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Short-Term Test Results: Multifamily Home Deep Energy Efficiency Retrofit

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Contents

List of Figures vi
List of Tables vi
Definitions vii
Executive Summary viii
1 Problem Statement 1
1.1 Introduction 1
1.2 Background 2
1.3 Relevance to Building America's Goals 2
1.4 Cost-Effectiveness 3
1.5 Tradeoffs and Other Benefits 3
1.5.1 Energy Savings versus Implementation Costs 3
1.5.2 Regulatory and Constructability Tradeoffs 4
1.5.3 Building Science "Risk Factors" 4
2 Research Questions 7
3 Retrofit Specifications 8
3.1 Selection and Cost-Effectiveness of Final DER Measures 8
3.2 Implementation, Commissioning, and Short-Term Testing of Final DER Measures 12
3.2.1 Building Envelope Infiltration Reduction 12
3.2.2 Duct Air Leakage Reduction 16
3.2.3 HVAC and Ventilation Equipment Efficiency Upgrade 19
4 Conclusions 22
4.1 Developing a DER Scope 22
4.2 Implementation, Commissioning, and Testing of Efficiency Upgrade Measures 23
4.3 Next Steps at Bay Ridge 24
References 25

List of Figures

Figure 1. Aerial view of Bay Ridge development; DER building outlined in red 1
Figure 2. Front view of three-story apartment building 1
Figure 3. Polyethylene layer on inside face of CMU wall assembly 4
Figure 4. Exterior wall section showing limitted depth furring and poly layer on inside face of CMUs 5
Figure 5. Air sealing opportunity at corners of duct boot where it meets ceiling drywall 12
Figure 6. Air sealing of duct register boot and an HVAC penetration 14
Figure 7. Floor plans for 3-bedroom and 2-bedroom apartments (same on all 3 floors) 15
Figure 8. Supply trunk for third-floor apartment exposed to attic (pre-retrofit condition) 17
Figure 9. Pre-retrofit HVAC return plenum 16
Figure 10. Diagram of duct bulkhead open to the attic space 18
Figure 11. Membrane application followed by SPF application to seal off top of duct bulkhead from attic 18
Figure 12. Energy end use reductions in the deep energy retrofit design 23

Unless otherwise noted, all figures were created by Newport Partners, LLC.

List of Tables

Table 1. Summary of Rejected Upgrade Measures 5
Table 2. Energy Efficiency Retrofit Measures 10
Table 3. Building Leakage: Blower Door Test Results 13
Table 4. Duct Leakage Test Results 17
Table 5. Energy Savings and Costs Analysis of Hybrid Heat Pump System 19

Unless otherwise noted, all tables were created by Newport Partners, LLC.

Definitions

AC	Air conditioner
ACH_{50}	Air changes per hour at 50 pascals
AFUE	Annual fuel utilization efficiency
CFL	Compact fluorescent lamp
cfm	Cubic feet per minute
cfm_{25}	Cubic feet per minute at 25 pascals
cfm_{50}	Cubic feet per minute at 50 pascals
CMU	Concrete masonry unit
DER	Deep energy retrofit
ERV	Energy recovery ventilator (or enthalpy recovery ventilator)
ETS	Environmental tobacco smoke
HERS	Home Energy Rating System
HSPF	Heating seasonal performance factor
IAQ	Indoor air quality
kBtu	Thousand British thermal units
MMBtu	Million British thermal units
MEA	Maryland Energy Administration
Pa	Pascal
RH	Relative humidity
SEER	Seasonal energy efficiency ratio
SHGC	Solar heat gain coefficient
SIR	Savings to investment ratio
SPF	Spray polyurethane foam
W	Watt

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 Program. Such buildings represent great potential for energy savings, while providing valuable research-generated efficiency measures, cost-effectiveness metrics, and risk factor strategies to the multifamily housing industry. The Bay Ridge project comprises 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 was applied to the entire complex, except for one 12-unit building that underwent the DER scope. The design and construction phase of the Bay Ridge project is now complete, and this report summarizes the commissioning, short-term testing, and analysis that occurred before, during, and just after the actual retrofit.

