

Case Study of the Maplewood Park Multifamily Retrofit for Energy Efficiency

December 2012

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Energy and Transportation Science Division

**CASE STUDY OF THE MAPLEWOOD PARK MULTIFAMILY
RETROFIT FOR ENERGY EFFICIENCY**

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CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	vii
ABBREVIATIONS, ACRONYMS, AND INITIALISMS	ix
EXECUTIVE SUMMARY	xi
1. INTRODUCTION	1
1.1 OVERVIEW	1
1.2 FUNDING PROCESS	2
1.3 CONSTRUCTION SCHEDULE	3
1.4 DEFINING THE BUILDING ENVELOPE	3
1.5 PRE- AND POST-RETROFIT BUILDING CHARACTERISTICS	5
1.5.1 Walls	5
1.5.2 Windows and Exterior Doors	6
1.5.3 Roof and Ceiling	6
1.5.4 Foundation	6
1.5.5 Heating, Ventilation, and Air Conditioning System	7
1.5.6 Domestic Water Heater	8
1.5.7 Plumbing	9
1.5.8 Lighting	9
1.5.9 Appliances	10
1.5.10 Other	10
1.6 COST OF RETROFIT MEASURES	11
2. DUCT AND ENVELOPE LEAKAGE TESTING	12
2.1 STANDARD PROGRAMMATIC TESTS IN SAMPLE UNITS	12
2.1.1 Duct Leakage Test	12
2.1.2 Single Point Envelope Leakage Test	12
2.1.3 Test Results	13
2.2 DETAILED INFILTRATION TESTS IN BUILDING #7	13
2.2.1 Guarded Multipoint Infiltration Test	14
2.2.2 Unguarded and Guarded Single Point Infiltration Test	16
3. ENERGY ANALYSIS	17
3.1 WHOLE-BUILDING ENERGY ANALYSIS OF A REPRESENTATIVE BUILDING	17
3.1.1 Weather Normalization of Billed Energy Use	17
3.1.2 Calibration of Building Energy Model	20
3.1.3 Analysis of Energy Efficiency Measures	22
3.2 ENERGY ANALYSIS OF SAMPLE UNITS	23
4. SUMMARY AND CONCLUSION	25
4.1 OPPORTUNITIES	25
4.2 CHALLENGES	26
4.3 MISSED OPPORTUNITIES	27
REFERENCES	29
APPENDIX A. MAPLEWOOD ARCHITECTURAL PLANS	A-1
APPENDIX B. MAPLEWOOD PHOTOGRAPHS	B-1
APPENDIX C. MAPLEWOOD QAP SUSTAINABILITY CHECKLIST	C-1
APPENDIX D. DIAGNOSTIC TEST DATA FOR SAMPLE UNITS	D-1
APPENDIX E. CALIBRATION RESULTS	E-1
APPENDIX F. CONSIDERATIONS FOR WHOLE-BUILDING ENERGY ANALYSIS	F-1

APPENDIX G. ASHRAE STANDARD 62.2 COMPLIANCE CHECK..... G-1
APPENDIX H: ENERGY EFFICIENCY MEASURES DESCRIPTION AND COST DATA..... H.1
APPENDIX I. REM/RATE™ RESULTS FOR ENERGY ANALYSIS OF SAMPLE UNITSI-1

LIST OF FIGURES

Figure	Page
Fig. 1. Aerial view of Maplewood Park Apartments.....	1
Fig. 2. View of Building #7 in Maplewood Park Apartments.	2
Fig. 3. LIHTC funding process.	2
Fig. 4. 3D rendering of buildings	4
Fig. 5. New fiber cement siding.	5
Fig. 6. New double-pane, low-e, vinyl-frame windows.	6
Fig. 7. Existing R-30 insulation in the attic.	6
Fig. 8. Attic insulation upgraded to R-38.	6
Fig. 9. Existing insulation and vapor barrier in the crawlspace.	7
Fig. 10. New insulation and vapor barrier in the crawlspace.....	7
Fig. 11. Existing indoor unit the air handler.	8
Fig. 12. New outdoor units of the heat pump.....	8
Fig. 13. Existing domestic water heater.....	8
Fig. 14. New domestic water heater.	8
Fig. 15. Existing plumbing fixtures.....	9
Fig. 16. New plumbing fixtures	9
Fig. 17. Existing incandescent lamp in a recessed lighting fixture.	9
Fig. 18. New CFLs in a bathroom vanity fixture.	9
Fig. 19. Existing kitchen appliances.....	10
Fig. 20. New kitchen appliances	10
Fig. 21. Pre-retrofit service penetrations through walls and ceiling.....	10
Fig. 22. Duct leakage testing setup showing revised methodology.....	12
Fig. 23. Blower door setup.....	12
Fig. 24. Statistics of pre and post-retrofit envelope and duct leakage based on the sample units.....	13
Fig. 25. Multifan set-up using TECLOG2 software.	14
Fig. 26. Regression model for pre- and post-retrofit multipoint blower door test.....	15
Fig. 27. Cluster column plot of billed energy use.	18
Fig. 28. Determination of billing period start and end dates.....	19
Fig. 29. Regression model for billed energy use.	19
Fig. 30. Calibrated simulation model compared with billed energy use data.	20
Fig. 31. Annual energy use for all EEMs.....	23
Fig. 32. Pre and post-retrofit site energy consumption for the sample units.....	24

LIST OF TABLES

Table	Page
Table ES- 1. Summary of energy and economic analysis for EEMs.....	xii
Table 1. Economics of the project.....	3
Table 2. Construction schedule.....	3
Table 3. Details of Maplewood units.....	5
Table 4. Manual J load calculations.....	7
Table 5. Installed cost of retrofit measures.....	11
Table 6. Pre- and post-retrofit multipoint blower door test results.....	16
Table 7. Pre-retrofit single point unguarded and guarded blower door test results.....	16
Table 8. Billed energy use for Building #7.....	17
Table 9. Baseline characteristics.....	20
Table 10. Results of energy and economic analysis of EEMs.....	22

ABBREVIATIONS, ACRONYMS, AND INITIALISMS

3-D	three-dimensional
ACE Protocol	Army Corps of Engineers Air Leakage Test Protocol for Building Envelopes
ACH	air change per hour
ACH ₅₀	Number of complete air changes that will occur in 1 hour with 50 Pascal of pressure applied uniformly across the building envelope
CDD	cooling degree days (amount of energy used to cool a building, using 70° as a baseline)
CFL	compact fluorescent lamp
CFM	cubic feet per minute
CFM ₂₅	Air flow (CFM) at 25 Pascal (duct leakage measurement)
CFM ₅₀	Air flow (CFM) at 50 Pascal (infiltration measurement)
CVRMSE	coefficient of variation root mean squared error
DCA	The Georgia Department of Community Affairs
DHW	domestic hot water
dwelling unit	A single unit providing complete independent living facilities for one or more persons, including permanent provisions for living, sleeping, eating, cooking and sanitation
EEM	energy efficiency measure
EF	energy factor, domestic water heating
ELA	elective leakage area
gpf	gallons per flush
gpm	gallons per minute
HDD	heating degree days (measure of energy used to heat a building, using 65° as a baseline)
HERS	Home Energy Rating System
HSPF	Heating Seasonal Performance Factor (heating efficiency)
HUD	US Department of Housing and Urban Development
HVAC	heating, ventilation, and air-conditioning
IECC	International Energy Conservation Code
IMT	Inverse Modeling Toolkit
LIHTC	Low-Income Housing Tax Credit
MMBtu	million British thermal units

QAP	Qualified Allocation Plan
RESNET	Residential Energy Services Network
SEER	Seasonal Energy Efficiency Ratio (cooling efficiency)
SHGC	Solar Heat Gain Coefficient
TMY	Typical metrological year
VOC	volatile organic compound

EXECUTIVE SUMMARY

Maplewood Park (Maplewood), a 110-unit multifamily apartment complex in Union City, Georgia, completed major renovations under the guidance of a third-party green building certification program in October 2012. Oak Ridge National Laboratory (ORNL) partnered with Southface Energy Institute (Southface) to use this project as a case study of energy retrofits in low-rise, garden-style, multifamily buildings in the southeastern United States. This report provides a comprehensive profile of this project including the project economics, findings of the building audit, and results of the analysis of energy retrofit measures specific to this project. With a main focus of energy retrofits, this report aims to discuss other aspects of multifamily building retrofit that would benefit future projects in terms of improved building audit process, streamlined tasks, and higher energy savings in low-rise, garden-style apartments.

Maplewood received Low Income Housing Tax Credit (LIHTC) financing via the 2010 Georgia Qualified Allocation Plan (QAP). To be eligible for QAP funds in Georgia, all major renovations must incorporate energy-efficiency measures and adopt a third-party green building certification. Because of the unique demands of this financing, including requirements for long-term ownership, property owners were also especially motivated to invest in upgrades that will increase durability and comfort while reducing the energy cost for the tenants.

The renovation of the eleven buildings of Maplewood was completed in six phases, with two buildings audited and renovated in each of the first five phases. The building audit included visual assessment of the building and diagnostic testing of a sample of unit to determine the existing conditions and potential improvements. Pre- and post-retrofit blower door and duct blaster testing were conducted on the sample units to determine the envelope and duct leakage and effectiveness of air sealing. An additional test with multiple blower doors was conducted on a representative building before and after the retrofits to quantify the air leakage to the outdoors and to the adjacent units.

The Maplewood project team exercised a whole-building approach to meet or exceed 2009 International Energy Conservation Code (IECC) by upgrading to a tighter and better insulated building envelope and replacing windows, doors, lighting, appliances, and HVAC and DHW systems with Energy Star® qualified products. In addition, other retrofit measures were implemented to improve the appearance and durability of the buildings.

Southface performed pre- and post-retrofit energy analysis of the sample units using REM/Rate™ software and generated Home Energy Rating Score (HERS) index for the units. The analysis showed an average HERS index of 107 before the retrofits and 87 after the retrofits, and an average of 20% reduction in annual energy use from the selected energy-efficiency measures.

ORNL conducted a whole-building energy analysis of a representative building in Maplewood using MulTEA (Multifamily Tool for Energy Audit) to predict post-retrofit energy savings and identify alternative potential energy savings measures. The building energy model was first calibrated using the pre-retrofit utility bills. Using this model, the analysis was conducted for the measures implemented on the building as well as some additional measures.

Table ES-1 summarizes the results of whole-building energy analysis. Among the eight measures (EEM 1 through 8) implemented in the building, window replacement shows as the most cost effective measure, followed by heat pump replacement and water heater replacement. Lighting replacement resulted in 4% energy savings but had 12 year payback period due to the cost of fixture replacement included in the measure cost. On the other hand, increasing attic insulation from R-30 to R-38 and kitchen appliance

replacement showed as the least cost effective measures with very small energy savings and 60-70 year payback period.

Six additional measures were considered for the analysis (EEM 9 through 14), which included insulating crawlspace walls, installing exterior insulation on exterior walls (since the wall siding replacement was considered for appearance and durability), installing window film, installing storm windows, and installing programmable thermostat. Among these, installing storm windows was the most cost effective measure with 3.6% energy savings and 5.4 year payback period, whereas installing window film resulted in very small savings. Other measures showed about 2% savings with 6-13 year payback period.

The analysis projected a 25% energy savings from the measures installed in the building with a payback period of 10 years. The analysis also indicated that, with a careful selection of measures, up to 38% energy savings could be achieved with a payback period of less than 6 years.

Table ES- 1. Summary of energy and economic analysis for EEMs

	EEM	Energy savings (%)	Cost of measure for Building #7 (\$)	Payback (year)
1	Insulate crawlspace ceiling with R-19 batt insulation	1.7%	\$300	1.1
2	Increase attic insulation from R-30 to R-38	0.1%	\$1,205	61.5
3	Replace windows and doors	9.4%	\$5,850	3.9
4	Replace 12 SEER, 7.5 HSPF heat pump with 14 SEER, 8.3/8.5 HSPF unit	7.2%	\$5,871	5.1
5	Replace incandescent lamps and fixtures with CFLs	4.1%	\$7,851	12.1
6	Replace kitchen appliances	1.0%	\$10,544	68.7
7	Replace 0.9 EF water heater with 0.93 EF unit	2.7%	\$3,012	6.9
8	Air seal building to reduce air infiltration by 25%	2.1%	\$4,758	14.0
9	Air seal crawlspace and insulate crawlspace walls with R-5 rigid insulation	1.8%	\$3,809	13.1
10	Air seal crawlspace and insulate crawlspace walls with R-13 batt insulation	2.1%	\$3,134	9.2
11	Install R-5 rigid insulation on exterior walls	2.1%	\$3,371	10.0
12	Install window film	0.4%	\$1,106	16.5
13	Install storm windows	3.6%	\$3,080	5.4
14	Install programmable thermostat	1.7%	\$1,700	6.2
Implemented EEMs package (1 through 8)		25.1%	\$39,390	9.8
Cost-optimized EEMs package (EEM 1, 3, 4, 5, 7, 8, 11, and 14)		37.9%	\$32,713	5.4

It is hoped that this study will also provide insight for the development of suitable and accessible audit tools and protocols that can be applied to other multifamily building types such as Maplewood.

Multifamily building retrofit presents challenges because, unlike in single-family audits, multiple players are involved— building owner, developer, contractor, architect, consultants, and tenants. Coordinating all involved parties requires extensive planning and execution, resulting in less flexibility.

1. INTRODUCTION

This case study focuses on the renovation of Maplewood Park Apartments (Maplewood), a multifamily apartment complex in Union City, Georgia 6 a suburb, 18 miles southwest from Atlanta, Georgia. Maplewood provides low-income rental housing for families and senior citizens. The renovation included energy upgrades such as air sealing, window and door replacement, replacement of heating, ventilation, and air-conditioning (HVAC) and domestic hot water (DHW) systems, lighting, and appliances, as well as other upgrades such as roofing and wall siding replacement. The energy upgrades selected to bring the buildings up to the current Georgia Code (i.e., 2009 International Energy Conservation Code (IECC)) are estimated to achieve 25% annual energy savings.

The federal Low Income Housing Tax Credit (LIHTC) provided funding for the project, which drove the decision process for the measures implemented into the renovation and mandated participation in a third-party green building certification program. This federal subsidy finances the development of low-income rental housing across the United States. Local housing and community development agencies, in this case the Georgia Department of Community Affairs (DCA), disburse the funds through a competitive process that provides incentives for projects to include features that improve energy efficiency. The specifics of this funding mechanism are covered in a subsequent section.

1.1 OVERVIEW

Built in 1993, Maplewood is an apartment complex with 11 buildings, each consisting of 10 units. Fig. 1 shows an aerial view of Maplewood with the building numbers shown on the buildings. Fig. 2 shows a view of Building #7 in Maplewood before renovation. The buildings underwent minor renovations in 2008, during which HVAC systems, appliances, and/or domestic water heater in some units were replaced due to specific system failures.



Fig. 1. Aerial view of Maplewood Park Apartments.
(Photo courtesy Google® Earth)



Fig. 2. View of Building #7 in Mapewood Park Apartments.

1.2 FUNDING PROCESS

Low-income subsidies through LIHTC (HUD 2010) funded the renovation of Mapewood. LIHTC encourages building owners and developers to undertake the renovation of existing low-income multifamily housing. Fig. 3 shows the funding process of LIHTC. The US Department of Housing and Urban Development (HUD) oversees the program and distributes tax credit funding to individual states based on demonstrated need. The designated agency for each state (e.g., the Georgia DCA) has a Qualified Allocation Plan (QAP) (e.g., GDCA 2010) that outlines the competitive process by which tax credits are awarded to individual projects. The QAP considerations are updated annually and new candidates are encouraged to apply in every cycle. Once a project has been selected for an award, the developer can hold the tax credit to offset the tax liability. However, typically, the developer sells the tax credits in the open market to an investor or syndicator to raise funds for the project in order to reduce the equity or debt financing required for the project. This allows the developer to provide affordable housing at reduced rental rates.

During the 2010 QAP cycle, 30 projects were accepted including Mapewood. Mapewood had a financial package typical of many affordable housing projects, combining affordable housing subsidies (such as LIHTC) and private equity funding. Table 1 shows the economics of the project including the sources of funds and allocation of those funds. The project received \$10.6 million, which included \$6.65 million (63%) from LIHTC and \$3.37 million (32%) as mortgage¹. Of the available funds, \$3.9 million (37%) was allocated as hard construction costs, and \$0.6 million (5.7%) was allocated as soft costs² to cover expenditure for programs, project management, administration, and marketing.

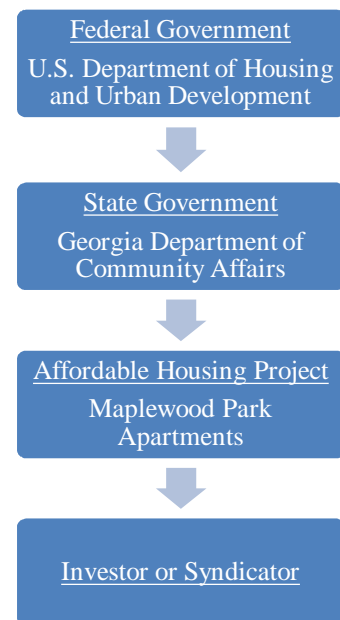


Fig. 3. LIHTC funding process.
Courtesy Kim et al. (2012)

¹ The annual mortgage rate was not public.

² The soft costs included \$8,500 for the third-party green building certification and \$15,000 for participating in a local utility's rebate/incentive program. The latter would provide the building owner \$90,450 in rebates.

