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A Method for Determining Optimal Residential Energy Efficiency Retrofit Packages

B. Polly, M. Gestwick, M. Bianchi, R. Anderson,
S. Horowitz, C. Christensen, and R. Judkoff
National Renewable Energy Laboratory

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1617 Cole Boulevard

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Definitions

AC	air conditioner
ACCA	Air Conditioning Contractors of America
ACH	air changes per hour
ACH50	air changes per hour at a pressure difference of 50 Pa
AEU	average energy use
AES	average energy savings
AFUE	annual fuel utilization efficiency
AHU	air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BSC	Building Science Corporation
BTP	U.S. Department of Energy Building Technologies Program
CEC	California Energy Commission
CEE	Consortium for Energy Efficiency
cfm	cubic feet per minute
CFL	compact fluorescent lamp
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EAC	equivalent annual cost
ECM	energy conservation measure
EEM	energy efficient mortgage
EER	energy efficiency ratio
EERE	U.S. Department of Energy, Energy Efficiency and Renewable Energy
EF	energy factor
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
gpm	gallons per minute
GSL	general service lamp
HVAC	heating, ventilating, and air conditioning
IEAC	incremental equivalent annual cost
IECC	International Energy Conservation Code
LBL or LBNL	Lawrence Berkeley National Laboratory
LFL	linear fluorescent lamp
MEF	modified energy factor
MURS	minimum upgrade reference scenario
nACH	natural air changes per hour
NAECA	National Appliance Energy Conservation Act

NIST	National Institute of Science and Technology
NL	normalized leakage
NREL	National Renewable Energy Laboratory
O.C.	on centers
ORNL	Oak Ridge National Laboratory
polyiso	polyisocyanurate
PW	present worth
R-value	thermal resistance, h·ft²·F/Btu [m^2·K/W]
RECS	Residential Energy Consumption Survey
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SLA	specific leakage area
TM3	Typical Meteorological Year 3
U-factor or U-value	thermal conductance, Btu/ h·ft²·F [W/ m^2·K]
WF	water factor
XPS	extruded polystyrene

Nomenclature

α	residual value
COST	cost of building component
d_n	nominal discount rate
d_r	real discount rate
i	inflation rate (fractional)
L	lifetime, years
N	number of years in analysis period
R	remaining lifetime, years
TC	total cost

Executive Summary

Introduction

Businesses, government agencies, consumers, policy makers, and utilities currently have limited access to occupant-, building-, and location-specific recommendations for optimal energy retrofit packages, as defined by estimated costs and energy savings. This report describes an analysis method for determining optimal residential energy efficiency retrofit packages and, as an illustrative example, applies the analysis method to a 1960s-era home in eight U.S. cities covering a range of International Energy Conservation Code (IECC) climate regions.

Background

Since 2003, the U.S. Department of Energy (DOE) has used BEopt, a building energy optimization software tool, to determine cost-effective, energy efficient building designs for new construction. BEopt evaluates the incremental energy and cost effects of different building designs relative to a reference building (e.g., a building that complies with IECC) and provides a "least-cost" curve that allows users to determine minimum-cost building designs at various levels of energy savings and under various sets of economic assumptions. In 2008, DOE's National Renewable Energy Laboratory (NREL) began research efforts to extend BEopt analysis capabilities to existing homes.

Preliminary efforts at NREL using BEopt for research regarding energy efficiency retrofit projects identified several analysis issues specific to existing homes. The issues generally fall in three categories:

- Measures
- Retrofit and replacement timing
- Economics.

To address the analysis issues in these three areas, NREL researchers modified BEopt to model home energy retrofits. Researchers added many new features to BEopt, and this report presents an analysis method that uses some of those features.[1]

Analysis Method

The heart of the analysis method is determining the annual energy use over the analysis period. Annual energy uses are calculated by performing annual building energy simulations, the results of which depend on the climate, building characteristics, and occupant behavior. Figure ES-1 shows an example of annual energy uses over a 30-year analysis period. In this example, not all existing equipment below the minimum standard is replaced during the retrofit, so the annual energy use changes over the analysis period when that equipment wears out and is replaced with more efficient equipment, as defined by the minimum standard.

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[1] Although the analysis method was implemented in BEopt, it is described in general terms (independent of a particular software program).