Findings from the implementation, commissioning, and short-term testing include air infiltration reductions of >60% in the DER building; a savings to investment ratio of >1 from the hybrid heat pump system (relative to a high efficiency furnace), which also gives the resident an added incentive for energy savings; and duct leakage reductions of >60% resulting from using an aerosolized duct sealing approach. Despite being a moderate rehab instead of a gut rehab, the Bay Ridge DER is currently projected to achieve energy savings ≥50% compared to pre-retrofit levels, and the short-term testing supports this estimate. Long-term monitoring throughout 2012 will evaluate actual performance.

1 Problem Statement

1.1 Introduction

Under this project, Newport Partners (Newport; as part of the Building America Partnership for Improved Residential Construction research team) is evaluating the installation, measured performance, and cost effectiveness of efficiency upgrade measures for a tenant-in-place[1] deep energy retrofit (DER) at the Bay Ridge multifamily development in Annapolis, Maryland. The design and construction phase of the Bay Ridge project is now complete, and this report summarizes the commissioning, short-term testing, and analysis that occurred before, during, and just after the actual retrofit.

Figure 1. Aerial view of Bay Ridge development; DER building outlined in red

The Bay Ridge project comprises a base scope retrofit that is estimated to achieve a >30% savings (relative to pre-retrofit) on 186 apartments, and a DER scope that is estimated to achieve 50% savings (relative to pre-retrofit) on a 12-unit building. The base scope was applied to the entire complex, except for one 12-unit building on which the DER scope approach was taken.

A wide range of efficiency measures was applied to achieve this savings target for the DER building, including improvements and 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 will build on the current body of knowledge of retrofits, specifically deep retrofits in multifamily projects. Toward this end, the research team collected and generated data on the selection of measures, their estimated performance, their measured performance, their estimated and actual cost effectiveness, risk factors and their impact on potential measures, and the overall energy savings from two different retrofit packages applied to the same types of buildings in the complex.

Figure 2. Front view of three-story apartment building

[1] Tenant-in-place refers to an approach to building renovation in which residents vacate their dwelling during the daytime, and return at night. Basic dwelling functionality is restored and health/safety risks are addressed at the end of each work day.

1.2 Background

DERs can result in >30% energy savings, and are much easier to implement when a building is undergoing a substantial remodel, in which contractors can have greater access to walls, ceilings, and duct systems. For projects like Bay Ridge that are not undergoing substantial remodels, which are more common, 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 (at least at night). 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 affect the ability of contractors to reliably and successfully apply them.

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

1.3 Relevance to Building America's Goals

This research project is part of the U.S. Department of Energy's Building America 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 team is investigating a common building type: a 1970s-era, three-story walk-up apartment building owned and operated by a major industry firm. In addition, the renovation incorporates a retrofit model that property owners and affordable housing advocates support: tenant-in-place (in which the tenant might be inconvenienced for a short period of time but is not displaced).

The research team is exploring risk factors and regulatory issues, and their roles in determining what efficiency measures might not be viable because they would jeopardize building performance, compromise occupant health, or trigger cascading regulatory requirements. Such risk factors are common and property owners need effective identification and mitigation strategies with which to navigate them.

Both building owners and energy efficiency program managers want to answer this question: How much energy did the project really save? Under this effort, the research team is validating estimated energy savings for two different retrofit scopes applied to the same building types with actual savings. The base scope retrofit is estimated at 30% savings and the DER scope is estimated at 50% energy savings. The research team deployed energy monitoring to evaluate post-retrofit performance characteristics.

Taken together, the components of this research will yield extremely valuable information to the U.S. Department of Energy and the multifamily building industry. This project will augment understanding of current capabilities in energy retrofits and remaining gaps.

1.4 Cost Effectiveness

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 ration (SIR; calculated).

Newport engineers and building analysts conducted energy modeling with REM/Rate to project the cost effectiveness of various measures on the basis of the SIR (highly relevant to multifamily projects that receive weatherization funding) and other metrics. Building Energy Optimization software was also evaluated for this work, but was ultimately bypassed because of its 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, when the retrofit project also became a Building America research effort, energy upgrade analysis using REM/Rate had already been under way for more than 6 months under contract with the Maryland Energy Administration (MEA).