Table 1. Economics of the project

Source of funds	Amount (\$)	Percent	Allocation of funds	Amount (\$)	Percent
First mortgage	3,370,000	31.9%	Land acquisition and buildings	3,200,000	30.3%
Low income tax credits	6,654,984	62.9%	Hard construction costs	3,900,445	36.9%
Tax credit assistance program	0	0.0%	Contingency	390,045	3.7%
Owner equity	0	0.0%	Soft costs	597,813	5.7%
Deferred developer fee	550,964	5.2%	Cost of issuance/financing fees	70,800	0.7%
			Capitalized interest	71,486	0.7%
			Startup and reserves	739,192	7.0%
			Relocation	141,670	1.3%
			Equity costs	130,939	1.2%
			Developer fees	1,333,558	12.6%
Total	10,575,948		Total	10,575,948	

1.3 CONSTRUCTION SCHEDULE

The renovation of Maplewood was scheduled to progress in six phases (Table 2). Phase I through V incorporated renovation of two buildings, each. Phase VI incorporated renovation of one building. Building audits were also conducted in phases based on the construction schedule. Pre-renovation assessments for the project began in December 2011. Assessors visited the site and performed a detailed inspection of the buildings and a sample set of units. The tenants were relocated before each phase began and allowed to return after the renovation was completed. The construction completed in October 2012.

Table 2. Construction schedule

Phase	Buildings	Completion month and year
I	5, 9	December 2011
II	4, 10	February 2012
III	6, 11	April 2012
IV	3, 7	May 2012
V	2, 8	October 2012
VI	1	October 2012

As part of the property assessment, the existing conditions of the buildings and sample units were documented in each phase to establish a baseline for the property's energy profile and other performance aspects, such as water use and durability. The potential improvements to the whole-building performance were examined by focusing on upgrades to the building envelope, HVAC system, DHW system, lighting, and appliances. In addition to energy savings, the project team considered cost and constructability before arriving at the final design specifications for the renovation. Inspections were also conducted after retrofits in each building to document the final upgraded conditions.

1.4 DEFINING THE BUILDING ENVELOPE

Due to the sloping site, the three-story buildings of Maplewood have foundation on two levels of a slab-on-grade floor towards the lower grade and vented crawlspace towards the higher grade. The units on the lowest floor (terrace level) have one wall abutting the crawlspace. The units on the upper floors have one party wall. Fig. 4 shows a three-dimensional (3D) rendering of the buildings. Three unit types were found across the 11 buildings of Maplewood: A, B, and C. Fig. 4 indicates the unit types found in the buildings. Table 3 provides an overview of characteristics of each unit type and their distribution across Maplewood. Appendix A includes the architectural plan of the three unit types. Each unit has an exterior entrance door opening to a breezeway located in the center of the building along the east-west axis. This arrangement

divides each building into two detached wings: wing one to the south and wing two to the north. A firewall runs up to the roofline, separating the vented attic above each wing. In collecting a unit's dimensions, RESNET protocols on measuring takeoffs of building components (RESNET 2012) were followed.

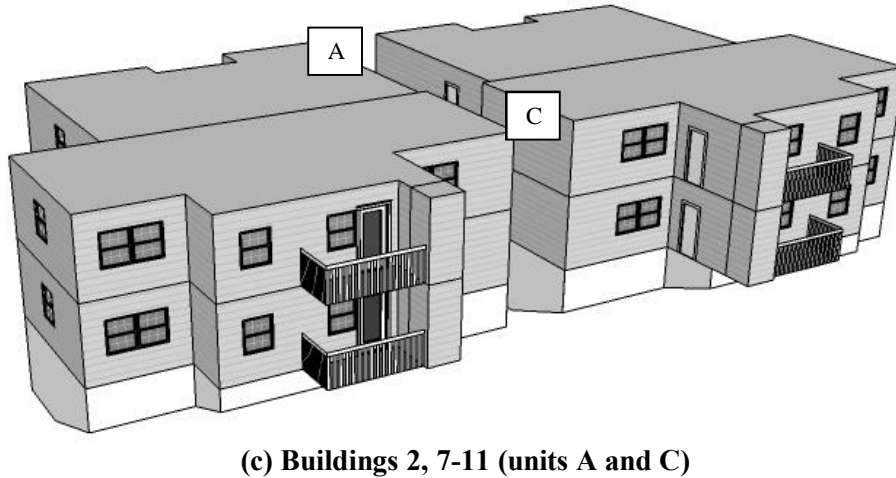
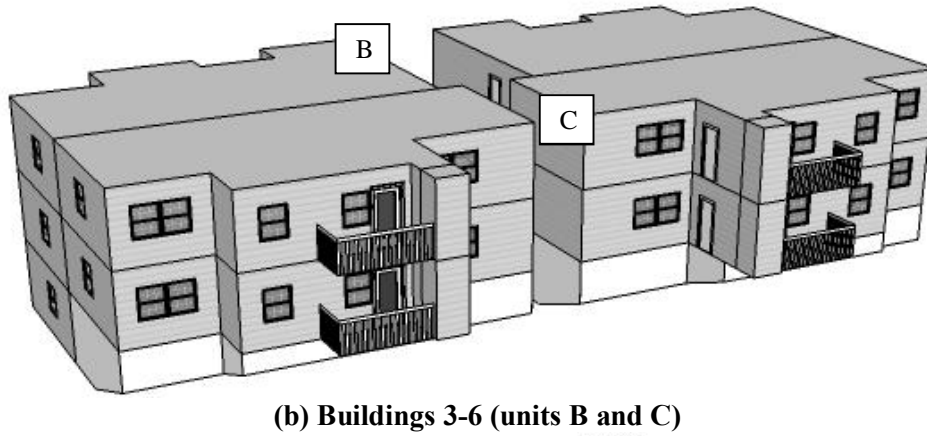
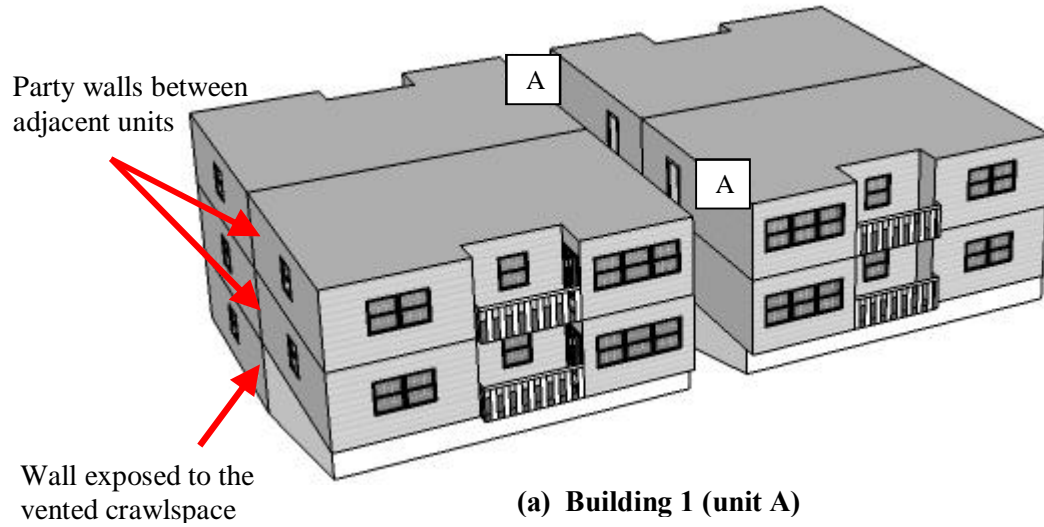


Fig. 4. 3D rendering of buildings

Table 3. Details of Maplewood units

Unit type	Description	Conditioned floor area (ft ²)	Number of units (by unit type) per building			Total number of units
			Building 1	Building 3-6	Building 2, 7-11	
A	Two bedrooms, two bath	1,049	10	-	6	46
B	Three bedroom, two bath	1,176	-	6	-	24
C	Three bedroom, two bath	1,260	-	4	4	40
Total		126,878				110

1.5 PRE- AND POST-RETROFIT BUILDING CHARACTERISTICS

Projects submitted under QAP cycle must earn a minimum of 10 out of 40 points in at least 4 out of 7 categories, which include energy efficient building envelope, lighting, water conservation, indoor air quality, resource efficiency, education, and innovation (see Appendix C for details of the project score card), while meeting or exceeding the following criteria:

- Compliance with applicable Georgia Energy Code (i.e., 2009 IECC)
- Minimum HVAC system efficiency based on the weather location
- Minimum domestic water heater efficiency (i.e., 0.62 EF for gas and 0.93 EF for electric water heater)
- Energy Star® appliances including refrigerators, dishwashers, and clothes washers³

Therefore, as part of the renovation, an energy upgrade package for the project was chosen to meet or exceed the State of Georgia 2010 QAP requirements for energy efficiency. The following sections describe the pre and post-retrofit building characteristics. Table 5 summarizes the specification and cost of energy retrofits. Appendix B includes additional photos taken during the pre- and post-renovation visits.

1.5.1 Walls

The walls of the units were constructed of 2×4 wood frame @16 in. o.c. The insulation in the wall cavities were determined to be R-13 fiberglass batt in the exterior walls and R-11 fiberglass batt in party wall. The existing exterior wall finish included a combination of vinyl siding and brick veneer.

The vinyl siding was replaced with fiber cement siding and brick veneer was replaced with new brick fascia (Fig. 5). No other changes were made to the walls.



Fig. 5. New fiber cement siding.

³ Clothes washers were not considered in this project because the units did not have pre-installed laundry equipment.

1.5.2 Windows and Exterior Doors

The existing windows were single hung, single pane with aluminum frame and shaded by interior vinyl blinds. The glass door leading to the balcony had single pane and were shaded by interior vinyl blinds and porch overhang. The entrance doors of the units had solid wood core panels.

The existing windows were replaced by Energy Star low-e, double pane, vinyl frame windows (Fig. 6) with a rated performance of 0.35 U-factor and 0.27 SHGC. The existing doors were replaced by R-3 insulated core metal doors.



Fig. 6. New double-pane, low-e, vinyl-frame windows.

1.5.3 Roof and Ceiling

The vented attic roof of the buildings was constructed of wood frame and had dark asphalt shingle roofing. The original R-19 ceiling insulation in the attic was upgraded to R-30 during the renovation in year 2008 by adding blown-in fiberglass insulation (Fig. 7).

The attics were upgraded by adding 4 inch of blown-in fiberglass (Fig. 8) to increase the attic insulation value to R-38. The existing roofing was replaced by new dark asphalt shingle roofing. In addition, several service penetrations through the ceiling were air sealed.



Fig. 7. Existing R-30 insulation in the attic.



Fig. 8. Attic insulation upgraded to R-38.

1.5.4 Foundation

All buildings had two foundation types: i) uninsulated slab-on-grade floor, and ii) vented crawlspace with concrete block walls, open-web ceiling truss, and fiberglass batt insulation between the ceiling truss. Over time, the batts have fallen down as a result of gravitational pull and gradual wear. Also, the vapor barrier on the crawlspace floor was not providing complete ground coverage and moisture protection (Fig. 9).

No changes were made to the slab-on-grade floor. In the vented crawlspace, R-19 fiberglass batt insulation was installed between the ceiling frame and new 6-mil poly vapor barrier was installed over the ground (Fig. 10). The vapor barrier was installed with overlapped seams, brought up to a minimum 6 in. from the ground along the perimeter of the crawlspace walls and piers, and secured in place with mastic and tape.



Fig. 9. Existing insulation and vapor barrier in the crawlspace.



Fig. 10. New insulation and vapor barrier in the crawlspace

1.5.5 Heating, Ventilation, and Air Conditioning System

Each unit had a dedicated central heat pump system with a rated performance of 12 SEER and 7.5 HSPF⁴. The two-bedroom units (Unit A) were served by 1.5 ton systems and the three-bedroom units (Unit B and C) were served by 2 ton systems. The air handler was located in a louvered closet in either a bathroom (Unit A), the utility room (Unit B), or a bedroom (Unit C) (Fig. 11). Ducts were located in the conditioned space within the dropped soffit. Outdoor condenser unit was installed on a concrete pad at the sides of the building.

The existing heat pump systems were replaced with Energy Star qualified heat pump systems (Fig. 12). Manual-J load calculations were performed for equipment sizing (Table 4). However, the systems selected for the replacement were of the same size as existing systems, which were about 1.5 times oversized. The two-bedroom unit (Unit A) were installed with 1.5 ton systems with a rated performance of 14.5 SEER and 8.3 HSPF. The three-bedroom units (Units B and C) were installed with 2 ton systems with a rated performance of 14.5 SEER and 8.5 HSPF. The inspection report notes that mastic was applied along the seams and joint connections of the ductwork in the air handler. No air sealing was performed for the ducts that were within the dropped soffits.

Table 4. Manual J load calculations

Unit type	Cooling load (kBtu/h)	Heating load (kBtu/h)
A	11.9	12.8
B	14.9	16.7
C	15.1	16.3

The existing ceiling-mounted exhaust fans in the bathrooms were replaced with new exhaust fans and connected to the existing exhaust ducts vented to the outside. The existing recirculating range hoods were replaced by new recirculating range hoods.

⁴ During the 2008 renovation, some of the outdoor units were upgraded for maintenance need and system failures.



Fig. 11. Existing indoor unit the air handler.



Fig. 12. New outdoor units of the heat pump.

1.5.6 Domestic Water Heater

All units were equipped with a 40-gal, lowboy electric water heater with a rated performance of 0.90 EF. Some of the inspected water heaters had insulation blankets⁵. All inspected water heaters were in poor condition with signs of corrosion (Fig. 13). All existing water heaters were replaced with new 40-gal electric water heaters with a rated performance of 0.93 EF (Fig. 14).



Fig. 13. Existing domestic water heater.



Fig. 14. New domestic water heater.

⁵ The effective average R-value for the insulation blankets was modeled as R-3 in REM/RateTM.

1.5.7 Plumbing

The existing plumbing fixtures in the units included 2 gpm faucets (Fig. 15), 1.6 gpf toilets, and 5.0 gpm showerheads, which were replaced by low-flow plumbing fixtures including 1.5 gpm faucets (Fig. 16), 1.28 gpf toilets, and 1.5 gpm showerheads.



Fig. 15. Existing plumbing fixtures



Fig. 16. New plumbing fixtures

1.5.8 Lighting

The existing lighting included 18-60W incandescent lamps in two bedroom units (Unit A), 21-60W incandescent lamps in three bedroom units (Units B and C) (Fig. 17), and two T12 lamps and a small 15W pin-base tube in the kitchen in all units. The lighting was upgraded to a 100% Energy Star lighting package, which included replacing the existing T12 lamps with new T12 lamps and replacing all incandescent lamps with 13W CFLs (Fig. 18).



Fig. 17. Existing incandescent lamp in a recessed lighting fixture.



Fig. 18. New CFLs in a bathroom vanity fixture.

1.5.9 Appliances

The existing appliances in a unit included a refrigerator, a dishwasher, and an electric range (Fig. 19). The appliances were from various manufacturers with unknown wattage. These appliances were replaced with Energy Star qualified 18 ft³ refrigerator (388 kWh/year rated energy use) and dishwasher (306 kWh/year rated energy use), and an electric range with two 6 in. (1500 W) and two 8 in. (2600 W) high-speed coil elements (Fig. 20).

The unit had connections for clothes washer and dryer for optional installation of these appliances by occupants. However, at the time of the audits, the units were unoccupied with no evidence of the use of laundry equipment during occupancy.



Fig. 19. Existing kitchen appliances



Fig. 20. New kitchen appliances

1.5.10 Other

Gaps were found around service penetrations through the walls and ceiling of the units (Fig. 21). Air sealing was performed to fill these gaps. In all units, the floor tiles and carpet were replaced and interior surfaces were repainted with low-VOC paints.

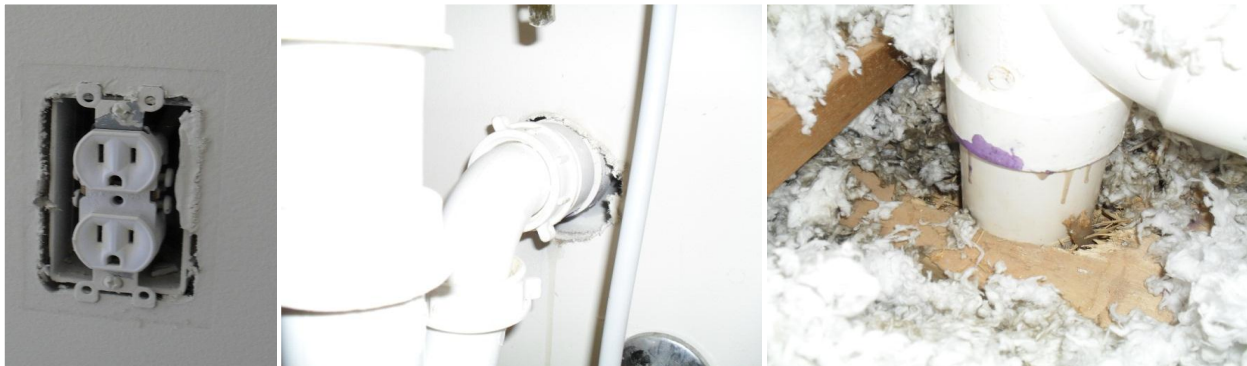


Fig. 21. Pre-retrofit service penetrations through walls and ceiling.

1.6 COST OF RETROFIT MEASURES

Table 5 outlines the cost of major retrofit measures installed in the buildings including the labor and material costs. The total cost for retrofit measures was \$938,086 averaging \$8,519 per unit⁶, of which only 52% contributed to energy upgrades. These energy upgrades were only 4.6% of the total cost of \$10.6 million for the project.