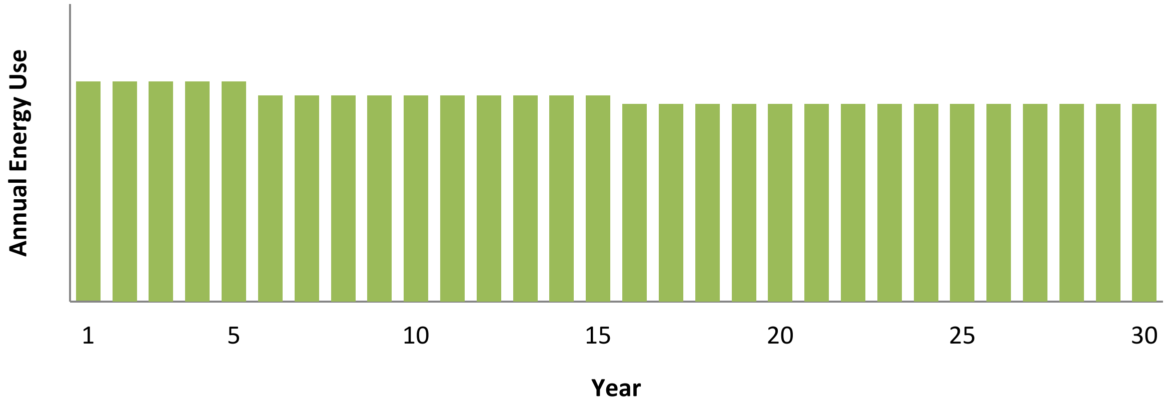

Figure ES-1. Example annual energy use diagram

In addition to annual energy uses, cash flows determine optimal retrofit packages. Cash flows consist of:

- Loan payments to cover initial retrofit package costs
- Replacement costs in the future
- Annual utility bill costs
- Residual values at the end of the analysis period.

Costs, excluding loan payments, are inflated based on the time they are incurred. Figure ES-2 shows an example cash flow[2] in nominal dollars (including the effect of inflation). For this example, a retrofit at the beginning of the 30-year analysis period is financed by a 5-year loan. Equipment is replaced throughout the analysis period as it wears out.

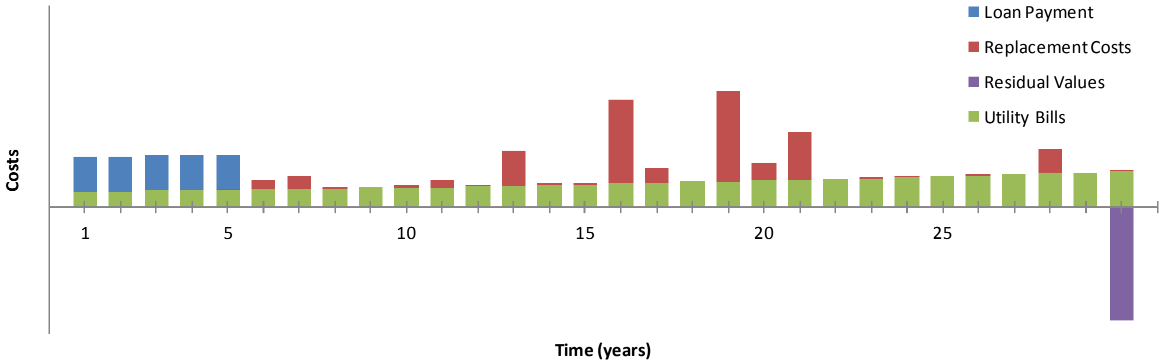

Figure ES-2. Example cash flow diagram

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[2] Cash flow diagrams presented in this report assume the following sign convention: expenses are positive and receipts are negative.

The analysis method computes two primary metrics for each retrofit scenario: average energy use (AEU) and equivalent annual cost (EAC). AEU is the average of the annual energy uses over the analysis period (e.g., Figure ES-1), and EAC is the annualized cash flows (e.g., Figure ES-2).

The EAC and AEU of a retrofit scenario can be compared to an alternative scenario to determine the additional cost incurred to achieve a given level of energy savings. This naturally leads to the definition of a reference scenario, the baseline against which energy upgrade scenarios are compared in terms of cost and energy use. This analysis method uses a minimum upgrade reference scenario (MURS) as the baseline. The MURS begins with the existing building at the start of the analysis period and assumes all equipment that wears out over the analysis period is replaced with the same level of efficiency or the current minimum standard, whichever is more efficient. Minimum upgrades are assumed for the reference building so as not to take credit for energy efficiency improvements that would have otherwise occurred through natural wear-out and replacement.

A sequential search technique determines optimal retrofit packages for different levels of energy savings by calculating the AEU and EAC relative to the MURS for each retrofit scenario investigated. These incremental calculations are the average energy savings (AES) and the incremental equivalent annual cost (IEAC). The optimization results in a least-cost curve, from which the most cost-effective retrofit packages can be identified at various levels of energy savings.