The modeling analysis generated a list of potential measures, but additional filters were applied to ensure that efficiency measures accounted for existing conditions and the project's rehab model. These additional considerations were as follows:

- Compatibility with a tenant-in-place rehab model
- Compatibility with a rehab scope that 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 or negative indoor air quality impacts).

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

1.5 Tradeoffs and Other Benefits

Several types of tradeoffs, described in the following subsections, were evaluated in the development and selection of the efficiency measures.

1.5.1 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 an SIR >1 generally passed this test, although this level is not a strict rule, and some measures with 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 because of the implementation cost and the SIR.

1.5.2 Regulatory and Constructability Tradeoffs

Several measures under consideration were not selected because of complications with residents returning to their dwellings each night, in addition to underlying risk factors within the building.

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. If enough aluminum wiring *was* exposed, however, the authority would likely require a full wiring change 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, and exposed nails, among potential hazards.

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

1.5.3 Building Science Risk Factors

Newport's invasive investigations of the building revealed an exterior wall assembly of uninsulated CMUs with a layer of poly 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 poly if insulation was added to the inner side of this assembly. As a result, laminating R-5 extruded polystyrene 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.

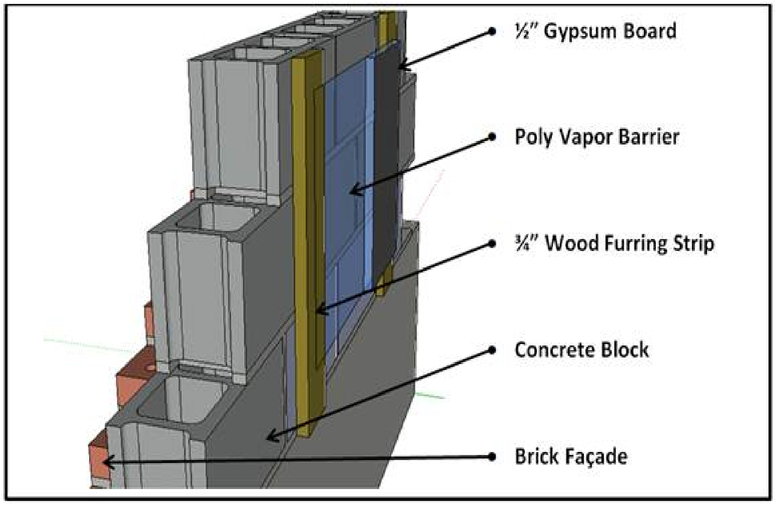

Figure 4. Exterior wall section showing limitted depth furring and poly layer on inside face of CMUs

Table 1 summarizes numerous measures that were considered during the DER scope development but ultimately rejected because of the factors discussed previously. Although 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, adhered to inside gypsum face of all exterior walls. One-inch rigid foam and sheetrock installed over existing wall surface. Extensions for windows, outlets, and switches	Strong risk of winter season condensation within wall assembly because of continuous layer of poly vapor retarder within exterior wall assembly
Spray Foam Attic Insulation	Existing blown-in and batts removed; 2-in. spray foam cap added to attic floor; reapplication of 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 and cooling loads	Schedule delays for permitting; site disturbance for loop;

Energy Efficiency Retrofit Measure	Description	Primary Reason for Rejection
High Efficiency Furnace	95+ AFUE furnace with electronically commutated motor (base scope used 92.5-AFUE two-stage furnace)	Hybrid heat pump system more cost effective in terms of SIR
Upgraded Windows	U-0.29, SHGC-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 AC (base scope: 15-SEER, 1.5 ton)	Limited energy savings and SIR relative to base scope
Auxiliary Dehumidification	Auxiliary dehumidification considered as an IAQ measure, given anecdotal reports of high indoor RH level and anticipated lower post-retrofit infiltration	ERV whole-dwelling ventilation selected instead for balanced ventilation and some amount of 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

Notes: AFUE, annual fuel utilization efficiency; SHGC, solar heat gain coefficient; SEER, seasonal energy efficiency ratio; AC, air conditioner; IAQ, indoor air quality; ERV, energy recovery ventilator; RH, relative humidity

2 Research Questions

The key research questions for this DER project included:

- Do two different specified >30% retrofit packages meet their respective energy savings targets based on post-retrofit analysis? If not, why?
- What are the roles of different building system improvements in meeting energy savings targets?
- How effective are different air sealing measures?
- What risk mitigation strategies are necessary to successfully implement these packages?