Table 5. Installed cost of retrofit measures

Retrofit measures	Pre-retrofit characteristics	Post-retrofit characteristics	Measure cost		
			Total (\$)	Average cost per unit (\$)	% of total
Energy retrofit measures					
Crawlspace insulation	No effective insulation	R-19 fiberglass batt under crawlspace ceiling	3,300	30	0.4%
Attic insulation	R-30 blown-in fiberglass	Added 4ö of blown-in fiberglass over existing insulation to achieve R-38	13,250	120	1.4%
Window replacement	Single-pane, aluminum frame (1.31 U-value, 0.80 SHGC)	Double-pane, low-e, vinyl frame (0.35 U-value, 0.27 SHGC)	64,349	585	6.9%
HVAC system replacement	Unit A: 18 kBtu/h, 12 SEER, 7.5 HSPF heat pump; Units B and C: 24 kBtu/h, 12 SEER, 7.5 HSPF heat pump	Unit A: 18 kBtu/h, 14.5 SEER, 8.3 HSPF heat pump; Units B and C: 24 kBtu/h, 14.5 SEER, 8.5 HSPF heat pump	64,580	587	6.9%
Domestic water heater replacement	Electric 40-gal, 0.90 EF	Electric 40-gal, 0.93 EF	33,132	301	3.5%
Lighting replacement	Unit A: Two T12 lamps, a 15W pin-base tube, and 18-60W incand. lamps; Units B and C: Two T12 lamps, a 15W pin-base tube, and 21-60W incand. lamps	Unit A: Two T12 lamps and 18-13W CFLs; Units B and C: Two T12 lamps and 21-13W CFLs	86,362	785	9.2%
Appliance replacement	Standard efficiency cooking range/oven, refrigerator and dishwasher	Standard cooking range/oven, Energy Star qualified refrigerator and dishwasher	115,981	1,054	12.4%
Air sealing ⁷	Gaps around service penetrations through walls and ceiling	Air sealing and caulking that reduced air leakage by 25%	53,289	484	5.6%
Subtotal			486,088	4,419	51.9%
Other retrofit measures					
Wall siding replacement	Vinyl siding	Fiber cement siding	305,800	2,780	32.6%
Roofing replacement	Asphalt shingles	Asphalt shingles	145,244	1,320	15.5%
Duct sealing	-	Mastic applied to the seams and joints of ductwork in the air handler	52,800	480	5.6%
Subtotal			451,044	4,100	48.1%
Total			938,086	8,519	100.0%

⁶ Separate costs for the unit types are not available because the subcontractors do not invoice by units.

⁷ Actual cost of air sealing was unavailable. The estimated cost is calculated based on \$0.42 per sq. ft. of floor area (NREL 2012).

2. DUCT AND ENVELOPE LEAKAGE TESTING

Two testing approaches were executed for this project: standard programmatic tests in the sample units to determine the duct leakage and envelope leakage, and detailed envelope leakage tests in Building #7 to determine the air leakage to the outdoors and between adjacent units of the building. The tests were performed under the guidance of the RESNET standards (RESNET 2011). The envelope leakage test was performed by depressurizing each unit to 50 Pa and measuring the airflow in cubic feet per minute (CFM_{50}) passing through the blower door fan. The duct leakage-to-outside test was performed by pressurizing the unit to 25 Pa and then the duct system to 25 Pa, measuring the airflow (CFM_{25}) passing through the fan. Of particular interest for researchers was determining the air leakage between adjacent units that occurs across the partition walls and ceiling/floor.

2.1 STANDARD PROGRAMMATIC TESTS IN SAMPLE UNITS

2.1.1 Duct Leakage Test

Using a Duct Blaster kit, duct leakage test was performed in sample units before and after retrofit. The HVAC system air handler was located in mechanical closets with an open return with a filter attached. There was not adequate space in the closet to place the kit at the return plenum because the lowboy water heater was located under the air handler (Fig. 26a). Therefore, a workaround had to be improvised for the standard RESNET protocols, which state that *the duct leakage testing system be attached to the largest return grille closest to the air handler*. As a work around, the filter was taken out and the return was sealed with duct tape. Figure 26a shows the location where the duct mask was placed (duct mask is not shown). The supply closest to the plenum was pressurized (as shown in Fig. 26b), with the reference hose leading to another return. The duct leakage-to-outside test was performed by pressurizing the building unit to 25 Pa and then pressurizing the duct system to 25 Pa, measuring the air flow at 25 Pa (CFM_{25}) through the fan.

2.1.2 Single Point Envelope Leakage Test

A single point infiltration test measures the air leakage of a unit at a single reference pressure using a blower door fan (Fig. 23). The testing procedures followed RESNET (2011), starting with preparing the building enclosure for testing by closing and latching all exterior doors and windows, opening all interior doors, and shutting down all HVAC and ventilation fans. During the single point test, adjacent units were left in their natural state with no induced pressures or opened windows.

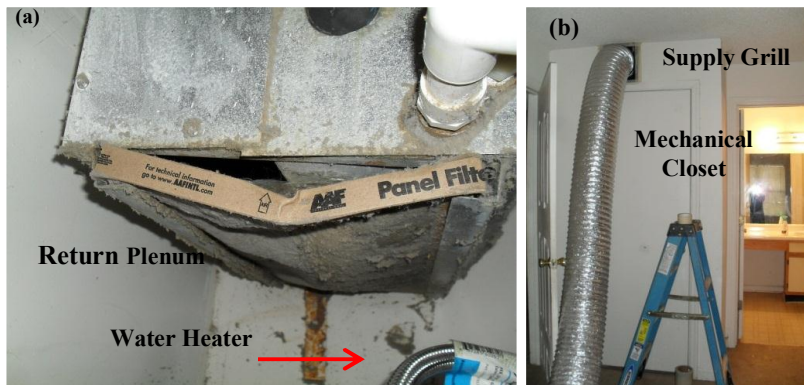


Fig. 22. Duct leakage testing setup showing revised methodology.



Fig. 23. Blower door setup.

2.1.3 Test Results

The statistics of the envelope and duct leakage based on the 21 sample units are shown in Fig. 24. The test results are shown in Appendix F. After renovations were completed, envelope leakage for most of the units was reduced to meet the IECC 2009 maximum acceptable infiltration threshold of 7 ACH₅₀.

Considering that the ducts were in the conditioned space inside the thermal and pressure boundary of the building, the reason for duct leakage to the outside was undetermined and remained a subject for investigation in future multifamily research.

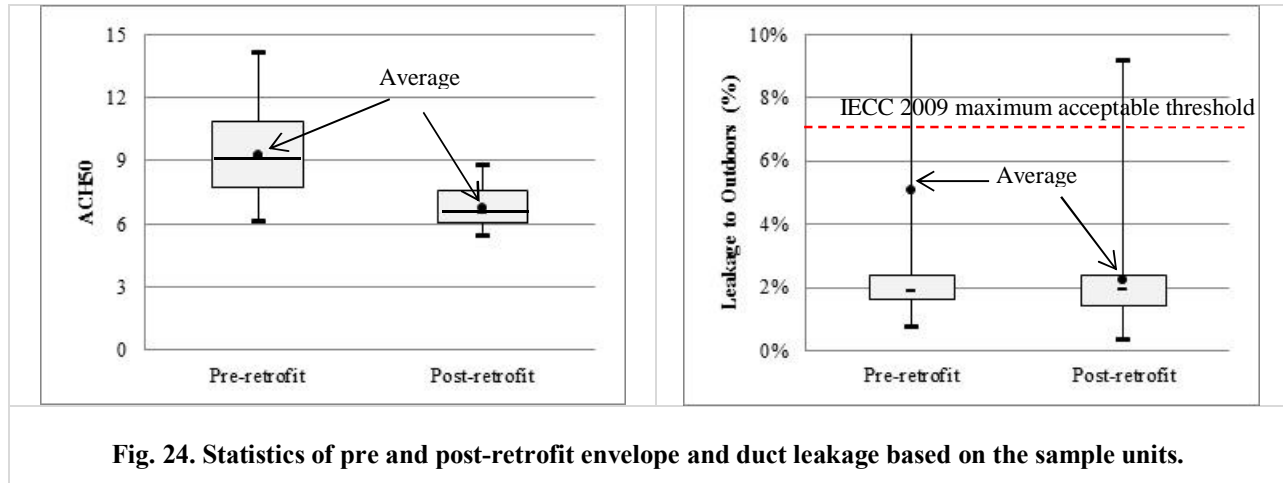


Fig. 24. Statistics of pre and post-retrofit envelope and duct leakage based on the sample units.

2.2 DETAILED INFILTRATION TESTS IN BUILDING #7

This experiment was conducted to provide results from guarded testing, an alternate infiltration testing method. Guarded tests of multifamily units can isolate leakage to the outdoors from leakage to adjacent units. The additional data and insight gathered from guarded testing require add to the cost and complexity given that additional personnel, equipment, and setup time are required. Two guarded test approaches were performed using multiple blower doors and the Energy Conservatory's TECLOG2 data logging software that provides simultaneous control of multiple blower door systems. Testing standards and protocols were followed using RESNET (2011), ACE (2012), and ASTM (1999). These tests were conducted on all ten units in Building #7 before and after retrofit.

A guarded test measures unit air leakage at a reference pressure while inducing the same reference pressure to adjacent units through the use of multiple blower door fans. Equalizing the induced pressure in the tested and adjacent units ensures that the measured air infiltration rate includes only air leakage to the outdoors. Since the central breezeway separates Building #7 into two wings, researchers isolated each wing to perform a separate series of guarded tests. The testing included two approaches. For the first test, a multipoint infiltration test was conducted treating each wing of Building #7 as a single enclosure area, with the five units of the wing tested simultaneously. The leakage rate of the entire building envelope of one of the wings was estimated by pressurizing all the apartments simultaneously. For the second test, a guarded single point test was conducted for each unit, inducing an identical reference pressure on all adjacent units to eliminate the air leakage across shared surfaces.

The testing setup in each unit was similar to unguarded single point testing (i.e., installing a blower door in the entrance door of the unit, closing and latching all other exterior doors and windows, opening all interior doors, and shutting down all HVAC and ventilation fans), with additional considerations to facilitate simultaneous control of the blower doors using TECLOG2. Fig. 25 shows the equipment setup.

Reference pressure tubes of blower doors were connected to a common reference point. In order for TECLOG2 to communicate with the blower doors, the digital manometer (DG-700) of each blower door was connected to a central computer running TECLOG2 using the CAT5 cable, five sets of CAT5 to DB9 adapters, and an eight-port DB-9 RS232 to USB adapter hub (Energy Conservatory 2010).

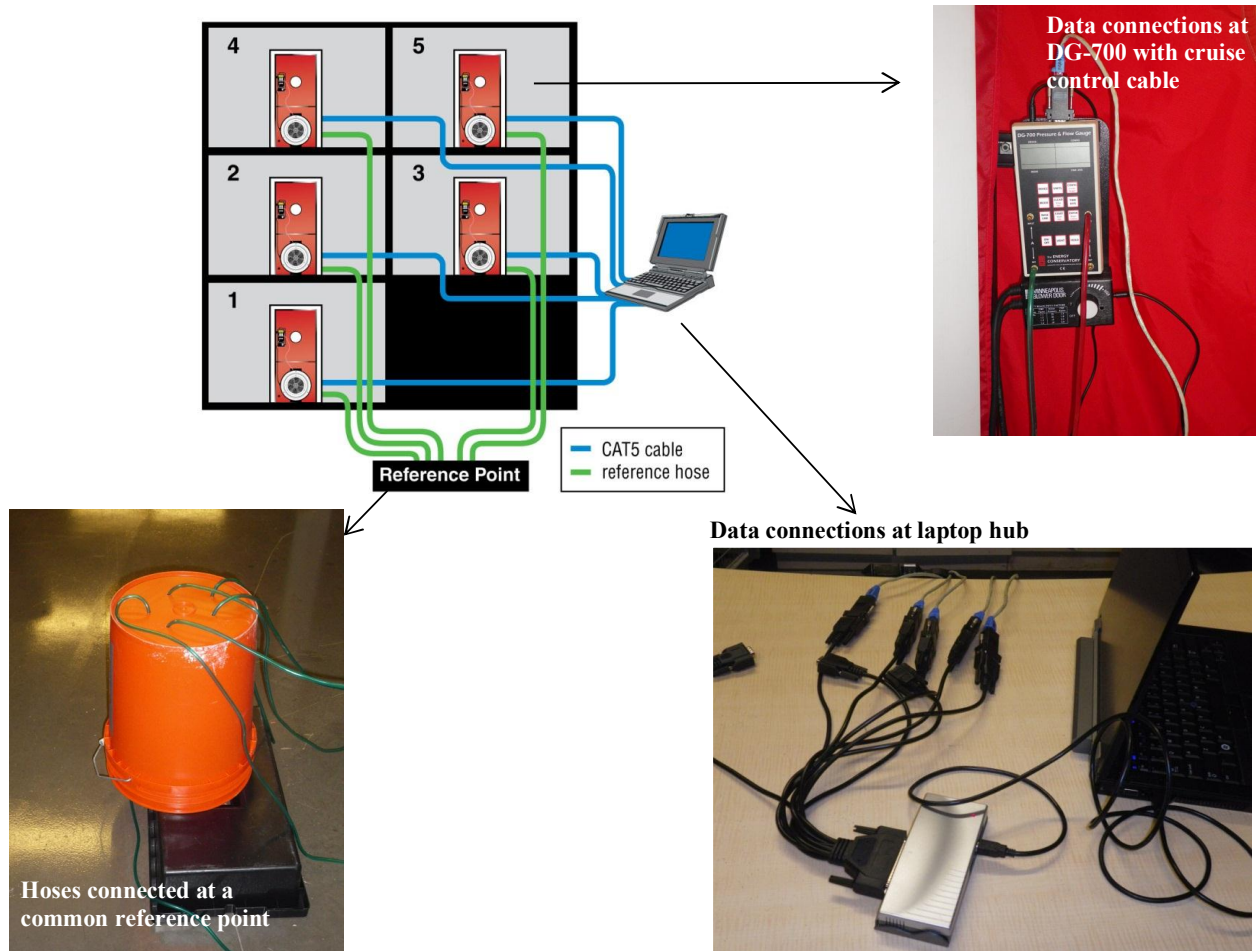


Fig. 25. Multifan set-up using TECLOG2 software.

2.2.1 Guarded Multipoint Infiltration Test

First, a multipoint infiltration test was conducted on each wing of Building #7 following procedures outlined in the ACE Protocol (ACE 2012). The test procedure requires a pre- and post-baseline measurement, averaged over a minimum of 120 seconds, and ten positive and ten negative flow measurements at induced reference pressures. The highest flow measurement must be taken at a reference pressure of at least 75 Pa and no more than 85 Pa, and there must be at least 25 Pa between the lowest and highest reference pressures. These flow measurements must be averaged over a minimum of 20 seconds. An air leakage rate for various reference pressures can then be derived using the resulting measurements.

This test treated each wing of the building as a single enclosure, with five units tested simultaneously. It is to be noted that the ACE Protocol and TECLOG2 software are typically used with a master fan to test large-volume commercial buildings that have good pressure communication throughout the test boundary.

Conducting the test on an enclosure consisting of five separate units required TECLOG2 to control induced pressure in each unit individually, instead of controlling a master fan.

The test procedure required six personnel, one in each unit to adjust blower door fan covers as required and a head researcher running the testing from the central computer. Two-way radios facilitated communication between the head researcher and those in each unit. Following test setup and confirmation that TECLOG 2 had a solid communication link, the head researcher began data logging with TECLOG 2 following guidance from the ACE Protocol. For this study, the researchers conducted only the negative pressure testing portion of the ACE Protocol, depressurizing the dwelling units in each wing and taking flow measurements at 12 reference pressures, starting at -75 Pa and ending with -20 Pa. Each flow measurement was averaged over a minimum of 30 seconds.

The results of multipoint pre and post-retrofit infiltration rates for the two wings of Building #7 are shown in Fig. 26. Table 6 shows that the air sealing the building reduced the air leakage to the outdoors by 21.4% in wing one and 18.1% in wing two. The overall infiltration level meets the 2009 IECC minimum threshold.

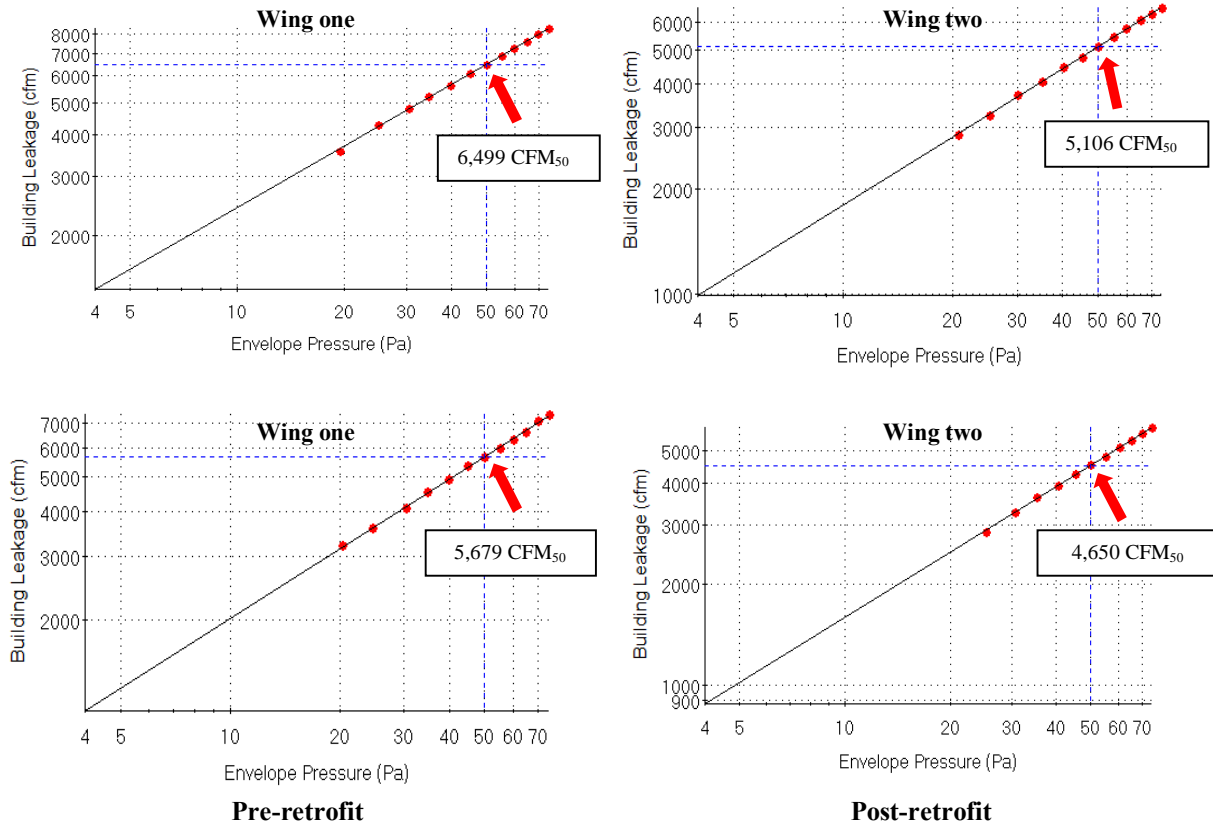


Fig. 26. Regression model for pre- and post-retrofit multipoint blower door test

Table 6. Pre- and post-retrofit multipoint blower door test results

	Pre-retrofit		Post-retrofit		Reduction (%)
	CFM ₅₀	ACH ₅₀	CFM ₅₀	ACH ₅₀	
Wing one	6,499	8.61	5,106	6.76	21.4
Wing two	5,679	7.52	4,650	5.99	18.1

2.2.2 Unguarded and Guarded Single Point Infiltration Test

Next, the researchers conducted guarded single point tests facilitated by the fan controls built into the TECLOG2 software. Focusing again on the five units in each wing of Building #7 separately, a single point infiltration test was conducted in each unit while the reference pressure in the four adjacent units was held at 50 Pa. Equipment setup and personnel for this test were the same as those used for the multipoint guarded test, with the exception that the unit undergoing the single point test was disconnected from communication and control with TECLOG2.