Example Analysis

Researchers implemented the analysis method in BEopt and used it to conduct a retrofit example analysis on a 1,280 ft^2, 1960s-era house in eight U.S. cities with climate-appropriate foundation types. Although they applied realistic pre-retrofit conditions and retrofit measures in the example analysis, the inputs and results are not intended to be representative of the U.S. housing stock as a whole. Instead, this example analysis demonstrates how the method can be used to generate recommendations for individual retrofit measures and packages of measures specific to a building, its occupants, and its location.

Table ES-1 gives the key assumptions for financial parameters in the example analysis.

Table ES-1. Assumed Values for Key Financial Parameters

Financial Parameter	Value
Analysis Period (years)	30
Inflation Rate (%)	3
Real Discount Rate (%)	3
Real Fuel Escalation Rate (%)	0
Annual Effective Loan Interest Rate (%)	7
Loan Period (years)	5

The list that follows contains the types of retrofit measures considered in the example analysis. This set of measures is used to illustrate the analysis method—it does not represent all possible measures that could be implemented in residential buildings:

- Air seal and insulate attic floor
- Close, condition, and insulate crawl space
- Insulate walls (drill-and-fill)
- Insulate basement walls
- Replace the following:
  - AC
  - Clothes washer
  - Furnace
  - Lamps
  - Refrigerator
  - Water heater
  - Windows
- Seal ducts
- Seal and insulate ducts.
- Whole house air seal

Table ES-2 shows the AES and IEAC for minimum-cost packages and for packages on the least-cost curve that are closest to neutral cost.[3] The AES values for the minimum-cost packages range from 18% (San Diego) to 34% (Seattle), and the IEAC values range from –$388 (Washington, DC) to –$55 (San Diego). Averaged over the eight cities in this analysis, the minimum-cost package achieves 30% AES at an IEAC of –$289. The AES values for the nearest to neutral cost packages[4] range from 29% (San Diego) to 48% (Seattle and Minneapolis).

Table ES-2. Minimum-Cost and Nearest to Neutral Cost Packages on Least-Cost Curve

Location	Minimum Cost		Nearest to Neutral Cost	
	AES (%)	**IEAC** (2010$)	**AES** (%)	**IEAC** (2010$)
Houston, Texas	30	–185	38	8
Phoenix, Arizona	33	–361	47	–31
Atlanta, Georgia	30	–293	41	–56
San Diego, California	18	–55	29	14
Seattle, Washington	34	–309	48	–39
Washington, D.C.	30	–388	43	–114
Chicago, Illinois	31	–351	47	–86
Minneapolis, Minnesota	32	–366	48	–121

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[3] Note the least-cost curve is defined by a set of discrete retrofit packages. There is no guarantee that any of the discrete packages delivers an IEAC of exactly $0.

[4] Targeting the nearest to neutral cost point may be an opportunity to realize significant savings when considered before any retrofit. Once a retrofit package is implemented to the minimum cost point, there can be a significant cost barrier to get to larger energy savings.

Conclusions

The method for analyzing the retrofit of existing houses described in this report uses an optimization scheme that considers AEU (determined from building energy simulations) and EAC to recommend optimal retrofit packages specific to the building, occupants, and location. Energy savings and incremental costs are calculated relative to a MURS, which accounts for efficiency upgrades that would occur in the absence of a retrofit because of equipment wear-out and replacement with current minimum standards.

The method was applied, as an illustrative example, to analyze the retrofit of a 1960s-era house in the eight U.S. locations. The following were the main conclusions of the example analysis:

- Results were specific to assumptions in the following categories: general (e.g., analysis period, MURS), financial (retrofit financing and measure costs), occupant, and building. Results should not be interpreted as “average” for U.S. housing stock.
- For the 1,280 ft^2, 1960s-era home and the specific set of retrofit measures considered in the analysis, minimum-cost packages varied in average energy savings from 18% in San Diego to 34% in Seattle.
- The nearest to neutral cost package gave significant additional savings beyond the minimum-cost package.
- Issues such as complexity of the retrofit package, on-site conditions, effect on occupant comfort, and so on were not considered, but they could justify certain measures that were not included in optimal packages as well as eliminate measures that were.

Future Work

Together, the analysis method and example analysis presented in this report are an introduction to retrofit optimization; improvements to the analysis method and additional studies considering a comprehensive range of building types, locations, and retrofit measures would further knowledge of retrofit optimization.

Some possible improvements to the analysis method include the following:

- Forecasting minimum standards for the MURS
- Modeling equipment performance degradation over the analysis period
- Modeling financing of future replacements
- Modeling heating, ventilating, and air-conditioning (HVAC) equipment down-sizing
- Modeling retrofit effect on occupant behavior
- Optimizing in the future to determine effect of improvements made over time
- Using EIA fuel price projections.