3 Retrofit Specifications

3.1 Selection and Cost Effectiveness of Final Deep Energy Retrofit Measures

To best understand the short-term test data that follows, it is necessary to first review the final selection of DER scope efficiency measures. Newport's chief initial role in the Bay Ridge project, while serving under contract to MEA and before the project became 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 asked to develop cost-effective additional 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 a hybrid heat pump in the DER instead of the gas furnace and AC 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 be cost-effectively implemented beyond the base scope measures to reach 50% savings? Note that the 50% savings metric compares the DER scope to the *pre-retrofit* building condition.

Given this background, Table 2 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%). Both of these levels exceed the project's goal and meet or exceed Building America goals. Above this row, the Home Energy Rating System (HERS) index values for all three building conditions are 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 values (78 versus 75) but a much larger 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 energy usage; the HERS index is not affected as significantly.

Note that SIR values in Table 2 are only provided for DER measures that went beyond the base scope. Some of these measures show SIR >1; others do not. To reach 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 Seiders and colleagues (2007) or estimated from industry data and 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.
- 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.

- The pre-retrofit energy model was based on building audit data and diagnostic tests, and was compared with limited historical utility data and found to be within 15%. This was deemed acceptable given uncertain resident densities and behavior trends, along with a well-documented model of the pre-retrofit building condition.
- Life cycle energy savings were reduced by 15% to estimate degradation of performance over time (MEA policy).
- No utility escalation was assumed.

These factors were used in the following calculation of SIR:

SIR = (Useful Life * Annual Energy Cost Savings * 0.85) / Implementation Cost

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: including all mechanical electrical plumbing penetrations; top plates of interior walls; 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 run-time controls or damper); not ASHRAE 62.2[a] 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; third-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, 92.5-AFUE 2-stage furnace backup (36/60 kBtu), 40°F transition temp; cooling: 15	1.3
Space Cooling	10 SEER AC Unit	15 SEER, 1.5 ton		

Building System/ Component	Pre-Retrofit Condition	Base Scope	DER Scope	DER Scope Measure SIR (with respect to Base Scope)
			SEER, 1.5 ton	
Domestic Water Heating	Central gas-fired storage, 100-gal, 0.54 energy factor (serving 12 dwellings)	100-gal, 95% thermal efficiency	Solar Hot Water with three flat-panel collectors, closed-loop glycol; solar storage tank upstream of 100 gal, 95% thermal efficiency water heater	0.5
Lighting	100% Incandescents	100% CFLs for all permanent luminaires	In addition to 100% CFL for permanent luminaires, supply resident with CFLs 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]). Estimated 10% savings rate based on literature and plans to train the residents on operating the retrofitted dwelling efficiently. Training to be given by the property manager	1.8
HERS Index **Predicted Energy Use Reduction (relative to Pre-Retrofit)**	127	78 35%	75 52%	N/A

Notes: SPF, spray polyurethane foam; HSPF, heating seasonal performance factor; CFL, compact fluorescent lamp
[a] ASHRAE (2010)

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. Some building systems where the most salient findings will be gained from the long-term energy monitoring will be discussed in future reporting.

3.2.1 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 ACH_{50} (guarded) based on a sample of three representative buildings, the cost effectiveness of air sealing in the base scope was found to be attractive (SIR ~5). Figure 6 shows some typical air sealing locations.

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

The DER scope built on 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 plumbing penetrations and the drywall/top plate joint of interior partitions. Although 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.