Table 7 summarizes the results of guarded and unguarded single point tests. The difference between unguarded and guarded single point measurements shows that for individual units, air leakage to adjacent units accounted for 5.6% to 19.5% of total air leakage of the unit measured using unguarded test. On an average, air leakage to adjacent units accounted for 13.4% of sum of air leakage measured using unguarded tests in wing one and 11.7% in wing two. It is to be noted that air leakage to adjacent units was highest for the units located on the middle floor of each wing (i.e., units 2, 3, 7 and 8) given that these units share the largest surface area with adjacent apartments.

The sum of guarded single point air leakage measurements for the two wings of the building compared well with the results of the multipoint testing completed using TECLOG2.

Table 7. Pre-retrofit single point unguarded and guarded blower door test results

Unit #	Unguarded CFM50	Guarded CFM50	Difference	
			CFM50	% unguarded
Wing 1				
1	1,628	1,445	183	11.2%
2	1,435	1,101	334	23.3%
3	1,718	1,400	318	18.5%
4	1,104	1,027	77	7.0%
5	1,544	1,458	86	5.6%
Total	7,429	6,431	998	13.4%
Wing 2				
6	1400	1,304	96	6.9%
7	1250	1,015	235	18.8%
8	1275	1,027	248	19.5%
9	1223	1,132	91	7.4%
10	1225	1,149	76	6.2%
Total	6,373	5,627	746	11.7%

3. ENERGY ANALYSIS

Two sets of energy analyses were performed. A whole-building energy analysis was conducted for a representative building in Maplewood to predict energy savings from the implemented set of measures as well as to identify a cost-optimized package of measures. Another set of analyses was performed for a sample of units randomly selected in the building during different construction phases to understand the variation in energy use in units.

3.1 WHOLE-BUILDING ENERGY ANALYSIS OF A REPRESENTATIVE BUILDING

Among the 11 buildings of Maplewood, energy and cost analyses of the EEMs implemented on Building #7 were performed. For the energy analysis, DOE-2.1e simulation input developed for MulTEA (Multifamily Tool for Energy Analysis) (Malhotra and Im 2012) was used. Twelve-month pre-retrofit utility bills (January–December 2011) and weather data for the corresponding billing periods (NCDC 2012) were used with Inverse Modeling Toolkit (IMT) (Kissock et al. 2002) to calibrate the building energy model. Using the observed/measured building data combined with *Building America House Simulation Protocols* (Hendron and Engebrecht 2010), a baseline building energy model was established, which was calibrated for further analysis. Since EEMs were already selected and implemented to Building #7 before energy and cost analyses were performed, the analysis was first performed for the measures implemented on the building to predict the savings, and then, for additional measures to identify a cost-optimized set of measures to develop recommendations for future retrofit projects. The following sections describe the analysis steps.

3.1.1 Weather Normalization of Billed Energy Use

For the energy analysis of existing buildings, calibration of the building energy model is very important. For multifamily buildings, utility bills, if available for individual units, provide a better understanding of how the units are occupied, used, and operated. For Maplewood Building #7, pre-retrofit monthly utility bills were available for individual units for the year 2011 (Table 8), which included all energy end uses of the units (i.e., heating, cooling, domestic water heating, lighting, and appliances). However, because of certain unknowns and anomalies, much effort was required for normalizing the billed energy use to make it useful for model calibration. These unknowns/anomalies and steps to handle them are described below.

Table 8. Billed energy use for Building #7

Unit #	Billed kWh/month in Year 2011											
	Billing period 1	Billing period 2	Billing period 3	Billing period 4	Billing period 5	Billing period 6	Billing period 7	Billing period 8	Billing period 9	Billing period 10	Billing period 11	Billing period 12
701	1,054	1,723	1,379	1,013	1,113	975	1,575	1,045	891	742	788	644
702	931	720	561	525	511	465	340	449	365	271	296	392
703	776	631	561	460	348	338	550	565	439	330	315	395
704	1,619	1,875	1,613	1,187	718	633	707	1,080	872	716	690	1,002
705	2,635	2,232	1,660	1,294	1,561	905	655	763	1,824	901	865	1,136
706	1,945	1,807	1,114	927	743	926	1,146	1,131	1,039	757	768	1,161
707	1,860	1,343	696	526	611	760	956	1,008	988	705	652	823
708	793	647	563	8*	0*	840	1,043	1,215	1,114	0*	0*	0*
709	53*	1,564	1,204	1,054	931	804	4*	600	578	418	235	128
710	1,479	1,465	803	788	604	576	685	784	820	602	649	794
Average	1,455	1,401	1,015	864	793	722	851	864	893	605	584	719
Minimum	776	631	561	460	348	338	340	449	365	271	235	128
Maximum	2,635	2,232	1,660	1,294	1,561	975	1,575	1,215	1,824	901	865	1,161

* Negligibly small energy bills were excluded while determining the averages, minimums, and maximums.

3.1.1.1 Handling unknowns and anomalies in utility bills

1. Anomalies in billed energy use across units

Table 8 shows that the billed energy use was negligibly small for some units during several billing periods. Assuming that these bills represent unoccupied periods, they were excluded from further analysis to determine if the remaining bills well represent the energy use during occupied periods. Fig. 27 shows the billed energy use during presumably occupied periods highlighting its variation across units, which is as much as 45% below average (for billing period 3) to 104% above average (for billing period 9). Furthermore, the ratio of highest to lowest bill for a specific billing period ranged from 2.7 (for billing period 8) to 9.1 (for billing period 12). Expecting the location and orientation of units in the building as possible factors for such variation, the utility bills were reviewed again by units. However, no correlation was found between location or orientation and utility bills. These variations suggest high irregularities in the occupancy, usage and operational characteristics of the units. To minimize the impact of these anomalies, further analysis was performed for the whole building, excluding the presumably unoccupied periods for which utility bills were negligibly small.

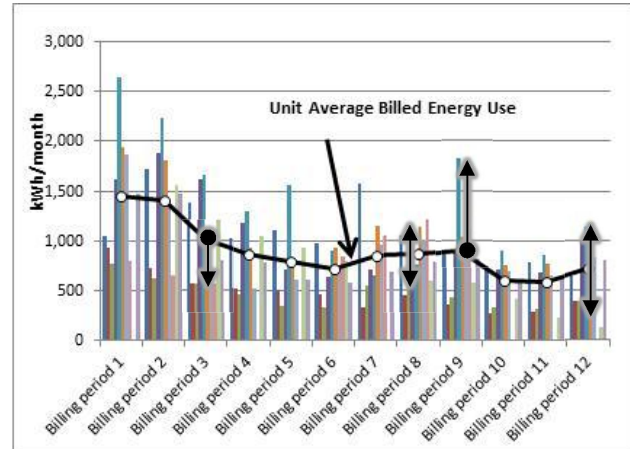


Fig. 27. Cluster column plot of billed energy use.

2. Anomalies in billed energy use across 12 months

Fig. 27 also shows that several units did not follow the typical weather-driven heating and cooling energy use profiles, and the energy use profiles were not consistent across units. Specifically, the billed energy use for billing periods 10, 11, and 12 was very small for most individual units for unexplainable reasons. Therefore, these billing periods were excluded from further analysis.

3. Unknown start and end dates of billing periods

The start and end dates of billing periods are required for weather normalization of billed energy use for energy model calibration. However, for this project, billing cycle dates could not be obtained. To ensure that the billed energy use align with the average temperature for the corresponding period, four scenarios for billing period start and end dates were assumed:

- Scenario 1: Billing cycle starting at the first day and ending at the last day of a month
- Scenario 2: Billing cycle starting at day 8 of a month and ending at day 7 of the next month
- Scenario 3: Billing cycle starting at day 15 of a month and ending at day 14 of the next month
- Scenario 4: Billing cycle starting at day 22 of a month and ending at day 21 of the next month

For each scenario, billed energy use was adjusted for the calendar months and plotted against monthly average temperatures for the year 2011. Fig. 28 shows the temperature-energy use scatter plot for the four scenarios described above. Among these, scenario 4 seems to have the best agreement between the energy use and temperature. Therefore, the billing period cycle for scenario 4 was selected for use in the next analysis steps.

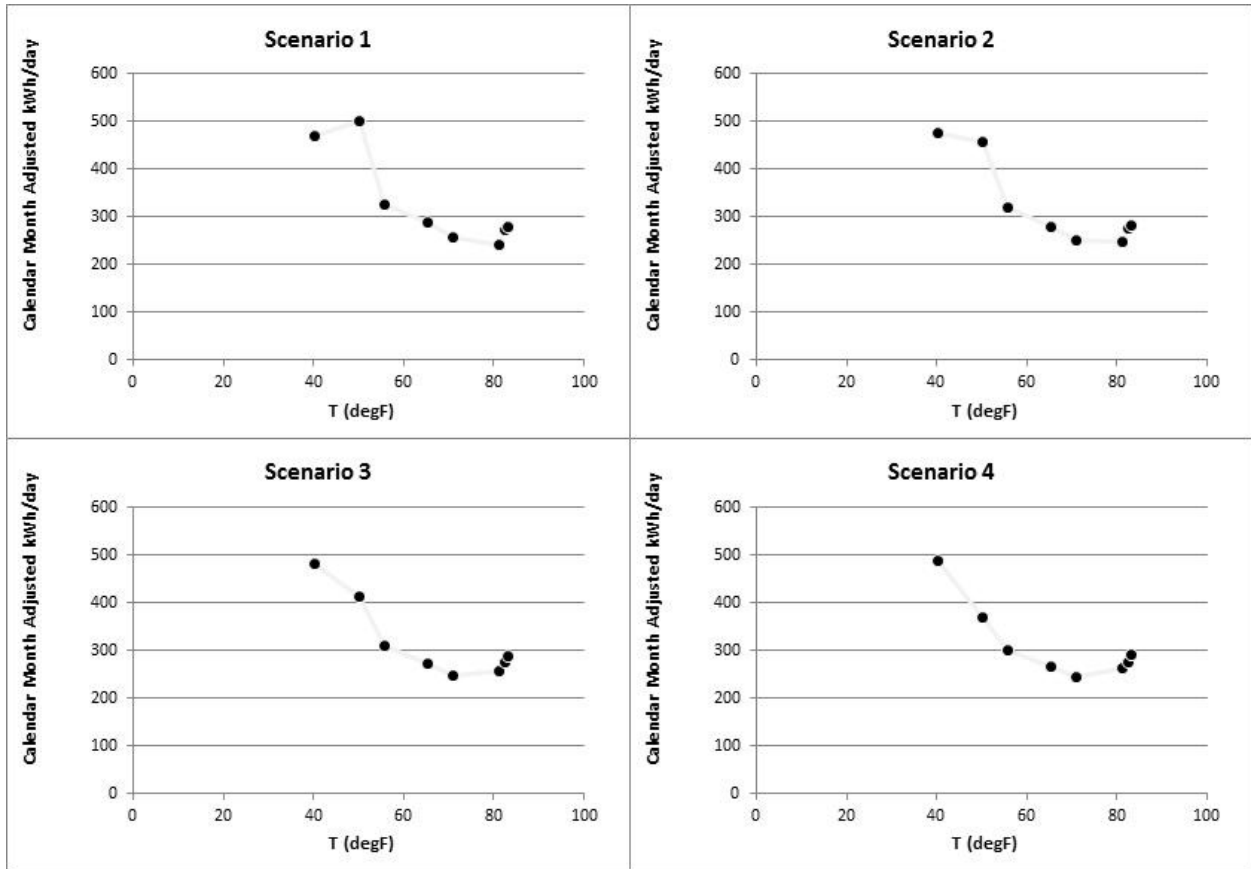


Fig. 28. Determination of billing period start and end dates.

3.1.1.2 Weather normalization of utility bills

Using the 8-month (i.e., January to August 2011) calendar month adjusted billed energy use and monthly average temperature with Inverse Modeling Toolkit (Kissock et al. 2002), a four-parameter regression model was established.

$$\begin{aligned}
 & \text{Weather Normalized Billed Energy Use (kWh/day)} \\
 &= 500 - 0.002 \times T^2 - 0.001 \times T \\
 &+ 0.002 \times T^2 - 0.001 \times T
 \end{aligned}$$

The CVRMSE (coefficient of variation of root mean squared error) of the model was 3.78%. Using the model, the calendar month adjusted billed energy use was normalized with respect to TMY3 weather data. Fig. 29 shows the four-parameter model for the calendar month adjusted billed and weather normalized energy use.

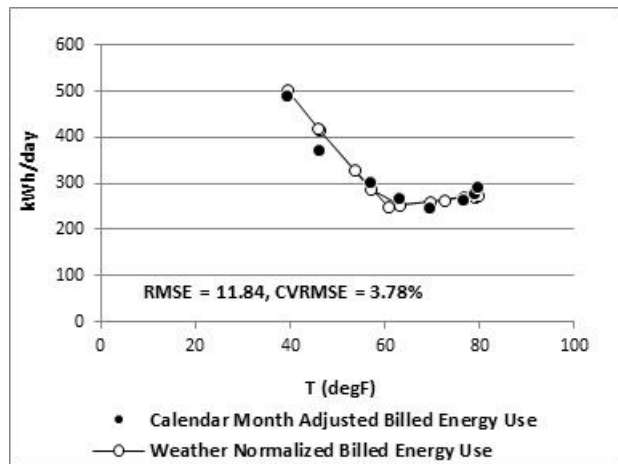


Fig. 29. Regression model for billed energy use.

3.1.2 Calibration of Building Energy Model

As recommended in Hendron and Engebrecht (2010), utility bills were not heavily relied on as a tool for model validation, but used as an approximate check of model accuracy. This choice recognizes that (1) it is extremely difficult to accurately determine occupant behavior during the time period reflected in the utility bills and (2) the large number of uncertain input parameters allows multiple ways to reconcile the model with the small number of utility bills, and there is no reliable methodology for performing this calibration because the problem is mathematically undetermined. Having said this, a building energy model was developed using the known (observed/measured) building details and default values for unknown building details and the effects of maintenance and repairs (Hendron and Engebrecht 2010). TMY3 weather data were used in the energy simulation. Weather normalized billed energy use and simulated energy use were used in the model calibration.

Adjustments to building energy model inputs were made, including lighting and equipment energy use, heating and cooling months, and setpoint temperatures during heating and cooling months. After the final set of adjustments to the energy model, a good match could be established between the simulated and billed energy use. Fig. 30 shows the results of the calibrated simulation model of the weather-normalized and simulated monthly average daily energy use for the building. The CVRMSE was 10.99%. The calibrated model was used as the baseline against which the EEMs were evaluated. Table 15 summarizes the building characteristics of the calibrated building model. Appendix F describes how base-case characteristics were quantified.

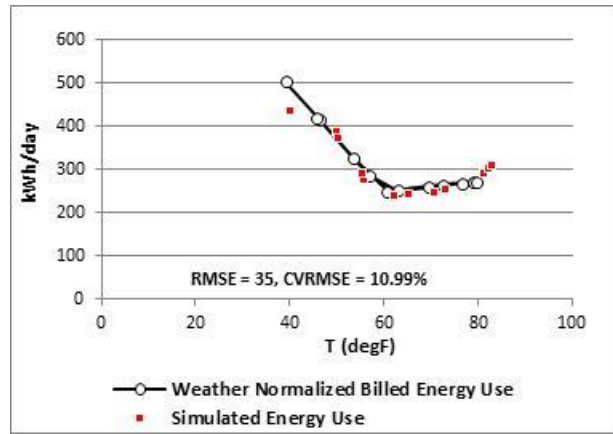


Fig. 30. Calibrated simulation model compared with billed energy use data.