Some possible improvements to future analyses are as follows:

- Adjusting retrofit costs city by city, similar to energy costs.

- Adding more house types (e.g., two-story houses). Ideally, the house types analyzed should be representative of the locations considered, including assumptions related to fuel types.
- Adding retrofit measures, including those for safety and health of the occupants (e.g., combustion air for atmospherically vented appliances).
- Investigating different metrics, financial mechanisms, and loan terms to cover a wider range of possibilities and perspectives.
- Comparing energy use and savings predictions to measured use and savings from laboratory tests, field tests, and pre- or post-retrofit utility bill analysis.

1.0 Introduction

The approximately 130 million homes in the residential sector account for 22% of the energy consumed in the United States (EIA 2009). Cost-effective improvements in the energy efficiency of the U.S. residential building stock would save energy, lower utility bill costs for homeowners, and create jobs. Businesses, government agencies, consumers, policy makers, and utilities currently have limited access to occupant-, building- and location-specific recommendations for optimal energy retrofit packages, as defined by estimated costs and energy savings. This report describes an analysis method for determining optimal residential energy efficiency retrofit packages and, as an illustrative example, applies the analysis method to a 1960s-era home in eight U.S. cities covering a range of International Energy Conservation Code (IECC) climate regions. The example analysis is an introduction to retrofit optimization; more comprehensive future analyses will consider a wider range building types, retrofit measures, and locations.

Section 2 is a background discussion on previous analysis efforts. Section 3 discusses key analysis issues for existing homes and contrasts them with those for new homes. Section 4 describes an analysis method for determining optimal retrofit packages in existing homes. Sections 4.1–4.4 describe approaches for modeling energy use, modeling cash flows, calculating key metrics, and performing optimizations, respectively. Section 5 presents the example analysis. Section 6 presents conclusions regarding the analysis method and example analysis, along with descriptions of possible future work. Appendix A defines the retrofit options for the example analysis; their associated costs come from the National Residential Efficiency Measures Database, version 1.0.0beta (NREL 2010).[5] Estimated energy and cost savings are presented for each retrofit measure. Least-cost packages of measures at various levels of energy savings in the different climates are presented based on optimization results. Appendix B discusses sensitivity of output to financial and performance assumptions.

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[5] Except for the refrigerator and clothes washer costs, which were estimated based on the Preliminary Analytical Tools under http://www1.eere.energy.gov/buildings/appliance_standards/residential_products.html, accessed between June and August 2010.

2.0 Background

Lack of information has long been cited as one reason why consumers do not invest in energy conservation measures (ECMs), and the Vice President's Middle Class Task Force, Council of Environmental Quality, recently recognized it as one of the three main barriers to establishing a self-sustaining retrofit market (MCTF 2009): "Consumers do not have access to straightforward and reliable information on home energy retrofits that they need to make informed decisions." This is true despite decades of work by researchers, engineers, and policy makers evaluating the retrofit potential at both local and national scales.

This document describes and applies emerging analysis capabilities developed at the National Renewable Energy Laboratory (NREL) on behalf of the U.S. Department of Energy (DOE) that will ultimately improve access to information needed to make informed decisions in a sustainable retrofit market. Key outcomes of the ongoing research are:

- Improvement of analysis methods and tools for existing homes
- Identification of cost-effective, safe, and durable retrofit measures and packages of measures
- Better understanding of gaps that must be filled to achieve higher energy savings levels.

Since 2003, DOE has used BEopt, a building energy optimization software tool, to determine cost-effective, energy efficient building designs for new construction (Christensen et al. 2006). BEopt evaluates the incremental energy and cost effects of different building designs relative to a reference building (e.g., a building that complies with IECC) and provides a "least-cost" curve that allows users to determine minimum-cost building designs at various levels of energy savings and under various sets of economic assumptions. In 2008, NREL began research efforts to extend BEopt analysis capabilities to existing homes, making the fundamental changes required to perform simulations and optimizations in the context of home energy retrofit.

The method developed for existing homes expands on previous retrofit analysis efforts. Many studies in the past focused on low-income weatherization (e.g., Schweitzer and Eisenberg 2002) and utility demand-side management programs (e.g., Fels and Keating 1993). These studies prescribed the retrofit measures and did not include optimization. Oak Ridge National Laboratory (ORNL) performed a study in the late 1980s to select optimal combinations of enclosure and heating equipment retrofits as part of an expanded weatherization program (McCold 1987). The ORNL study used a life-cycle cost-benefit metric evaluated over a range of retrofit packages for the life of the measures to determine the most cost-effective weatherization upgrade. The ORNL study also considered the energy interactions when changing multiple components of a house.