In terms of implementation, the general contractor's scope included detailed prescriptive requirements for air sealing that established what locations to seal, what sealing materials to apply, and how much sealant to apply. Additionally, the general contractor led integrated coordination meetings among the trades, and conducted multiple on-site walk-throughs with the insulation contractor. Newport and Patuxent Environmental Group (the auditor for the base scope) also conducted frequent on-site inspections.

Despite these efforts, the implementation of air sealing measures was inconsistent. This was partly the result of frequent turnover in the insulation contractor crew. The prescriptive nature of the air sealing requirements also had a role in this inconsistency, because 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 recommended that the property owners consider a performance-based air sealing approach for future projects. Such an approach would incorporate the following:

- 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 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 Table 3.

Table 3. Building Leakage: Blower Door Test Results

	Max ACH_{50}[a]	Min ACH_{50}[a]	Average ACH_{50}[a]	Average ACH_{50} Reduction (compared to pre-retrofit condition)	Average ACH_{50} of Third-Floor Dwellings (n = 4)[a]	Ratio of Outdoor to "Total" Leakage[b]
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%

[a] 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.
[b] 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 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, 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, which is between conditioned space and outdoors and between conditioned space and 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).

The surface area proportion, however, does not align with the measured distribution of air leakage in either case. This suggests that air leakage sites were 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

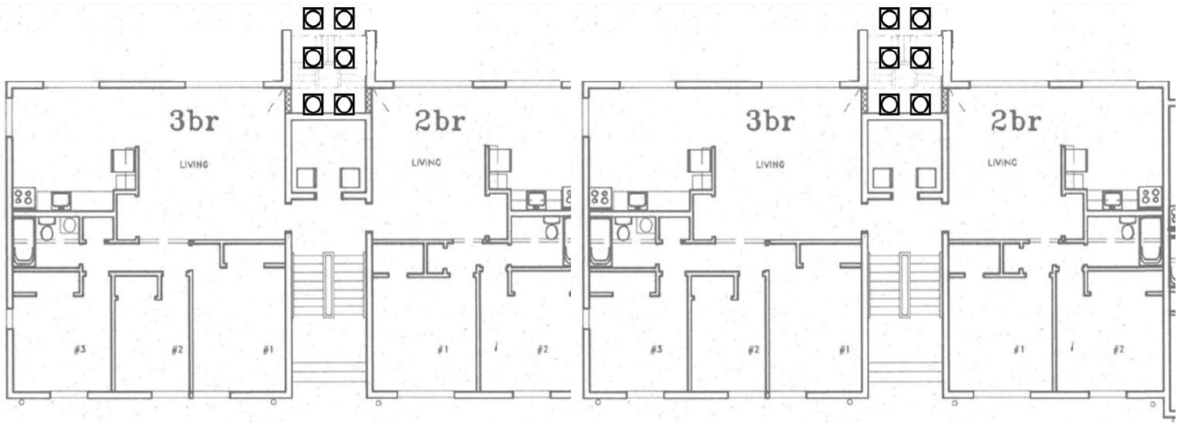

Figure 7. Floor plans for three-bedroom and two-bedroom apartments (same on all three floors)

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 those that were "connected" through the shared mechanical room on each floor were simultaneously depressurized to –50 Pa and maintained at this level while a cfm_{50} reading was recorded for each. Arranging access for this level of testing, in addition to assembling enough technicians and equipment, was a significant effort. As a result, pre- and post-retrofit testing was conducted only on a sample of apartments and stairwells, as noted in Table 3.

In examining the disconnect 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 the possibility 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 that 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), the team found that 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. As a result, 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).

Newport's researchers separated 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. The rough magnitude of the difference, however, is reasonable given the costs and logistical challenges of guarded testing in this type of multifamily building where depressurizing nine apartments would have been the ideal setup. In addition, other factors such as more extensive leakage paths to outdoors might also have contributed to this difference.

3.2.2 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 a vacuum to collect and expel dust before aerosolized sealing. Duct cleaning before aerosolized duct sealing is recommended if the ducts are extremely dirty. Because of this recommendation and the general conditions of the ducts and the old plywood plenums (see Figure 8), duct cleaning was part of the retrofit base scope for all apartments.