Table 9. Baseline characteristics

Characteristic	Description	Comments
General		
Building type and configuration	A 3-story, 10-unit multifamily building configured as two detached blocks, each consisting of a 2-bedroom unit and a vented crawlspace on level 1 (terrace level), and a 2-bedroom and a 3-bedroom unit on levels 2 and 3. The six 1048 ft ² , 2-bedroom units and four 1260 ft ² , 3-bedroom units amount to 11,328 ft ² of total building area	Modeled as two blocks of five 1132.8 ft ² , 2.4-bedroom units arranged in the observed configuration
Surroundings	Green grass (observed on three sides); No building-shading objects within 30 ft of the building	Modeled as 0.15 ground reflectance
Construction details		
Above-grade walls	2×4 wood studs @ 16 in. o.c., R-13 high-density fiberglass batt cavity insulation	Modeled as R-11 to account for 19% R-value derating ^a
Windows and glass doors	Single-pane, clear, aluminum frame windows; interior blinds; no exterior shading	Modeled as 1.31 U-value, 0.8 SHGC windows ^b and 0.7 interior shading multiplier ^a
Opaque doors	Solid wood core	Modeled as 0.49 U-value doors

Characteristic	Description	Comments
Attic	Unconditioned vented attic; 2×6 wood joists/rafters @ 24 in. o.c.; R-30 high-density glass fiber-batt attic insulation, dark asphalt shingle roofing	Modeled as R-24 to account for 19% R-value derating ^a
Crawlspace	Vented crawlspace; concrete masonry walls; deteriorated insulation between 2×10 wood joists/open truss system @ 24 in. o.c. of above-crawlspace floor	Model as 8 in. hollow concrete block walls, uninsulated above-crawlspace floor and sillbox
Slab-on-grade floor	Concrete slab, no perimeter insulation	Modeled as 4 in. heavyweight concrete with no insulation; 80% carpet and 20% linoleum tile floor finish
Infiltration	Ranging between 1,000 and 1,500 CFM ₅₀ for individual units, amounting to a whole-building infiltration of 12,058 CFM ₅₀ ; vented attic and vented crawlspace	Modeled as 0.424 ACH in units, 15 ACH in the attic, and 3 ACH in the crawlspace
Space conditions		
Occupancy	Unknown	Modeled as 28 occupants, assuming 2 occupants in 2-bedroom units and 4 occupants in 3-bedroom units; consistent with BA Protocols ^a
Lighting	18 incandescent lamps in 2-bedroom units; 20 incandescent lamps in 3-bedroom units; 2 T12 fluorescent lamps and a 15 W pin-base tube in all units	Modeled as 0.364 W/ft ² peak usage, adding 100% as sensible heat gain (See Appendix F)
Equipment	Standard-efficiency appliances including a refrigerator, a dishwasher, and a cooking range/oven; Presence of a clothes washer, dryer, and miscellaneous appliances is unknown	Modeled as 0.512 W/ft ² equipment power density, adding 57% as sensible and 14% as latent heat gains (see Appendix F)
Schedules ^a	Unknown	Modeled hourly schedules for occupancy, lighting and equipment (see Appendix F)
Mechanical systems		
HVAC system	12 SEER, 7.5 HSPF central heat pump, air handler located in the conditioned space; heating and cooling capacity: 18 kBtu/h in the 2-bedroom units, 24 kBtu/h in the 3-bedroom units	Modeled as 10.63 SEER, 6.64 HSPF assuming 6-year age of the equipment and 3% maintenance factor (seldom or never maintained) ^a
HVAC system operation	Unknown	Heating season: January through May and October through December; cooling season: April through October ^a
Setpoint temperature	Unknown	Heating mode: 74°F with no setback period; cooling mode: 78°F with no setup period
DHW system	A 40-gallon storage tank type electric water heater located in the conditioned space; deteriorated tank insulation on some water heaters; rated performance of 0.9 EF	Modeled as 0.87 EF assuming 19-year age of the equipment and 0.2% maintenance factor (seldom or never maintained) ^a ; 0.98 recovery efficiency, 5.5 kW rated input
Domestic hot water use	Unknown	Supply temperature: 130°F; hot water use calculated by month considering water mains temperature (see Appendix F).
Ducts	Inside the conditioned space	No duct loss modeled

^a Source: *Building America House Simulation Protocols* (Hendron and Engebrecht 2010)

^b Source: RESNET's *Mortgage Industry National Home Energy Rating Systems Standards* (RESNET 2012)

3.1.3 Analysis of Energy Efficiency Measures

From the as-retrofitted information for the building, eight EEMs were identified. Six additional EEMs were considered for the analysis to identify an alternative more cost-effective measure package. Since retrofit of Building #7 was completed before the analysis was performed, accurate cost data for implement measures #7 was available. Cost of additional measures was estimated using NREL (2012). Cost analysis was performed based on the electricity cost of 0.145 \$/kWh (DOL 2012) using simple payback.

Table 10 lists these measures and summarizes the results of individual and combined measures analysis. The annual energy use results with EEMs implemented individually and combined is shown in Fig. 31. Among the eight measures (EEM 1 through 8) implemented in the building, window replacement shows as the most cost effective measure, followed by heat pump replacement and water heater replacement. Lighting replacement resulted in 4% energy savings but had 12 year payback period due to the cost of fixture replacement included in the measure cost. On the other hand, increasing attic insulation from R-30 to R-38 and kitchen appliance replacement showed as the least cost effective measures with very small energy savings and 60-70 year payback period. Although some measures provided savings due to increased air-tightness, attributing the savings to individual measures was very difficult. Further improvements to the airtightness of the building can be accomplished; however, considering ASHRAE 62.2 ventilation requirements (ASHRAE 2010; see Appendix G), increased airtightness of the building would necessitate mechanical ventilation.

Six additional measures were considered for the analysis (EEM 9 through 14), which included insulating crawlspace walls, installing exterior insulation on exterior walls (since the wall siding replacement was considered for appearance and durability), installing window film, installing storm windows, and installing programmable thermostat. Among these, installing storm windows was the most cost effective measure with 3.6% energy savings and 5.4 year payback period, whereas installing window film resulted in very small savings. Other measures showed about 2% savings with 6-13 year payback period.

The analysis projected a 25% energy savings from the measures installed in the building with a payback period of 10 years. The analysis also indicated that, with a careful selection of measures, up to 38% energy savings could be achieved with a payback period of less than 6 years.

Table 10. Results of energy and economic analysis of EEMs

EEM	Energy use (kWh)	Savings			Measure Payback	
		kWh	%	\$	cost (\$)	(year)
Baseline	110,411	-	-	-	-	-
1 Insulate crawlspace ceiling with R-19 batt insulation	108,508	1,903	1.7%	\$276	\$300	1.1
2 Increase attic insulation from R-30 to R-38	110,276	135	0.1%	\$20	\$1,205	61.5
3 Replace windows and doors	99,990	10,421	9.4%	\$1,511	\$5,850	3.9
4 Replace 12 SEER, 7.5 HSPF heat pump with 14 SEER, 8.3/8.5 HSPF unit	102,488	7,923	7.2%	\$1,149	\$5,871	5.1
5 Replace incandescent lamps and fixtures with CFLs	105,921	4,490	4.1%	\$651	\$7,851	12.1
6 Replace kitchen appliances	109,352	1,059	1.0%	\$154	\$10,544	68.7
7 Replace 0.9 EF water heater with 0.93 EF unit	107,403	3,008	2.7%	\$436	\$3,012	6.9
8 Air seal building to reduce air infiltration by 25%	108,073	2,338	2.1%	\$339	\$4,758	14.0
9 Air seal crawlspace and insulate crawlspace walls with R-5 rigid insulation	108,413	1,998	1.8%	\$290	\$3,809	13.1
10 Air seal crawlspace and insulate crawlspace walls with R-13 batt insulation	108,062	2,349	2.1%	\$341	\$3,134	9.2
11 Install R-5 rigid insulation on exterior walls	108,078	2,333	2.1%	\$338	\$3,371	10.0
12 Install window film	109,949	462	0.4%	\$67	\$1,106	16.5
13 Install storm windows	106,447	3,964	3.6%	\$575	\$3,080	5.4
14 Install programmable thermostat	108,513	1,898	1.7%	\$275	\$1,700	6.2
Implemented EEMs package (EEM 1 through 8)	82,650	27,761	25.1%	\$4,025	\$39,390	9.8
Cost-optimized EEMs package (EEM 1, 3, 4, 5, 7, 8, 11, and 14)	68,590	41,821	37.9%	\$6,064	\$32,713	5.4

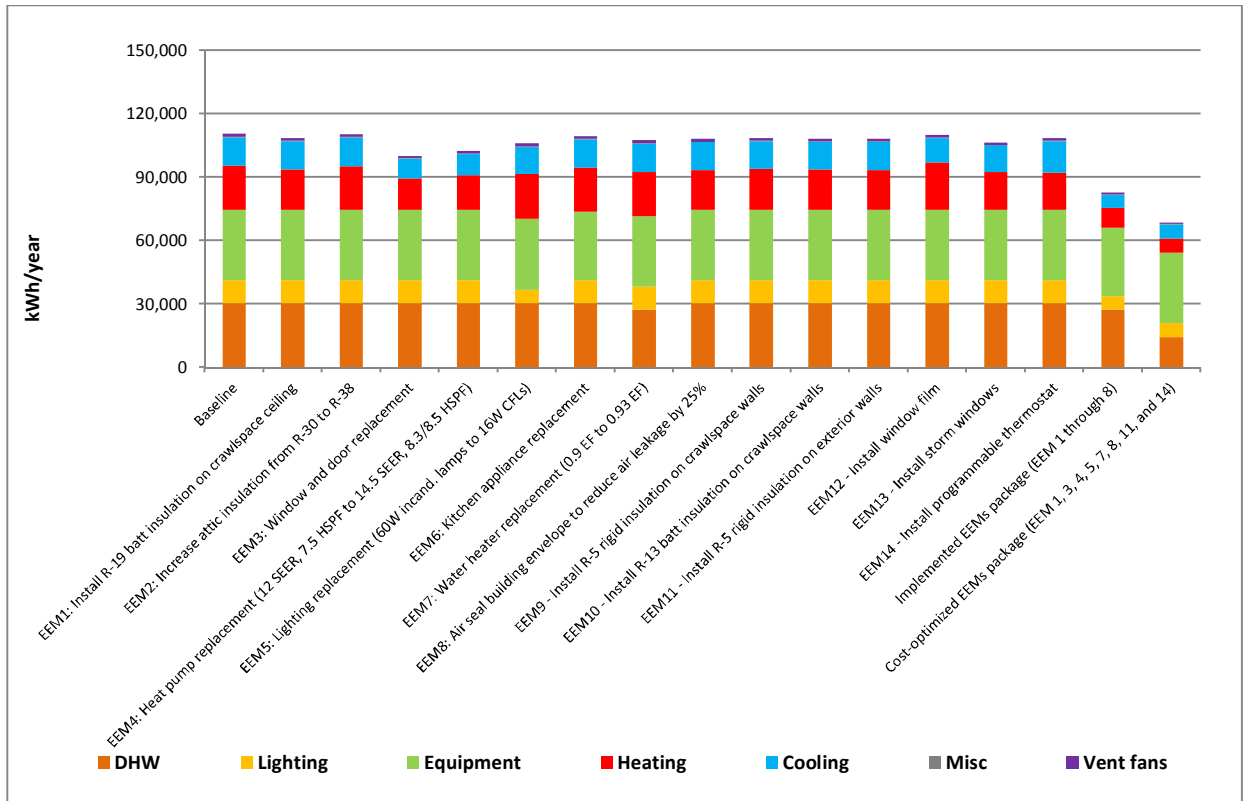


Fig. 31. Annual energy use for all EEMs.

3.2 ENERGY ANALYSIS OF SAMPLE UNITS

Using the diagnostic testing results and unit characteristics, REM/RateTM energy models were created to determine the estimated consumption in the sample units. Appendix D shows a comparison of the same unit type for pre- and post-energy-retrofit consumption based on the four major loads within the units: heating, cooling, water heating, and lighting and appliances. Using the software, a Home Energy Rating System (HERS) index was generated for both pre- and post-upgrade analysis. The average initial HERS index for the sample units was 107. The average final HERS index was 87, a 20% improvement from the average initial index. The mean initial annual site energy consumption for the units was 50 MMBtu and the mean post-retrofit consumption is 40 MMBtu, for an average estimated 18% in savings (Fig. 32).

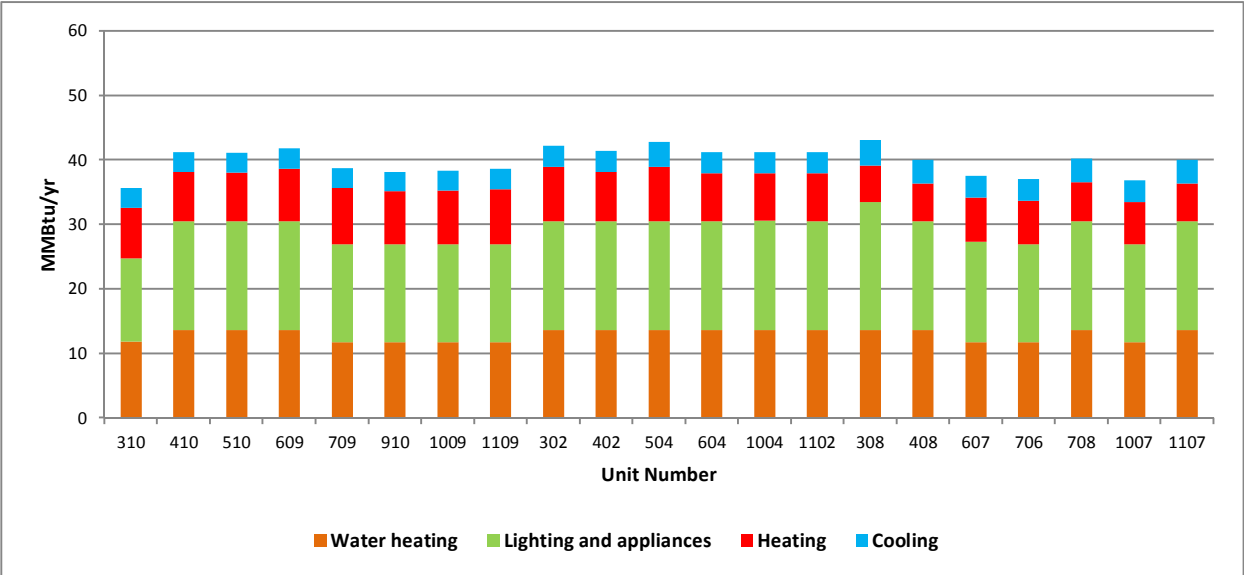
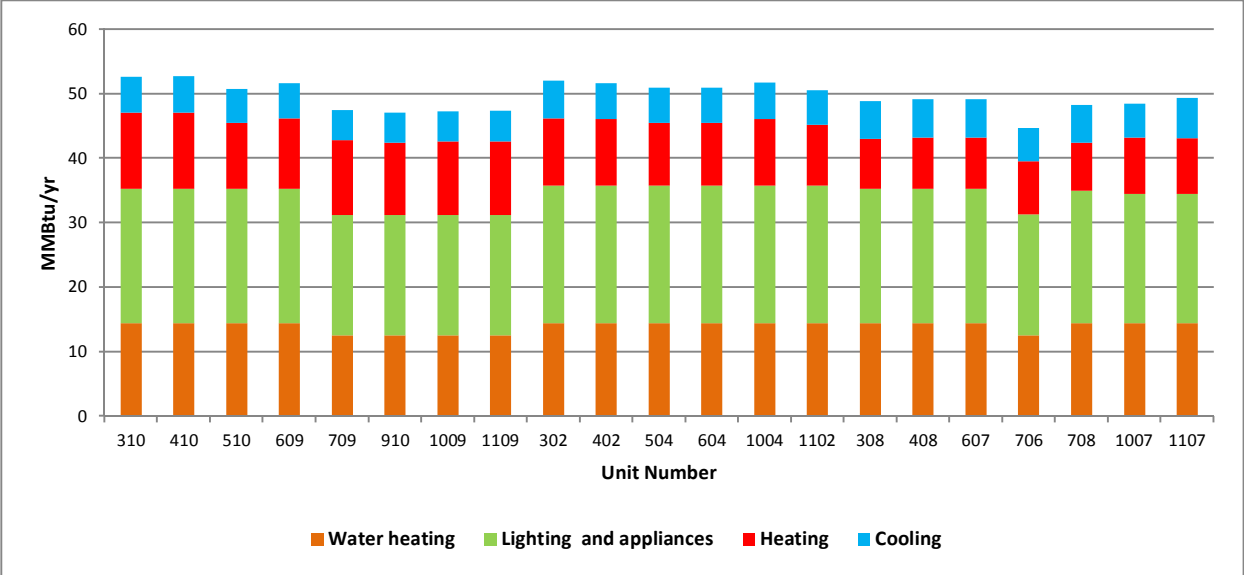


Fig. 32. Pre and post-retrofit site energy consumption for the sample units.

4. SUMMARY AND CONCLUSION

Maplewood completed major renovations under the guidance of a third-party green building certification program in October 2012. Existing conditions were analyzed for one of the eleven Maplewood buildings, as well as for sample units selected across different buildings in the complex through visual assessment for general conditions and blower door measurements for envelope and duct leakage. For renovations, a whole-house approach was exercised: upgrading the building envelope with air-sealing, adding insulation, and replacing windows and replacing lighting, major appliances, heating and cooling systems, and domestic water heaters.

Because of the unique demands of this financing, including requirements for long-term ownership, the project aimed to add value to the property by improving the comfort, durability, and appearance of the building, as well as to provide energy and cost savings for the tenants. The project provided unique opportunities to learn about several aspects of a multifamily building retrofit that would benefit future projects in terms of improved building audit process, streamlined tasks, and higher energy savings. However, the project presented many challenges in accomplishing a number of tasks. Several missed opportunities were identified, some of which resulted from the challenges and some of which were not originally planned. The following sections describe these lessons learned.

In a previous study on a multifamily renovation with a similar scope of work, Flipper Temple (Kim et al. 2012), only 3% of the total construction cost was attributed to EEMs. Based on these two studies, less than 10% of a project's construction cost is dedicated strictly to EEMs.