Other studies evaluated broader retrofit potential at the national (e.g., Guler et al. 2001, Koomey et al. 1991) or state levels (e.g., Pigg and Nevius 2000) by extrapolating across a housing stock using survey data. Savings prediction methods included engineering analyses and statistical evaluations using previous programmatic results. Engineering analysis techniques can be focused, looking at savings on the component level, or highly integrated, using simulation tools and looking at the complex interactions that occur in buildings of all types. Often these studies used simple economic metrics to evaluate cost-effectiveness. Simple payback (cost of measure divided by cost savings per year), used by Pigg and Nevius (2000), or the energy savings per dollar invested, used by Guler et al. (2001), are easy for the general population to understand and are sometimes desirable when taking a short-term view, such as evaluating individual ECMs. Simple metrics, however, can obscure important time-value-of-money issues and impose a short-term view of the retrofit, thereby excluding costlier, deep retrofit packages with positive long-term cash flow projections.

A comprehensive analysis recognizes that homeowners may have other investment options and limited access to capital. Investments in their home, where utility bill savings are a primary driver, should provide returns at a rate similar to other opportunities. Deep energy retrofits, where a house receives a large overhaul to dramatically reduce energy consumption, commonly require longer term financing to cover the cost of the project. This adds significant complexity to evaluating retrofit cost-effectiveness, because financing mechanisms such as home equity loans and energy efficient mortgages naturally lead to a longer term time horizon for the financial decision. In addition, homeowners have several retrofit options (e.g., “Should I replace my inefficient furnace, add more insulation in the attic, install new windows?”). The analysis method presented here was developed with these considerations in mind.

3.0 Key Analysis Issues

BEopt has identified least-cost paths, technology gaps, and research needs for new homes (Anderson and Roberts 2008). Preliminary efforts at NREL using BEopt for similar research regarding ECM retrofit projects identified several analysis issues specific to existing homes. The following list describes key analysis issues for existing homes related to measures, retrofit and replacement timing, and economics, and contrasts them with issues for new home construction.

- Measures
    - *Design versus Retrofit*—A new home is an abstract entity until it is built. Changes can be made easily during the design stage, when there are few constraints caused by existing conditions. This is not true of existing homes. For example, in new homes it is easy to add foam insulation to the exterior of the wall during construction to reduce enclosure loads. For existing homes, however, the presence of existing exterior finish (e.g., wood siding or brick) can make adding exterior foam insulation challenging.
    - *Costs*—Adding or replacing a component in an existing home can have different labor and material costs than in a new home. For example, adding foam sheathing to exterior wall may require removing old siding and adding new siding, which dramatically increases the labor and material costs compared to the same level of insulation in new construction.
    - *Equipment Sizing*—For new homes, the heating, ventilating, and air-conditioning (HVAC) systems can be right-sized based on the design of the building, so there is often an HVAC down-sizing cost benefit to reducing the loads of the building. For existing homes, however, down-sizing cost benefits can only be achieved when the HVAC system is replaced (which may not coincide with the retrofit measures that reduce the load).
- Retrofit and replacement timing
    - *Equipment Remaining Life*—In new construction, all equipment and components begin their working lives at the same time—when the house is built. In an existing home, each piece of equipment may be at a different point in its lifetime at the time of retrofit. Therefore, the cost-effectiveness of upgrading the equipment at the time of retrofit must be compared to the cost-effectiveness of waiting until wear-out to replace or upgrade the equipment.
    - *Minimum Standard Equipment*—In new construction, equipment meets or exceeds the minimum federal standards when the house it built. In an existing house, some of the equipment may be below the current minimum federal standards[6] at the time of retrofit. Only equipment at least meeting current minimum standards is evaluated as replacement options.[7] The requirement to upgrade to minimally compliant equipment (e.g., seasonal energy efficiency ratio

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[6] From this point forward, minimum federal standards are referred to as "minimum standards," "minimum equipment," or "minimum upgrades."

[7] Assuming only new equipment is available (no used equipment).

    [SEER]13 air conditioner [AC]) at wear-out affects the cost-effectiveness of other retrofit measures (e.g., wall insulation).

    - *Reference Building*—The baseline or reference building for new homes is a predefined, hypothetical construction (e.g., IECC 2009). This is a necessary point of comparison because no as-built frame of reference exists. In retrofit analysis, the existing house is often the baseline. This may not be appropriate when evaluating the building over a longer term, however—natural upgrades occur as old equipment fails and is replaced with higher efficiency units required by minimum standards. If the existing house is the baseline in these cases, energy savings can be attributed to the retrofit that would have otherwise occurred through equipment wear-out and replacement according to minimum standards.