Figure 8. Pre-retrofit HVAC return plenum

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 9).

Figure 9. Supply trunk for third-floor apartment exposed to attic (pre-retrofit condition)

Table 4 gives the results of pre- and post-retrofit duct blaster testing. 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 8)—were also replaced with sheet metal plenums.

Table 4. Duct Leakage Test Results

	Total Duct Leakage (cfm_{25})
Pre-Retrofit Condition	481
Post-Retrofit Base and DER Scope Dwellings	180
% Reduction	63%

Insulating and air sealing the open-top bulkhead shown in Figures 9 and 10 involved a two-step process specified by Patuxent Environmental Group (the base scope auditor). It involved (1) removing insulation from the bulkhead area and putting 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 in Figure 11. This process proved to be effective when properly implemented. In some cases, however, 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.

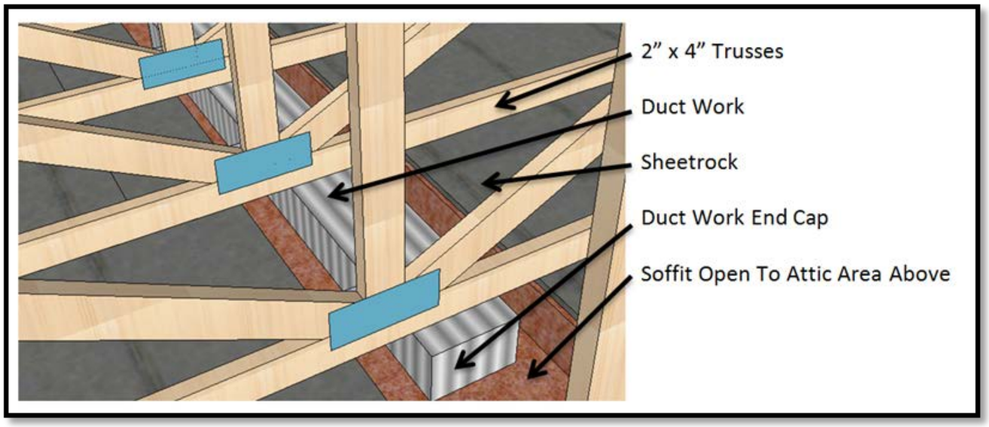

Figure 8. Diagram of duct bulkhead open to the attic space

Figure 9. 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 third-floor apartments noted in Table 3.

3.2.3 HVAC and Ventilation Equipment Efficiency Upgrade

The pre-retrofit HVAC systems were ~15-year-old furnaces and split system AC units. Labeled efficiency levels were 80 AFUE and 10 SEER, respectively. The base retrofit scope upgraded these systems to a 2-stage, 92.5-AFUE condensing furnace and a 15-SEER split AC system. Given the mixed-climate zone location (~4,700 heating degree days; 17°F heating design temp) and the utility rates, Newport investigated hybrid heating options involving both electric 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 that changing from the base scope's 92.5 AFUE, 2-stage gas furnace with 15 SEER AC to a hybrid heat pump (15 SEER, 8.50 HSPF with 92.5 AFUE furnace backup) was a cost-effective, energy-saving measure with an SIR of 1.3. Given that the base scope already utilized a 15 SEER split AC 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 their electric bills. Electricity 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 (see Table 5).

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

Scope	HVAC	Total Annual Heating Energy (MMBtu)	Total Annual Heating Energy Cost ($)	Total Electric Cost ($, resident)	Total Natural Gas Cost ($, property owner)
Base	92.5 AFUE, 36/60 kBtu furnace; 15 SEER, 1.5 ton AC	30.4	512	20	492
DER	15 SEER, 8.5 HSPF 1.5 ton heat pump w/ 92.5 AFUE, 36/60 kBtu furnace	22.1	401	122	279
DER Savings for Resident or Property Owner		8.3	111	(102)	213

Although 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 this added electric cost 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 scope in retrofits, increased utility payments (and the potential impact on allowable rents in affordable housing developments) are a key consideration.