4.1 OPPORTUNITIES

Energy-saving opportunities

- Energy analysis of the sample units using REM/Rate™ showed an average 20% reduction in the HERS index (pre-retrofit HERS index of 108 reduced to an index of 86 after the retrofit measures were implemented). Whole-building energy analysis of a typical 10-unit building of Maplewood showed a 25% savings projection from implemented measures.

Added property value

- All measures implemented in Maplewood greatly improved the appearance and durability of the buildings and its systems and improved thermal comfort for the occupants.

Learning opportunities

- By conducting unguarded and guarded blower door tests, it was possible to investigate the infiltration across the shared units.
- Comparing results of the two sets of energy analyses—one for sample individual units and one for the whole building—showed that the sampling set determined by the field team would be reasonably sufficient for whole-building energy analysis. At the same time, the results of a typical whole-building analysis could be generalized to similar buildings.
- The results of the detailed whole-building energy simulation to evaluate additional energy-retrofit measures emphasized the importance of having energy consultants involved at an early decision making stage.

4.2 CHALLENGES

During planning and decision making process

- Unlike in single-family audits, multiple team players are involved in multifamily housing audits: building owner, developer, contractor, architect, consultants, and tenants. Coordinating all involved parties requires extensive planning and execution, resulting in less flexibility.
- The application process for DCA QAP candidates did not involve the energy consultants in determining the EEMs. By the time developers approached Southface to implement a green building certification program, most of the EEMs had already been determined. Therefore, additional consultation could not be provided because the project schedule had already been initiated. Energy modeling iterations were produced after construction began. An evaluation of the process is necessary so that resources are optimized and expectations for every party involved are met.
- Different multifamily programs adhere to different sampling standards. For example, Maplewood is part of a third-party green building certification program that requires 33% sampling; additionally, Maplewood participated in a local utility rebate program that requires 15% sampling of units on each floor of a building. Consistency is important to effectively communicate a project's design intent and to prevent confusion across teams.

Obtaining and interpreting utility data

- Acquiring utility bills is not a requirement for local program implementation of multifamily projects. Lack of access to unit-by-unit data or total building consumption prevents consultation on energy conservation measures by evaluating utility bills for a baseline. Based on the local utility company's policy, individual tenant waivers must be signed. These waivers grant access to the building portfolio of the complex. Although pre-retrofit utility data were obtained for Maplewood, detailed billing information such as billing cycle dates could not be obtained. Such limitations presented challenges in weather normalizing the utility data and providing more accurate energy consumption characterizations. With QAPs driving many projects in the multifamily market, more research focus should be placed on how utility bills impact low-income families. If provided with such data, organizations such as DCA and HUD might be better able to market the value proposition of incorporating EEMs to lure developers to actively seek more affordable housing projects.
- More insight is needed to fully grasp the impact of EEMs on multifamily buildings. Researchers need information to resolve several issues related to occupancy levels and occupant characteristics:
 - ó Uncertainty about occupancy details in units is an obstacle to benchmarking savings.
 - ó Gaining access to occupancy level in each unit presents privacy issues, which could potentially hinder a project's construction progress.
 - ó Normalization of utility bills was difficult with unexplainable energy use profile observed in the utility bill data.

Implementation of measures

Selection of certain measures was based on cost, ignoring the ease of implementation, durability, and effectiveness of the measure. An example is the installation of floor insulation. Because of the significant cost difference between the quoted prices for spray foam (\$1.50/ft²) and batt insulation (\$0.30/ft²), the developers initially decided to use batt insulation under the framed floors. The open-web truss wood framing system made clean, proper installation between the framing members difficult. The field team had to make multiple quality assurance visits to Maplewood for each phase because of the shortcomings

found in the installation of batt insulation under the subfloor. The installers expressed frustration with the difficulty in achieving a clean, proper installation because of the challenges presented by the framing structure and plumbing lines. The additional costs for time and labor incurred to the developer due to extra effort should not be ignored while developing scopes of work.

Determining cost-effectiveness of retrofit measures

- Several building envelope measures (including adding attic insulation, roofing and wall siding replacement, window replacement, and installing above-crawlspace floor insulation) resulted in energy savings due to reduced conduction losses as well as supplemental benefits from reduced infiltration. The cumulative effect of these measures, combined with air-sealing, was observed through post-retrofit blower door tests. However, it was difficult to apportion the air-sealing benefits to individual measures. Thus energy savings and cost-effectiveness from these measures were underestimated because the energy savings did not account for savings due to reduction in air infiltration.

4.3 MISSED OPPORTUNITIES

Energy savings

Several energy savings opportunities were missed partly as a result of the late involvement of energy consultants and partly due to the selection criteria for retrofit measures. Detailed whole-building energy analysis of one of the buildings showed that

- Several measures implemented in the building resulted in very small and/or not cost-effective energy savings. These measures were implemented mainly to add value to the building. This is a common practice in multifamily buildings. However, such measures can be strategically selected or combined with other potential energy retrofit measures to result in an overall cost-effective package. For example, exterior wall siding was replaced, but not as an energy-retrofit measure. However, such a measure can be combined with adding exterior continuous insulation to provide energy savings for a lower installation cost than would be incurred otherwise. Roofing replacement, if considered from the standpoint of improving the long-term durability of the building, can result in energy savings if products with improved thermal properties are selected.
- With a careful selection of measures, energy savings of up to 37% could be achieved with a payback period of 6 years, whereas the EEMs implemented are projected to provide a 25% energy savings with 20 years of simple payback.

Human comfort and indoor air quality

Although improving comfort was one of the goals for this project, some comfort aspects were not considered in this project.

- Lighting replacement did not consider visual comfort (i.e., lighting level requirements) in different spaces of the units. The decision mainly considered incandescent wattage versus equivalent lower-wattage compact fluorescent light bulbs for lamps.
- The building envelope retrofit measures were selected mainly to reduce infiltration to the outdoors. In multifamily buildings, attention should also be given to air-sealing shared surfaces for reduced infiltration as well as improved acoustics of the units.
- ASHRAE 62.2-2010 (ASHRAE 2010) calculations with pre-retrofit guarded blower door measurements and exhaust deficits in the bathrooms and kitchen revealed that the units were under-ventilated. The air-sealing retrofit measure decreased the air infiltration rate by about 25% and

required a higher mechanical ventilation rate to comply with ASHRAE 62.2. However, no consideration was given to achieving compliance with ASHRAE 62.2 and providing mechanical ventilation.

- For replacement of HVAC systems, post-retrofit system sizing calculations were not performed. The replacement HVAC systems were selected based on the sizes of the existing systems. Post-retrofit reduced loads may result in system oversizing and increased cycling of systems, thereby reducing performance and thermal comfort in the units.

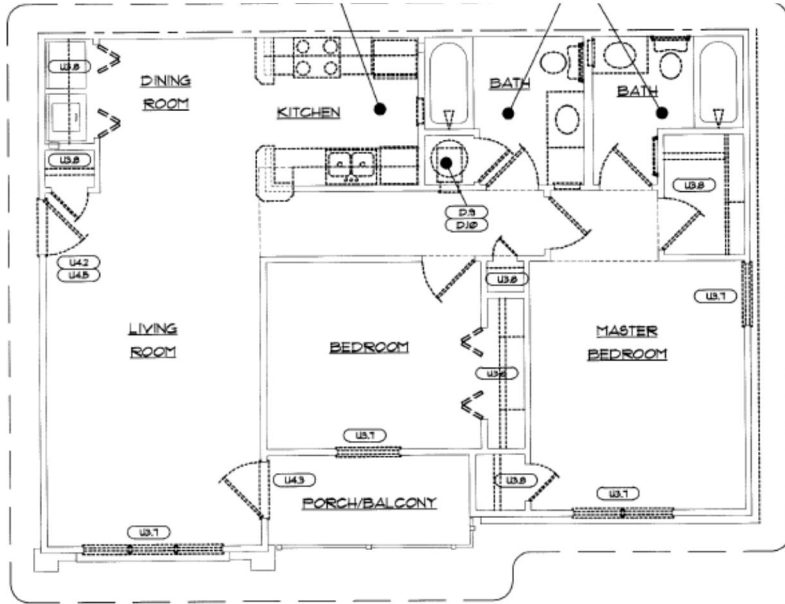
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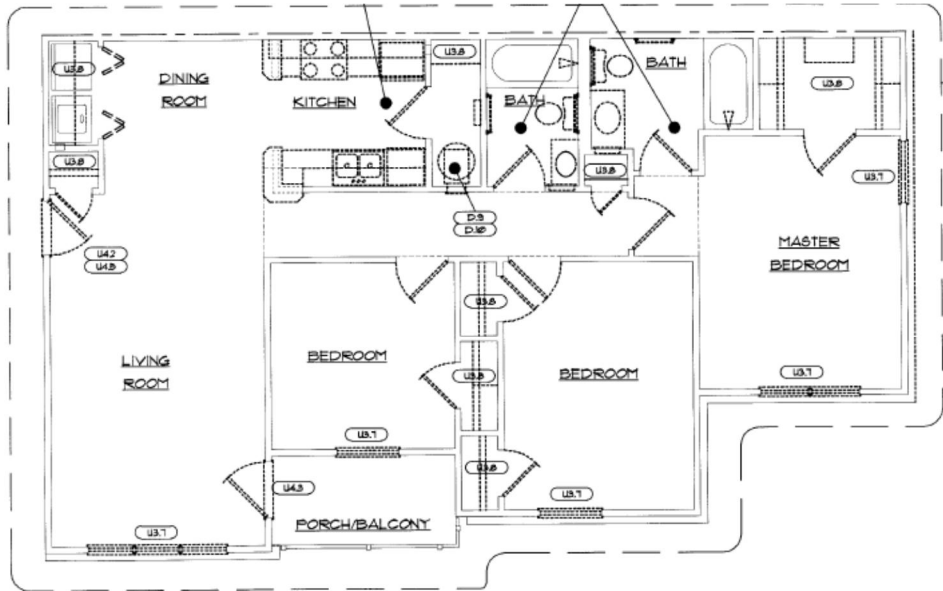
APPENDIX A
MAPLEWOOD ARCHITECTURAL PLANS

APPENDIX A. MAPLEWOOD ARCHITECTURAL PLANS



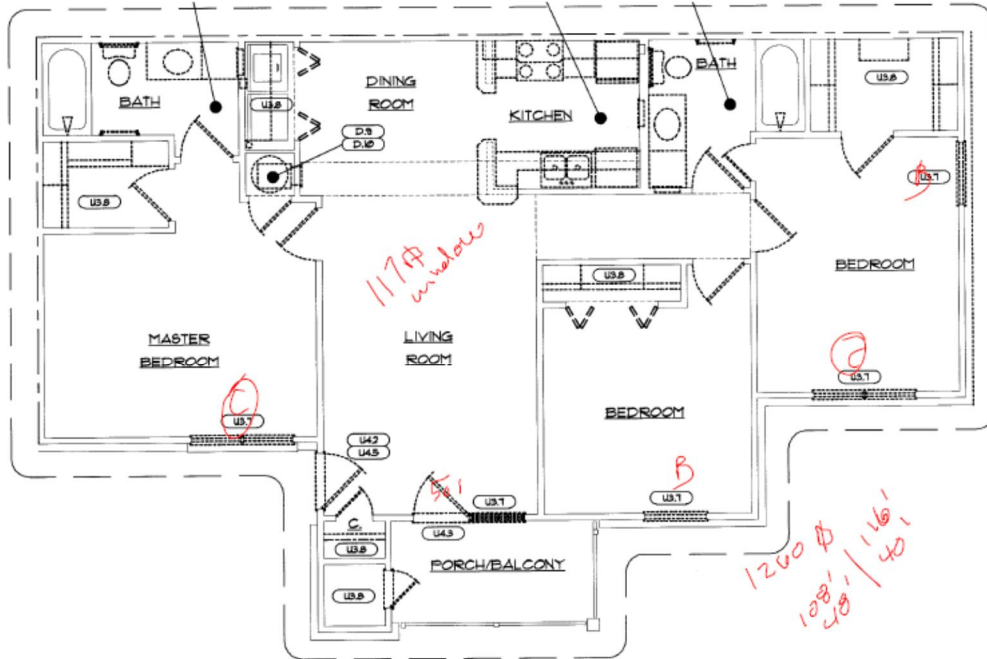
1 UNIT TYPE 'A' PLAN - DEMO
1/4" = 1'-0"

Unit A (two-bedroom unit).



2 UNIT TYPE 'B' PLAN - DEMO
1/4" = 1'-0"

Unit B (three-bedroom unit).



3 UNIT TYPE 'C' PLAN - DEMO
 1/4" = 1'-0"

Unit C (three-bedroom unit).

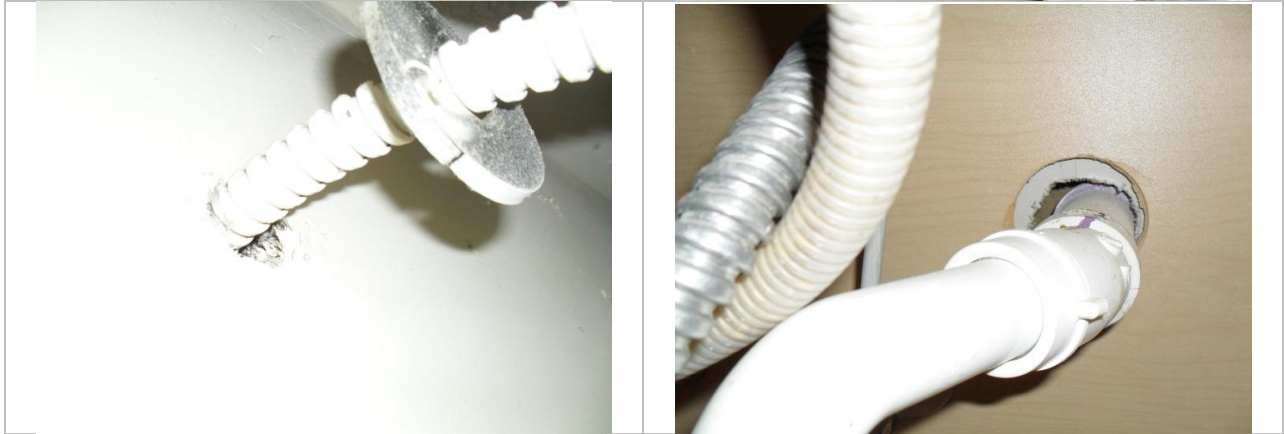
APPENDIX B
MAPLEWOOD PHOTOGRAPHS

APPENDIX B. MAPLEWOOD PHOTOGRAPHS

Pre-Retrofit Photographs



Interior spaces



Wall penetrations

Pre-Retrofit Photographs (Cont.)

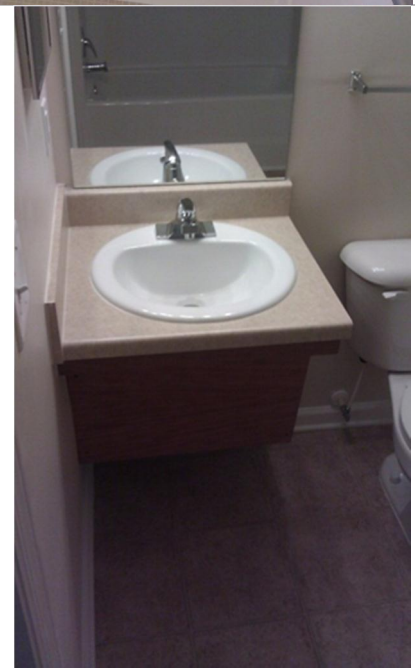


Attic

Post-Retrofit Photographs



Building exterior



Interior spaces



HVAC and DHW systems



Crawlspace



Attic

APPENDIX C
MAPLEWOOD QAP SUSTAINABILITY CHECKLIST

APPENDIX C. MAPLEWOOD QAP SUSTAINABILITY CHECKLIST

**Georgia Department of Community Affairs
2010 Qualified Allocation Plan**

**EXHIBIT A to APPENDIX I
Building Sustainability Certification**

Project Name:	MAPLEWOOD PARK
DCA Project Number:	
Project Location (City & County):	UNION CITY

Compliance with Threshold Section 15 - Building Sustainability requires projects obtain **10 points** from the menu of options below. At least **4 categories** must be addressed. The Building Sustainability Certification must be completed, signed, and submitted with Step II architectural submittals as defined in the Architectural Submittals manual. Developers are encouraged to consult with the project architect and engineers to determine the options that best suit each individual project. Projects proposing the reuse of a historic structure may be eligible for a waiver from these requirements and should contact DCA prior to Application submission to determine what building sustainability requirements will apply.