- Economics
    - *Financing*—In BEopt's new construction analysis, the cost of energy measures is included in the mortgage and the interest portion of the mortgage payment is tax deductible. For existing homes, retrofit costs are typically financed over a shorter period[8] via cash payments or a home equity loan.
    - *Metrics*—For new construction, measures are implemented at the time of construction. Cost-effectiveness can therefore be calculated using the first-year incremental mortgage and utility bill costs along with the first-year energy savings as a surrogate for life-cycle analysis. For existing homes, measures can be implemented in different years, causing cash flows and energy savings to change over time. The time-dependent nature of the energy costs and savings requires life-cycle-based metrics.

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[8] Alternatively, one could consider using longer-term financial products like the energy efficient mortgage (EEM). More information can be found at http://www.energystar.gov/index.cfm?c=mortgages.energy_efficient_mortgages.

4.0 Retrofit Analysis Method

To address the analysis issues identified in Section 3, NREL modified BEopt to model retrofits of existing homes. This involved adding many new features to BEopt, and this section describes an analysis method that uses some of those features—modeling energy use in Section 4.1, modeling cash flows in Section 4.2, key metrics in Section 4.3, and an optimization approach in Section 4.4.

4.1 Modeling Energy Use

The heart of the analysis method is determining of the annual energy use over the analysis period. Annual energy uses are calculated by performing annual building energy simulations, the results of which depend on the climate, building characteristics, and occupant behavior. The climate is assumed to be the same from year to year over the analysis period. The modeled occupant behavior follows the recommendations of the Building America House Simulation Protocol (NREL 2010), where occupant behavior is the same from year to year, except for lighting.[9] Thus, the changes in energy use are primarily caused by changes in building characteristics.

4.1.1 Enclosure Assumptions

Similar to the analysis approach used in BEopt for new home construction, the analysis method considers all enclosure efficiency improvements only at the time of the initial retrofit. In other words, this analysis method does not evaluate enclosure improvements performed in the future. The analysis focuses on the effects of measures implemented at the beginning of the analysis period as opposed to those implemented later. Enclosure improvements at the beginning of the analysis period affect the energy use of the building over the entire analysis period.

This analysis approach evaluates multiple enclosure improvements. Performance characteristics for the existing enclosure and all enclosure improvements must be defined to generate the annual building energy simulations. In some cases, retrofit options can be linked to other options. For example, air-sealing measures can be linked with mechanical ventilation measures to address indoor air quality/durability/combustion safety issues.

4.1.2 Equipment Assumptions

Equipment replacement is one of the reasons the analysis approaches used for new construction cannot be used directly for retrofit analysis. The equipment in existing homes may be below the current minimum standard, and may have remaining useful life. For this analysis method, when equipment wears out in the future, it is replaced with either the same level of efficiency or the minimum standard efficiency, whichever is more efficient. In other words, this analysis method does not evaluate equipment efficiency upgrades in the future beyond those required by minimum standards. Similar to enclosure measures, the analysis concentrates on the effect of retrofit packages implemented at the beginning of analysis period as opposed to retrofit packages implemented later. Even though future upgrades beyond the minimum standard are not evaluated, the annual energy use can change over time as equipment below the minimum standard wears out and is replaced with the current minimum standard.

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[9] Ten percent of the energy savings from compact fluorescent lamps (CFLs) is taken back by assuming longer hours of operation.

Multiple types of equipment can be evaluated with various levels of efficiency considered for each equipment type. Performance inputs for the existing equipment and any possible replacements must be defined. In the present analysis method, equipment efficiency is assumed to be constant over the life of the equipment. Section 6.1 identifies modeling degradation of equipment and enclosure technology as an area of future work.

HVAC equipment sizing is relevant in this analysis approach—it requires information about the existing HVAC equipment size and whether equipment installed at the time of retrofit and at wear-out is properly sized. For this analysis method, simulations determine the HVAC equipment size and all replacement equipment is the same size as the existing equipment. These are simplifications. In the field, various approaches are used for equipment sizing, from rules of thumb (e.g. tons/square foot) to detailed calculations (such as the Air Conditioning Contractors of America (ACCA) Manual J [ACCA 2006]). A particular home may have over- or undersized HVAC equipment (over-sizing is more common) before or after a retrofit. Additionally, when HVAC equipment is replaced at the same time or after other improvements to the enclosure, reduced heating and cooling loads may allow for equipment downsizing, which can save energy and reduce the replacement cost. More research will help determine how consistently and properly HVAC equipment is resized on replacement.

4.1.3 Determining Annual Energy Uses

Based on the enclosure and equipment analysis approaches described, annual building energy simulations determine the annual energy uses over the analysis period. Figure 4-1shows an example of the annual energy uses over a 30-year analysis period. In this example, not all existing equipment below the minimum standard is replaced during the retrofit, so the annual energy use changes over the analysis period when that equipment wears out and is replaced with more efficient equipment, as defined by the minimum standard (replacements decrease the annual energy use at years 5 and 15 in this example).

