windows, around wiring and plumbing penetrations through drywall or framing, behind shower/tub inserts, and around fan housings. Establishing performance-based air sealing agreements with contractors was also identified as a method to help ensure acceptable results and streamline the training and implementation process.

Air sealing from the attic space also proved to be effective in the DER building. This measure involved removing the existing insulation, applying spray foam at all penetrations as well as drywall/wall top plate joints, and then re-insulating the attic space (R-49). This work can be scheduled separately from the work inside the apartments, and ideally should be scheduled for cooler periods of the year, which improves the installation quality and worker safety.

Duct leakage reduction with aerosolized duct sealant also proved effective (63% reduction), especially given that most ducts were inaccessible. However, aerosolized duct sealing should not necessarily be the *only* measure applied to improve conditioned air distribution system performance. In this project, the ducts for the top-floor apartments were accessible, and in need of remediation because they were located in a bulkhead left open to the attic space above. Methods to correct this type of assembly must both air seal and insulate the area where the ducts are located. This favors the use of spray foam and a resilient backer material. Again, work quality and worker safety are enhanced if this fairly detail-oriented work can be performed during cooler periods.

HVAC systems offer the largest energy savings opportunity in MF retrofits where the envelope cannot be substantially changed. A hybrid heat pump system optimized energy performance at Bay Ridge, and was cost effective because the marginal cost above a furnace and A/C system was reasonable (~$975/system) compared to energy savings. The use of a hybrid system presents several opportunities and challenges. First, if natural gas is master metered for the building but residents pay their own electricity bills, switching to dual fuel heat pumps shifts a portion of the heating load (and cost) to the resident. This offers an opportunity to align conservation incentives, because the person setting the thermostat also pays for some of the heating cost.

To take advantage of this opportunity, however, resident education is needed. As seen in Table 6 above, it appeared that all of the apartments had fairly high thermostat set points during the winter. With increased education regarding potential cost savings on monthly utility bills, residents might be more inclined to lower their thermostat settings. Commissioning of hybrid heat pump systems is also crucial to ensure proper operation, and to optimize the transition temperature. Transition temperatures can be set by rule of thumb, or calculated more precisely to minimize either energy usage or energy cost.

Whole-dwelling ventilation in an MF DER is an important consideration when significant envelope air sealing is also specified. Balanced ventilation was specified in the Bay Ridge DER to avoid ventilation-induced unit-to-unit air movement and the migration of odors and ETS. These ERV units were superior to the base scope ventilation system in terms of air flow, energy efficiency, and maintaining reasonable average indoor humidity levels. However, quantifying the resulting IAQ benefits to justify the cost difference can be challenging. Even so, this does not diminish the importance of whole-dwelling ventilation especially in a DER project.

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