Categories:	Point Value	Points Earned
1. Energy Efficient Building Envelope	8	4
2. Lighting	1	1
3. Water Conservation	12	4
4. Indoor Air Quality	7	0
5. Resource Efficiency	4	0
6. Education	4	2
7. Innovation	4	0
** minimum 10 points required	40	11

1. Energy Efficient Building Envelope		
a. High performance heating equipment. ARI rated furnace (90% AFUE), or heat pump (HSPF 8.0 or greater). Projects that do not plan to utilize a typical split system for heating (e.g. ductless mini-split, a heat pump in combination with a PTAC (packaged terminal air conditions), etc.) in more than 50% of the units must submit the specifications and manufacturer's data for the proposed equipment so that DCA can verify that the efficiency rating is equivalent to the above efficiency standards. Projects must submit a Certificate of ARI-Certified Performance from the American Refrigeration Institute (ARI) by September 30, 2011.	2	2
b. High performance cooling equipment. ARI rated SEER 13 with variable blowers or SEER 14 cooling equipment or with sensible heat ratio less than 0.75. Projects that do not plan to utilize a typical split system for cooling (e.g. ductless mini-split, a PTAC (packaged terminal air conditions) etc.) in more than 50% of the units must submit the specifications and manufacturer's data for the proposed equipment so that DCA can verify that the efficiency rating is equivalent to the above efficiency standards. Projects must submit American Refrigeration Institute (ARI) certificate of heating & cooling unit pair on or before September 30, 2011.	2	2
c. Locate HVAC ductwork in conditioned spaces. A minimum of 90% of the ducts in each unit must be so located to qualify for these points) Projects that plan to utilize Packaged Terminal Air Conditioners (PTAC's) or mini-splits in more than 50% of the units are not eligible for this option.	2	
d. The exterior envelope wall systems, including the rim (band) joist spaces, insulated with a spray applied insulation material such as cellulose or a foam product (installed to manufacturers specifications to limit settling). R-value to meet Energy Codes.	2	

**Georgia Department of Community Affairs
2010 Qualified Allocation Plan**

2. Lighting

a. Installation of common area lighting with Energy star rating and controlled with either photocells or timer	1	1
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3. Water Conservation

a. All plumbing fixtures in all units: toilets < 1.3 gpf	4	4
c. Provide a system for the reuse of site water run off (rainwater harvesting) for landscaping irrigation for at least 75% of irrigation water annual. (Note: any site with an environmental restriction for re-use of groundwater is not eligible for these points.) The system must comply local building codes.	4	
d. Design and install a graywater reuse system for landscaping irrigation use (i.e., not a septic system) or indoor water use. The system must include a tank or dosing basin that can be used as part of the irrigation system. Graywater must be collected from at least one of the following: clothes washer; showers; some combination of faucets and other source estimated to exceed 5,000 gallons per year. The system must comply local building codes.	4	

4. Indoor Air Quality

a. The HVAC system to be designed to include the controlled introduction of outside air based upon the standard set forth by ASHRAE 62.2-2004. Operable windows are not a permissible method of providing ventilation. Provide a letter from the project's mechanical engineer, which includes the engineer's stamp, that states ventilation system meets this standard as designed by September 30, 2011.	2	
b. When combustion equipment is utilized, equipment is designed an installed with closed combustion (i.e. sealed supply air and exhaust ducting); power-vented exhaust; and carbon monoxide monitor in each unit	2	
c. The kitchen range hood ventilation to be ducted to the exterior and equipped with a damper	1	
d. Energy Star ceiling fans in living rooms, sunrooms and all bedrooms: (Kitchens and dining rooms not applicable.)	2	

5. Resource Efficiency

a. Pre Construction: Posted and enforced job site waste management plan--recycle 75% of 3 materials; provide DCA with management plan with Step II documents	2	
b. Post Construction: Provide recycling infrastructure for the development, alternative to trash compactor/dumpster, and for each unit (recycling receptacle/station in each unit) in accordance with local requirements. Provide letter from local jurisdiction regarding the local requirements and availability of recycling for the project.	2	

6. Education

a. Educate tenants with a project manual provided to each tenant upon move-in and at least 1 class by December 31, 2012 on green building features of the units. Submit a copy of the manual to DCA before LIHTC final allocation along with a schedule for the class. See an example at http://www.practitionerresources.org/cache/documents/639/63997.doc	2	2
b. Educate management and maintenance staff with an orientation and produce a green operations and maintenance manual detailing sustainable features, the staff's role in maintaining those features, and a replacement parts product source guide. Submit a copy of the manual to DCA before LIHTC final allocation along with a schedule for the class. See an example at http://www.practitionerresources.org/cache/documents/639/63995.doc	2	

**Georgia Department of Community Affairs
2010 Qualified Allocation Plan**

7. Innovation

a. Innovative materials & technologies such as green roofs, solar hot water systems, photovoltaics, porous paving, high reflectance roofs & paving, recycled materials, etc. Proposed innovations must be submitted by pre-approval request prior to Application Submission detailing the proposed innovation(s), product data, development plans, cost, and suggested points structure.	4	
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The undersigned certifies to the Georgia Department of Community Affairs (DCA)/Georgia Housing and Finance

Applicant Signature _____

Date _____

Architect Signature & Stamp _____



2-11-11

Date _____

APPENDIX D
DIAGNOSTIC TEST DATA FOR SAMPLE UNITS

APPENDIX D. DIAGNOSTIC TEST DATA FOR SAMPLE UNITS

Unit #	Type	Conditioned floor area (ft ²)	Envelope leakage				Duct leakage					
			Pre-retrofit		Post-retrofit		Leakage reduction (%)	Pre-retrofit		Post-retrofit		Leakage reduction (%)
			Blower door fan flow (CFM ₅₀)	ACH ₅₀	Blower door fan flow (CFM ₅₀)	ACH ₅₀		Duct blaster fan flow (CFM ₂₅)	Leakage to outside (%)	Duct blaster fan flow (CFM ₂₅)	Leakage to outdoors (%)	
Terrace floor												
310	B	1,176	1,739	11.1	1,190	7.6	31.6%	10	0.9%	4	0.3%	0.5%
410	B	1,176	1,664	10.6	907	5.8	45.5%	30	2.6%	20	1.7%	0.9%
510	B	1,176	1,720	11.0	848	5.4	50.7%	12	1.0%	12	1.0%	0.0%
609	B	1,176	1,807	11.5	1,201	7.7	33.5%	22	1.9%	22	1.9%	0.0%
709	A	1,049	1,520	10.9	1,227	8.8	19.3%	8	0.8%	26	2.5%	-1.7%
910	A	1,049	1,530	10.9	942	6.7	38.4%	18	1.7%	12	1.1%	0.6%
1009	A	1,049	1,983	14.2	1,064	7.6	46.3%	18	1.7%	34	3.2%	-1.5%
1109	A	1,049	1,050	7.5	1,050	7.5	0.0%	25	2.4%	25	2.4%	0.0%
Second floor												
302	B	1,176	1,336	8.5	990	6.3	25.9%	114	9.7%	20	1.7%	8.0%
402	B	1,176	1,462	9.3	954	6.1	34.7%	24	2.0%	30	2.6%	-0.5%
504	C	1,260	1,301	7.7	1,033	6.1	20.6%	17	1.3%	16	1.3%	0.1%
604	B	1,176	967	6.2	967	6.2	0.0%	39	3.3%	39	3.3%	0.0%
1004	C	1,260	1,691	10.1	966	5.8	42.9%	22	1.7%	18	1.4%	0.3%
1102	B	1,176	958	6.1	958	6.1	0.0%	27	2.3%	27	2.3%	0.0%
Third floor												
308	B	1,176	1,324	8.4	1,021	6.5	22.9%	711	60.5%	28	2.4%	58.1%
408	B	1,176	1,427	9.1	901	5.7	36.9%	22	1.9%	108	9.2%	-7.3%
607	B	1,176	1,252	8.0	1,252	8.0	0.0%	19	1.6%	19	1.6%	0.0%
706	A	1,049	1,252	9.0	1,135	8.1	9.3%	14	1.3%	20	1.9%	-0.6%
708	C	1,260	1,201	7.1	1,023	6.1	14.8%	40	3.2%	26	2.1%	1.1%
1007	A	1,049	1,427	10.2	967	6.9	32.2%	20	1.9%	8	0.8%	1.1%
1107	A	1,049	911	6.5	911	6.5	0.0%	25	2.4%	25	2.4%	0.0%
Average			9.2		6.7		24.1%	5.1%		2.2%		2.8%

APPENDIX E
CALIBRATION RESULTS

APPENDIX E. CALIBRATION RESULTS

Weather normalization of billed energy use

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year 2011 temperature (°F)	40.2	50.0	55.8	65.3	70.9	81.3	82.4	83.1	73.3	62.2	55.7	50.5
Year 2011 billed energy use (kWh/day)	490	371	301	266	246	264	277	292	226	195	221	232
Year 2011 predicted energy use (kWh/day)	491	370	299	255	262	275	276	277				
Residual, billed - predicted	-0.5	0.3	1.6	10.5	-16.4	-10.7	0.9	14.3				
Residual, billed - predicted (%)	-0.1	0.1	0.5	4.1	-6.3	-3.9	0.3	5.2				

$$TMY3 \text{ temperature } (T_{TMY3}) = T_{TMY3} - T_{TMY3} \times T_{TMY3} - T_{TMY3} + T_{TMY3} \times T_{TMY3} - T_{TMY3}$$

RMSE = 11.84, CVRMSE = 3.78%

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMY3 temperature (°F)	39.2	46.2	56.8	63.0	69.4	76.6	79.0	79.7	72.5	60.8	53.4	45.9
Weather-normalized billed energy use (kWh/day)	503	417	286	252	260	269	272	273	264	249	328	421

Comparison of weather normalized utility bills and calibrated building energy model

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
TMY3 temperature (°F)	39.2	46.2	56.8	63.0	69.4	76.6	79.0	79.7	72.5	60.8	53.4	45.9
Weather-normalized billed energy use (kWh/day)	503	417	286	252	260	269	272	273	264	249	328	421
Simulated energy use (kWh/day)	433	387	274	243	245	290	303	309	252	237	291	370
Residual, weather-normalized - simulated	70	30	12	9	15	-21	-30	-36	12	12	37	52
Residual, weather-normalized - simulated (%)	13.9%	7.1%	4.3%	3.6%	5.9%	-7.8%	-11.2%	-13.3%	4.7%	4.9%	11.3%	12.2%

RMSE = 35, CVRMSE = 11.99%

APPENDIX F
CONSIDERATIONS FOR WHOLE-BUILDING ENERGY ANALYSIS

APPENDIX F. CONSIDERATIONS FOR WHOLE-BUILDING ENERGY ANALYSIS

F.1 Estimation of Lighting Power Density

The pre-retrofit hardwired lighting system consisted of eighteen 60W incandescent lamps, two T-12 fluorescent lamps, and a 15 W lamp over the sink in two-bedroom units and twenty-one 60 W incandescent lamps, two T-12 fluorescent lamps, and a 15 W lamp over the sink in three-bedroom units. For the post-retrofit hardwired lighting system, all incandescent lamps were replaced with 13W compact fluorescent lamps and more efficient (lower wattage) fluorescent lamps. The wattage and distribution of pre- and post-retrofit hardwired lighting system characteristics are shown in Table F.1. With these characteristics, the average hardwired lighting power density was 1.10 W/ft² before the retrofits and 0.29 W/ft² after the retrofits. No change in the plug-in lighting system was assumed. Pre- and post-retrofit lighting energy use was modeled using the peak lighting W/ft² use (derived from the benchmark lighting budget combined with the adjustments for installed hardwired lighting system characteristics, as shown in Table F.2) and the usage schedule (Fig. F.1).

Table F.1. Pre- and post-retrofit hardwired lighting system characteristics

Space	Number of lamps		Lamp wattage		Installed wattage			
	2-bedroom unit	3-bedroom unit	Pre-retrofit	Post-retrofit	Pre-retrofit		Post-retrofit	
					2-bedroom unit	3-bedroom unit	2-bedroom unit	3-bedroom unit
Bedrooms	4	6	60	13	240	360	52	78
Bathrooms	8	8	60	13	480	480	104	104
Closet/store	2	3	60	13	120	180	26	39
Hallway	2	2	60	13	120	120	26	26
Living room	2	2	60	13	120	120	26	26
Kitchen (T-12)	2	2	40	32	80	80	64	64
Kitchen (15 W over the sink)	1	1	15	15	15	15	15	15
Installed wattage W/ft ²					1175	1355	313	352
Average W/ft²					1.10		0.29	

Table F.2. Pre- and post-retrofit lighting energy use calculations

Lamp type	Lamp efficacy (Eff _{lamp}) lm/W	Default lamp type fraction (F _{default,lamp})	Installed lamp type fraction (F _{installed,lamp})	
			Pre-retrofit	Post-retrofit
Incandescent	15	66%	94%	0%
CFL	55	21%	0%	80%
LED	50	0%	0%	0%
T8	88	13%	0%	0%
T12	82	0%	6%	20%
Lighting energy use (assuming default lamp types)				
Interior hardwired lighting (kWh/year)	$L_{HW} = 0.8*(FFA*0.542+334)$		758.4	
Interior plug-in lighting (kWh/year)	$L_{Plug} = 0.2*(FFA*0.542+334)$		189.6	
Adjustments			Pre-retrofit	Post-retrofit
Lamp type adjustment factor	$Adj_{LampType} = 1 + \sum[(F_{installed,lamp} - F_{default,lamp}) * Eff_{lamp} / Eff_{incand}]$		1.208	0.516
Smart lamp replacement factor	$SRF = 1.1 * F_{inc}^4 - 1.9 * F_{inc}^3 + 1.5 * F_{inc}^2 - 0.7 * F_{inc} + 1$		6	1.0 ⁸
Take back	10% for lamp replacement (post-retrofit)		6	10%
Adjusted hardwired lighting (kWh/year)	$L_{HW,adj} = L_{HW} * [Adj_{LampType} * SAF * 0.9 + 0.1]$		916	467
Total lighting energy use (kWh/year)	$L_{Total} = L_{HW,adj} + L_{Plug}$		1105.6	656.6
Average daily lighting energy use (kWh/day)	$L_{daily} = L_{Total} / 365$		3.03	1.80
Peak W/ft²	$L_{peak\ WSF} = L_{daily} * Peak\ Fraction\ of\ Daily\ Sum$		0.364	0.216

⁸ Smart lamp replacement factor was ignored, since all lamps were replaced (as opposed to the replacement of high-use lamps first).

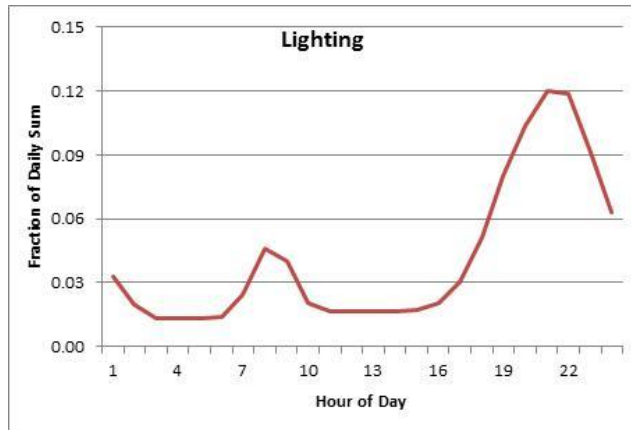


Fig. F.1. Lighting schedule.

F.2 Estimation of Equipment Power Density

Equipment power density (EPD) was estimated for an average unit assuming all-electric appliances including a refrigerator, dishwasher, cooktop/oven, clothes washer, clothes dryer, and miscellaneous appliances commonly found in a multifamily unit. The energy use for these appliances was estimated using the *Building America Simulation Protocols* combined with the federal standard for appliance energy performance for the pre-retrofit case and rated energy performance for the post-retrofit case. Table F.3 shows the pre and post-retrofit appliance characteristics and EPD. These values combined with the equipment schedule (Fig. F.2) were used for modeling the equipment energy use.

Table F.3. Pre- and post-retrofit equipment characteristics and energy use

Equipment	Description	Energy use (kWh/year)	
		Pre-retrofit	Post-retrofit
Refrigerator	Pre-retrofit: <i>Building America Simulation Protocols</i> (434 kWh/year) Post-retrofit: Whirlpool WRT138TFYB (388 kWh/year)	434	388
Dishwasher	Pre-retrofit: 0.6 EF Post-retrofit: Whirlpool DU850SWP (306 kWh/year => 0.7 EF) <i>Annual energy use = Machine energy use fraction * Number of cycles per year / EF_{dishwasher}</i> <i>Machine energy use fraction = 44%</i> <i>Number of cycles per year = 215*(1/2 + N_{br}/6)</i>	142	121
Cooktop/oven	Pre-retrofit: Assumed characteristics: Cooktop: Non-reflective pans, rounded coil elements (73.7% EF) Oven: Standard door seals, standard vent rate, standard insulation (10.9% EF) Post-retrofit: Whirlpool RF114PXSBB; Assumed characteristics: Cooktop: Reflective pans, flat coil elements (77.7% EF) Oven: Improved door seals, reduced vent rate, high-density insulation (12.1% EF) <i>Annual energy use = (86.5 + 28.9*N_{br})/EF_{cooktop} + (14.6 + 4.9*N_{br})/EF_{oven}</i>	453	418
Clothes washer	Pre-retrofit: <i>Building America Simulation Protocols</i> Post-retrofit: No change <i>Annual energy use = (38.8 + 12.9*N_{br})</i>	70	70
Clothes dryer	Pre-retrofit: <i>Building America Simulation Protocols</i> Post-retrofit: No change <i>Annual energy use = (538.2 + 179.4*N_{br})</i>	969	969
Miscellaneous electrical loads (MELs)	Pre-retrofit: <i>Building America Simulation Protocols</i> assuming the following appliances: A microwave, a toaster, a blender, a TV, a DVD player, ceiling fans in each bedroom, an iron, a smoke detector, a doorbell, a desktop PC and monitor, a vacuum cleaner, a cordless phone charger, 2 cellphone chargers, an answering machine, and air handler standby losses. Post-retrofit: No change	1,275	1,275
Total kWh/year		3343	3241
W/ft²	<i>1000* [Annual Energy Use / Hours of Operation per Year] / Average Area of a Unit</i>	0.512	0.496



Fig. F.2. Equipment schedule.

F.3 Estimation of Internal Heat Gains

Internal heat gains from appliances were estimated using the latent and sensible load fractions as shown in Table F.4, and modeled as sensible and latent heat gain fractions combined with the equipment usage schedule (Fig. F.2). The combined sensible and latent heat gain fractions were 0.565 and 0.143 for the pre-retrofit case and 0.545 and 0.138 for the post-retrofit case.