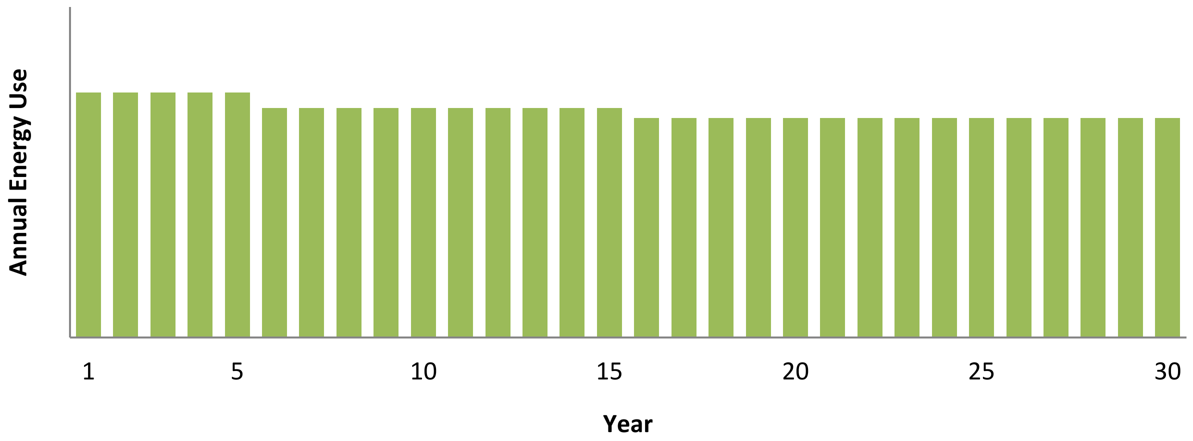

Figure 4-1. Example annual energy use diagram

4.2 Modeling Cash Flows

In addition to annual energy uses, cash flows determine optimal retrofit packages. Cash flows consist of loan payments to cover initial retrofit package costs, replacement costs in the future, annual utility bill costs, and residual values at the end of the analysis period. Costs, excluding loan payments, are inflated based on the time they occur[10] in the analysis period using

$$COST_{year=k} = COST_{initial}(1+i)^k, \qquad (4\text{-}1)$$

where i is the inflation rate, $COST_{initial}$ is the cost at the beginning of the analysis period, and $COST_{year=k}$ is the cost at the end of year k. Under this approach, the inflation rate is assumed to be the same every year.

4.2.1 Loan Costs

Energy efficiency upgrades for new homes are typically bundled into the mortgage, because improvements are made at the time of construction. For retrofits of existing homes, homeowners commonly use shorter-term financing such as home equity loans and, in some cases, pay for energy efficiency retrofits using cash. In this analysis method, the terms of the financing are flexible. Any loan period less than or equal to the analysis period can be considered. The loan finances all measures made at the time of retrofit (time = 0), assuming all other replacements in the future are paid for in cash. The yearly loan payments for principal and interest depend on the assumed annual effective interest rate and loan period.

The cost of the retrofit package represents the sum of the labor and material costs of the retrofit. Costs for the retrofit depend greatly on the existing conditions of the home, especially if problems exist related to moisture, mold, indoor air quality, insects, asbestos, fire hazards, the building structure, and so on. No single set of costs applies to all possible retrofit measures for all types of existing homes. Judgment should be made as to the existing conditions of the home and the specific material and labor requirements for each retrofit measure.

4.2.2 Replacement Costs

As described in Section 4.1, enclosure components are not replaced beyond the beginning of the analysis period, while all equipment is replaced with minimum standard efficiency equipment or the same equipment, whichever is more efficient. Equipment replacement costs are included in the cash flow analysis and are adjusted based on the assumed inflation between the beginning of the analysis period and the time of replacement.

4.2.3 Utility Bill Costs

Utility bill costs are estimated from the annual energy uses, assuming energy rates (dollars/therm, dollars/kilowatt-hour) inflate with time according to Equation 4-1.