Along with the shift to combined heat pump/furnace space heating, the researchers integrated whole-dwelling ventilation based on ASHRAE 62.2 rates (ASHRAE 2010). 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 run-time controls on the central air-handling unit, was deemed insufficient by the research team in terms of energy performance and IAQ.
- Because of frequently cited IAQ concerns caused by apartment-to-apartment air leakage (such as environmental tobacco smoke [ETS]), balanced ventilation was preferred over supply- or exhaust-based.
- Reports and observations of poor IAQ conditions (strong ETS 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 members, Newport's researchers determined that controlling indoor RH in the summertime (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 (ASHRAE 2010).

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

- The hybrid heat pump systems did not cycle into furnace operation at the agreed-on transition temperature.
- Because of miscommunications from the general contractor 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. Because the winter was mild, there were few 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 furnaces assumes 100% of the heating load.
- After two or three <40°F nights without furnace operation, Newport alerted the general contractor and HVAC contractor that the furnace was not operating when it should. The underlying problem was that the thermostats were not wired correctly to the furnace. The

research team also learned that the outdoor temperature sensor relies on a wireless, battery-powered sensor to communicate with the unit. Although 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 backup heat.

DER apartment residents were given limited education on the hybrid heat pump system. The property manager did offer residents a basic overview of the features of the DER apartments. The session, however, 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). Although the residents now have an aligned incentive for heating energy conservation (e.g., modest set points and keeping windows closed), there appears to be some reluctance to highlight that residents now pay for part of their own heating.

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

4 Conclusions

The DER project at Bay Ridge has yielded numerous findings related to the selection of the DER scope; the ability to achieve >50% energy savings; and the implementation, commissioning, and short-term testing of efficiency upgrade measures. And because the building type at Bay Ridge is quite common, many of these findings will also apply to other multifamily retrofit projects. Key conclusions are noted in the following sections.

4.1 Developing a DER Scope

When evaluating potential energy upgrades to include in a retrofit of this type, several types of trade-offs 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 >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, with the exceptions of attic insulation, whole-dwelling ventilation, and the solar hot water system. Note that these values were developed conservatively; energy savings estimates were conservative and made relative to the base rehab scope. In addition, a 15% performance degradation factor was applied to all measures.

Beyond the question of energy savings versus implementation cost, several other critical trade-offs must be considered in developing a retrofit work scope. These factors can greatly affect the cost, complexity, and effectiveness of energy upgrades, and include the following:

- **Regulatory tradeoffs.** Within this project, the presence of aluminum wiring in the building was addressed through an industry-recognized copper-aluminum crimping system. If a large amount of aluminum wiring were to be exposed, however (e.g., as part of an air sealing effort), 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 multifamily units), combustion safety, and even environmental impacts (e.g., related to ground source heat pump loop installation).

- **Constructability tradeoffs.** In this project, the residents returned to the apartments at night, which required the dwelling to be safe and habitable at the end of each work day. This ruled out the possibility of some energy upgrade measures because of constructability—the contractors simply could not complete the work scope within these parameters. Residency issues, as well as scheduling constraints, might rule out some measures.

- **Building science risk factors.** This is a broad category of pitfalls to keep in mind when evaluating different energy upgrade measures, covering thermal and moisture considerations along with other factors such as radon and combustion safety. In this project, the presence of poly sheeting within the exterior wall assembly posed a significant condensation risk if interior insulation had been added.

Despite these challenges in specifying workable efficiency upgrade measures, the Bay Ridge DER is estimated to achieve a 52% reduction in energy use compared to the pre-retrofit building. The measures used to achieve this reduction are listed in Table 2. Figure 12 shows the distribution of these savings across energy end uses.