Table F.4. Pre- and post-retrofit internal heat gains from household appliances

Appliance	Sensible load fraction	Latent load fraction	Pre-retrofit			Post-retrofit		
			Annual energy use (kWh/year)	Sensible heat gains (kWh/year)	Latent heat gains (kWh/year)	Annual energy use (kWh/year)	Sensible heat gains (kWh/year)	Latent heat gains (kWh/year)
Refrigerator	1.0	0.0	434	434	0	388	388	0
Dishwasher	0.60	0.15	142	85	21	121	73	18
Range	0.40	0.30	453	181	136	418	167	126
Clothes washer	0.80	0.0	70	56	0	70	56	0
Clothes dryer	0.15	0.05	969	145	48	969	145	48
MELs	0.734	0.20	1275	936	255	1275	936	255
Total (kWh/year)				1889	478		1.765	447
Internal heat gain fraction				0.565	0.143		0.545	0.138

Internal heat gains from domestic hot water use in shower, bath, and sink were estimated as shown in Table F.5 and modeled as sensible and latent heat gain fractions of source Btu/h combined with the domestic hot water usage schedule (Fig. F.3) for both pre and post-retrofit cases. The combined internal heat gains were estimated as 3,745 Btu/h with sensible and latent heat gain fractions of 0.594 and 0.406, respectively.

Table F.5. Internal heat gains from domestic hot water use

	Sensible heat gains (Btu/day)	Latent heat gains (Btu/day)	Comments
Shower	1,334	1,267	Sensible: 741 + 247*Number of Bedrooms Latent: 703 + 235* Number of Bedrooms
Bath	334	0	Sensible: 185 + 62* Number of Bedrooms Latent: Negligible
Sink	557	253	Sensible: 310 + 103* Number of Bedrooms Latent: 140 + 47* Number of Bedrooms
Total	2,225	1,520	
Internal heat gain fraction	0.594	0.406	

^a Internal heat gains from dishwasher and clothes washer use are modeled as part of the internal gains from appliances (included in Table G.4).

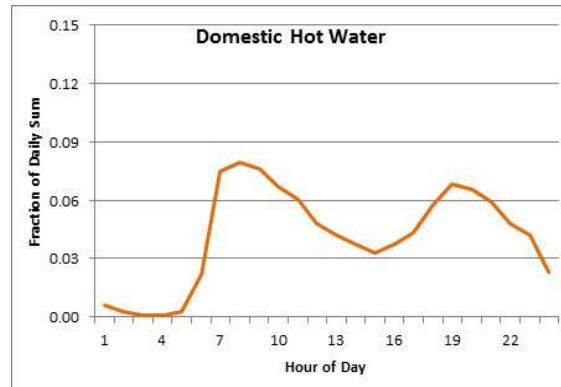


Fig. F.3. Domestic hot water use schedule.

The building was modeled with 2.8 occupants per unit, 220 Btu/h per occupant of sensible heat gains, and 164 Btu/h per occupant of latent heat gains. Internal heat gains from occupants were modeled with the occupancy schedule shown in Fig. F.4.

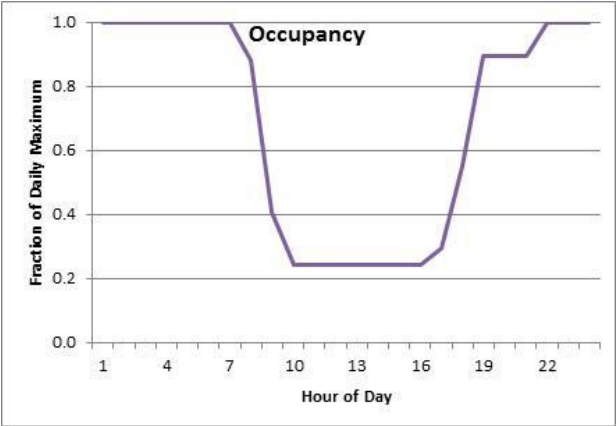


Fig. F.4. Occupancy schedule.

F.4 Estimation of Domestic Hot Water Use

First, the base-case domestic hot water use by end-use was calculated for an average 2.4-bedroom unit, which adds up to 8.3 gal/day of hot water use at 130°F and 54.0 gal/day of hot water use at 110°F (as shown in Table F.6).

Table F.6. Domestic hot water consumption by end-use

Number of bedrooms (N_{br}) = 2.4				
End use	End-use water temperature	Water usage (gal/day)	Base-case water usage (gal/day)	Total ($V_{mixed,N}$) (gal/day)
Clothes washer	130°F	$2.35 + 0.78 * N_{br}$ (Hot Only)	4.2	$V_{hot,130°F} = 8.3$
Dishwasher	130°F	$2.26 + 0.75 * N_{br}$ (Hot Only)	4.1	
Shower	110°F	$14.0 + 4.67 * N_{br}$ (Hot + Cold)	25.2	$V_{mixed,110°F} = 54.0$
Bath	110°F	$3.5 + 1.17 * N_{br}$ (Hot + Cold)	6.3	
Sinks	110°F	$12.5 + 4.16 * N_{br}$ (Hot + Cold)	22.5	

Next, the monthly average water mains temperature was calculated for an average day of each month using the Building America Simulation Protocols to account for the impact of location and time of year (Fig. G.5). Finally, the monthly average daily domestic hot water use at a 130°F supply temperature was calculated for each location to account for the use of cold water at mains temperature to achieve the required mixed temperature for various hot water end uses.

$$V \text{ (gal/day)} = V_{hot,130°F} + V_{mixed,110°F} * (110 \text{ } \delta \text{ } T_{mains}) / (130 \text{ } \delta \text{ } T_{mains})$$

The calculated hot water supply volume is plotted in Fig. F.5, which was used for the analysis of domestic hot water energy use and associated retrofit measures.

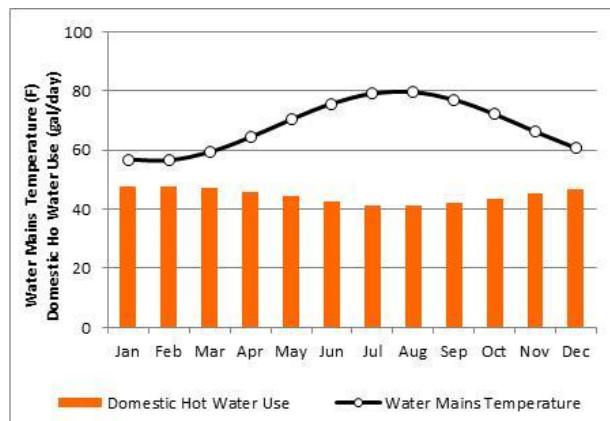


Fig. F.5. Water mains temperature and domestic hot water use.

F.5 Analysis of Domestic Hot Water Energy Use

The characteristics of the existing and replacement water heater are shown in Table F.7.

Table F.7. Water heater characteristics

	Pre-retrofit	Post-retrofit
Energy factor	0.9 (modeled as 0.87 ^a)	0.93
Recovery efficiency	0.98	0.98
Burner capacity (Btu/h)	5.5 kW	5.5 kW
Tank UA (Btu/h.°F)	3.74	1.53

^aThis accounts for 19 year age of equipment and 0.002 maintenance factor.

Analysis of domestic hot water energy use was performed using the WHAM model (Lutz 1998) for the existing and the replacement electric water heater. Table F.8 shows the domestic hot water energy use with the existing and replacement water heater. The analysis used a 130°F supply water temperature, a 74°F ambient temperature, and monthly variation in water mains temperature as shown in Fig. F.5. With these inputs, the replacement electric water heater resulted in a 10% water heating energy savings.

Table F.8. Domestic hot water energy use

Month	T _{mains} (°F)	V _h (gpd)	Pre-retrofit		Post-retrofit	
			kBtu/ day	kWh/mo.	kBtu/ day	kWh/mo.
Jan	56.7	47.5	34.2	3,108	31.4	2,856
Feb	56.5	47.6	34.3	2,816	31.5	2,589
Mar	59.3	47.0	32.9	2,986	30.1	2,734
Apr	64.3	45.8	30.2	2,659	27.4	2,413
May	70.3	44.2	27.1	2,464	24.3	2,208
Jun	75.7	42.4	24.3	2,138	21.5	1,889
Jul	79.0	41.1	22.6	2,050	19.7	1,791
Aug	79.5	40.9	22.3	2,028	19.5	1,769
Sep	77.0	41.9	23.6	2,079	20.8	1,829
Oct	72.1	43.6	26.2	2,380	23.4	2,123
Nov	66.1	45.4	29.3	2,576	26.5	2,330
Dec	60.6	46.7	32.2	2,922	29.4	2,669
Total				30,207		27,199
Energy savings						10.0%

APPENDIX G
ASHRAE STANDARD 62.2 COMPLIANCE CHECK

APPENDIX G. ASHRAE STANDARD 62.2 COMPLIANCE CHECK

Calculations for ventilation requirements using ASHRAE Standard 62.2-2010 (ASHRAE 2010) were performed for an average unit of the building for pre- and post-retrofit cases using the pre- and post-retrofit multi blower door measurements (Table G.1). For the pre-retrofit case, a 25 CFM local exhaust deficit (due to recirculating-type kitchen exhaust fans), minus a 21 CFM infiltration credit (due to 1206 CMF@50 PA) resulted in a 41 CFM mechanical ventilation requirement. For the post-retrofit case, a 25 CFM local exhaust deficit due to the recirculating-type kitchen exhaust fan, minus the 13 CFM infiltration credit ([due to 898 CMF@50 PA] after air sealing the building) resulted in a 49 CFM mechanical ventilation requirement.

Table G.1. Minimum mechanical ventilation requirement in a unit

Inputs	Pre-retrofit	Post-retrofit	Comments
State-City	GA-Atlanta	GA-Atlanta	
Apartment floor area	1132.8 ft ²	1132.8 ft ²	Average
Average floor height	8 ft	8 ft	
Height of the building	24 ft	24 ft	
Number of occupants	2.8	2.8	Assumed
Number of bedrooms	2.4	2.4	Average
Number of bathrooms	2	2	
Bathroom 1: Exhaust fan	50 CFM	50 CFM	Vented to outside; Assumed fan flow
Bathroom 2: Exhaust fan	50 CFM	50 CFM	Vented to outside; Assumed fan flow
Kitchen Exhaust fan	0	0	Not vented to outside
Measured infiltration rate	1,206 CFM@50Pa	898 CFM@50	Average
Intermediate calculations			
Leakage area (ASTM 779)	0.46 ft ²	0.34 ft ²	0.055×144
Normalized leakage	0.57	0.42	$1000 \times \frac{0.055 \times 144}{0.055 \times 144} \times \frac{0.055 \times 144}{8}$
Weather factor	0.75	0.75	From ASHRAE 136-1993 (RA 2006)
Air change rate from infiltration	0.42 ACH	0.32 ACH	$0.055 \times 144 \times 0.055 \times 144$
Infiltration flow rate	64 CFM	48 CFM	$0.055 \times 144 \times 0.055 \times 144 \times 60$
Default infiltration credit	23 CFM	23 CFM	$0.02 \times 0.055 \times 144$
Excess infiltration	41 CFM	25 CFM	$0.055 \times 144 \times 0.055 \times 144 - 0.02 \times 0.055 \times 144$
Results			
Ventilation air requirement	37 CFM	37 CFM	$0.01 \times 0.055 \times 144 + 7.5 \times 0.055 \times 144 \times 0.055 \times 144 + 1$
Deficit for higher occupant density	0	0	$7.5 \times 0.055 \times 144 \times 0.055 \times 144 - 0.055 \times 144 \times 0.055 \times 144 + 1$
Local exhaust deficit	25 CFM	25 CFM	$0.25 \times 0.055 \times 144 - 0.055 \times 144 + 0.055 \times 144$
Infiltration credit	21 CFM	13 CFM	$-0.5 \times 0.055 \times 144$
Mechanical ventilation requirement	41 CFM	49 CFM	$0.055 \times 144 \times 0.055 \times 144 - 0.055 \times 144 \times 0.055 \times 144 + 0.055 \times 144 \times 0.055 \times 144 - 0.055 \times 144 \times 0.055 \times 144$

APPENDIX H
ENERGY EFFICIENCY MEASURE DESCRIPTION AND COST DATA

APPENDIX H: ENERGY EFFICIENCY MEASURES DESCRIPTION AND COST DATA

Energy efficiency measures	Measure description		Measure cost for Building #7
	Pre-retrofit characteristics	Post-retrofit characteristics	
1 Insulate crawlspace ceiling	No insulation	R-19 fiberglass batt insulation	\$300 (installed cost)
2 Add attic insulation	R-30 blown-in fiberglass insulation	R-38 blown-in fiberglass insulation	\$1,205 (installed cost)
3 Window and door replacement	Single pane, aluminum frame windows, solid wood core doors	Low-e, double pane, vinyl frame windows, insulated core metal doors	\$5,850 (installed cost)
4 HVAC system replacement	12 SEER, 7.5 HSPF heat pump	14.5 SEER, 8.3/8.5 HSPF heat pump	\$5,871 (installed cost)
5 Lighting replacement	60 W incandescent lamps	16 W compact fluorescent lamps	\$7,851 (installed cost)
6 Kitchen appliance replacement	Standard efficiency cooking range/oven, refrigerator and dishwasher	cooking range/oven with high-speed coil elements, Energy Star qualified refrigerator and dishwasher	\$10,544 (installed cost)
7 Domestic water heater replacement	0.9 EF electric water heater	0.93 EF electric water heater	\$3,012 (installed cost)
8 Air seal building envelope		Air leakage reduced by 25%	\$4,758 (\$0.42 per ft ² of floor area ^a)
9 Air seal crawlspace and install rigid insulation on crawlspace walls	Vented crawlspace with 3 ACH infiltration rate, no insulation	Unvented crawlspace with 0.5 ACH infiltration rate, R-5 XPS insulation on crawlspace walls	\$3,809 (\$1.3 per ft ² of crawlspace wall area for installing insulation, \$0.72 per ft ² of crawlspace floor area for air sealing ^a)
10 Air seal crawlspace and install batt insulation on crawlspace walls	Vented crawlspace with 3 ACH infiltration rate, no insulation	Unvented crawlspace with 0.5 ACH infiltration rate, R-19 fiberglass batt insulation on crawlspace walls	\$3,134 (\$0.86 per ft ² of crawlspace wall area for installing insulation, \$0.72 per ft ² of crawlspace floor area for air sealing ^a)
11 Install rigid insulation on exterior walls	No exterior insulation	R-5 XPS insulation	\$3,371 (\$0.98 per ft ² of wall area for adding insulation when replacing siding ^b)
12 Install window film	-	Reduced effective window SHGC to 0.6	\$1,106 (\$2.25 per ft ² of window area ^b)
13 Install storm windows	-	Reduced effective window U-value and SHGC	\$3,080 (\$70 per window ^b)
14 Install programmable thermostat	No night setback and afternoon setup	Night setback to 68°F and afternoon setup to 78°F for 6 hours	\$1,700 (\$170 per unit ^a)

^aSource: National Energy Efficiency Measures Database (NREL 2012).

^bSource: PNNL database

APPENDIX I
REM/RATE™ RESULTS FOR ENERGY ANALYSIS OF SAMPLE UNITS

APPENDIX I. REM/RATE™ RESULTS FOR ENERGY ANALYSIS OF SAMPLE UNITS

Unit #	Type	Pre-retrofit					HERS Index	Post-retrofit					HERS index	Difference (%)
		Energy Use (MBtu/h)						Energy Use (MBtu/h)						
		Heating	Cooling	Water heating	Lighting and appliances	Total		Heating	Cooling	Water heating	Lighting and appliances	Total		
Terrace floor														
310	B	11.8	5.5	14.4	20.9	52.6	106	7.9	3.1	11.8	12.9	35.7	87	32.1%
410	B	11.8	5.6	14.4	20.9	52.7	107	7.6	3.1	13.6	16.9	41.2	87	21.8%
510	B	10.2	5.3	14.4	20.9	50.8	105	7.5	3.1	13.6	16.9	41.1	87	19.1%
609	B	10.9	5.4	14.4	20.9	51.6	105	8.1	3.2	13.6	16.9	41.8	87	19.0%
709	A	11.6	4.7	12.5	18.7	47.5	106	8.8	3	11.7	15.2	38.7	89	18.5%
910	A	11.2	4.7	12.5	18.7	47.1	107	8.3	2.9	11.7	15.2	38.1	88	19.1%
1009	A	11.4	4.7	12.5	18.7	47.3	107	8.4	3	11.7	15.2	38.3	89	19.0%
1109	A	11.4	4.8	12.5	18.7	47.4	107	8.6	3.1	11.7	15.2	38.6	89	18.6%
Second floor														
302	C	10.4	5.8	14.4	21.4	52	109	8.4	3.3	13.6	16.9	42.2	87	18.8%
402	C	10.3	5.5	14.4	21.4	51.6	107	7.6	3.3	13.6	16.9	41.4	85	19.8%
504	C	9.7	5.5	14.4	21.4	51	106	8.4	3.9	13.6	16.9	42.8	90	16.1%
604	C	9.7	5.5	14.4	21.4	51	107	7.4	3.3	13.6	16.9	41.2	88	19.2%
1004	C	10.3	5.6	14.4	21.4	51.7	108	7.3	3.3	13.6	17	41.2	85	20.3%
1102	C	9.4	5.4	14.4	21.4	50.6	105	7.4	3.3	13.6	16.9	41.2	88	18.6%
Third floor														
308	B	7.7	5.9	14.4	20.9	48.9	105	5.6	4	13.6	19.9	43.1	85	11.9%
408	B	7.9	6	14.4	20.9	49.2	106	5.9	3.6	13.6	16.9	40	85	18.7%
607	B	7.9	6	14.4	20.9	49.2	106	6.9	3.4	11.7	15.6	37.6	85	23.6%
706	A	8.2	5.2	12.5	18.8	44.7	107	6.8	3.4	11.7	15.2	37.1	87	17.0%
708	C	7.4	5.9	14.4	20.6	48.3	103	6.1	3.6	13.6	16.9	40.2	83	16.8%
1007	A	8.7	5.3	14.4	20.1	48.5	109	6.6	3.4	11.7	15.2	36.9	86	23.9%
1107	A	8.6	6.3	14.4	20.1	49.4	111	5.9	3.6	13.6	16.9	40	87	19.0%
Average		9.8	5.5	13.9	20.4	49.7	106.6	7.4	3.3	12.9	16.3	39.9	86.9	19.6%