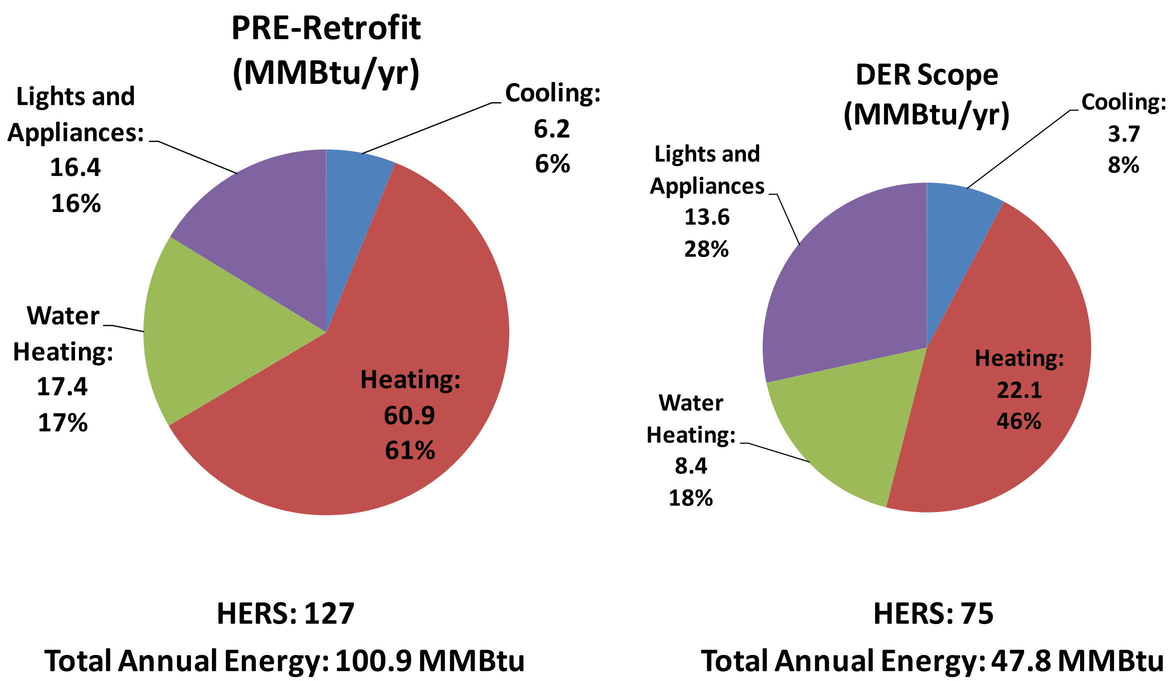

Figure 10. Energy end use reductions in the DER design

4.2 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, significant infiltration reductions (63%) were realized by applying an “inside-out” air sealing strategy that reestablished 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. These locations included 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 reinsulating the attic space (R-49). This work can be scheduled separately from the work inside the apartments. Ideally, it 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. Aerosolized duct sealing, though, should not necessarily be the *only* measure applied to improve thermal distribution system performance. In this project, the ducts for the top-floor apartments were indeed 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 location where the ducts are located, which 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 multifamily retrofits where the envelope cannot be substantially changed. A dual fuel heat pump system optimized energy performance at Bay Ridge, and was cost effective because the marginal cost above a furnace and AC system was reasonable (~$975/system) compared to energy savings. The use of a dual fuel system presents several opportunities and challenges. First, if natural gas is master-metered for the building but residents pay their own electric bills, switching to dual fuel heat pumps shifts a significant amount of 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. Commissioning of dual fuel 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 a multifamily 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 and energy efficiency; however, quantifying the resulting IAQ benefits to justify the cost difference can be challenging. This does not, though, diminish the importance of whole-dwelling ventilation, especially in a DER project.

4.3 Next Steps at Bay Ridge

The research team specified, installed, and commissioned a long-term energy monitoring system in two DER apartments and two base scope apartments. This system will measure whole-dwelling energy usage; dual fuel heat pump run time, energy use, and efficiency; indoor and outdoor temperature and RH; hot water consumption; and window state (open or closed). These data will allow further analysis of the actual energy performance of the two DER apartments and the two base scope apartments. Electric utility bills for each of these four apartments are also being collected and will be used to complement the data acquisition system data. Pre-retrofit utility bill histories for the apartments are not available because the pre-retrofit residents have moved and the accounts are in their names. All monitoring will continue into January 2013. Final analysis and reporting to update this report will take place in April 2013.

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