4.2.4 Residual Values

All components that wear out during the analysis period are assumed to have no residual value (e.g., salvage value, resell value, or scrap value). The fact that multiple technologies are modeled with different useful lives, however, inevitably leads to components with remaining life at the end of the analysis period. As recommended in NIST Handbook 135: Life-Cycle Cost Manual

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[10] An end-of-year convention is used: all costs incurred during a specific year are modeled as incurring at the end of that specific year.

for the Federal Energy Management Program (Fuller and Petersen, 1995), the "value in place" of a component with remaining life at the end of the analysis period is calculated by linearly prorating its initial cost (α):

$$\alpha = COST_{End}\frac{R}{L}, \tag{4-2}$$

where $COST_{End}$ is the inflated cost at the end of the analysis period, R is the component remaining life (years), and L is the component lifetime (years). The residual value for each component with remaining life at the end of the analysis period is included as a receipt in the cash flow at the end of the analysis period. These receipts represent the value added to the building when components are expected to function beyond the end of the analysis period. Accounting for residual values prevents technologies from being unfairly favored or penalized depending on how their service lives line up with the end of the analysis period.

4.2.5 Cash Flow Diagrams

Figure 4-2 shows an example cash flow[11] in nominal dollars (including the effect of inflation). For this example, a retrofit at the beginning of the 30-year analysis period is financed by a 5-year loan. Replacements occur throughout the analysis period, the smallest of which correspond to CFL replacements; the large replacement costs in years 16 and 19 correspond to major equipment replacements. All replacements are paid for in cash at the time of the replacement. In this example, energy rates increase over time because of the assumed inflation rate, which causes the increase in utility bills seen in the figure.

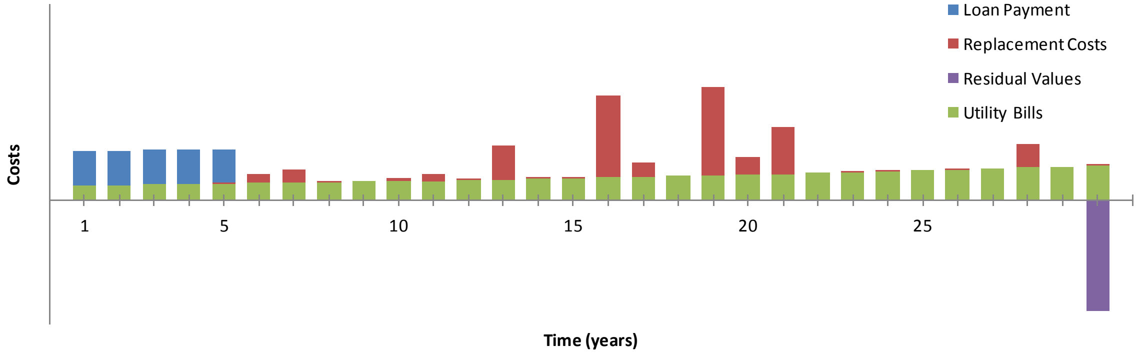

Figure 4-2. Example cash flow diagram

4.3 Metrics

This analysis method computes two primary metrics for each scenario: average energy use (AEU) and equivalent annual cost (EAC).

4.3.1 Average Energy Use

AEU is the average of the annual energy uses over the analysis period:

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[11] Cash flow diagrams presented in this report assume the following sign convention: expenses are positive and receipts are negative.

$$AEU = \frac{\sum_{k=1}^{k=N} EU_k}{N}, \tag{4-3}$$

where EU_k is the energy use in year k and N is the number of years in the analysis period.

4.3.2 Equivalent Annual Cost

EAC is calculated by annualizing the cash flows (e.g., Figure 4-2). The most straightforward way to annualize complex cash flows is to determine the present worth (PW) of the cash flow by converting the total cost (TC) for each year to the value at the beginning of the analysis period:

$$PW = \sum_{k=0}^{k=N} -TC_{year=k}(1 + d_n)^{-k}, \tag{4-4}$$

where $TC_{year=k}$ is the total cost in year k and d_n is the nominal discount rate. The EAC is then determined by annualizing the PW using the real discount rate,[12] d_r:

$$EAC = \frac{-PW(d_r)}{\left(1 - \frac{1}{(1 + d_r)^N}\right)}, \tag{4-5}$$

which gives the annual equivalent cost for the complex, time-series cash flow. The nominal and real discount rates are related as

$$(1 + d_n) = (1 + i)(1 + d_r). \tag{4-6}$$

4.3.3 Minimum Upgrade Reference Scenario

The EAC and AEU of a retrofit scenario can be compared to an alternative scenario to determine the additional cost incurred to achieve a given level of energy savings. This naturally leads to the definition of a reference scenario, the baseline against which energy upgrade scenarios are compared in terms of cost and energy use. This analysis method uses a minimum upgrade reference scenario (MURS) as the baseline. The MURS begins with the existing building at the start of the analysis period and assumes all equipment that wears out over the analysis period is replaced with the same level of efficiency or the current minimum standard, whichever is more efficient. Minimum upgrades are assumed for the reference building so as not to take credit for energy efficiency improvements that would have otherwise occurred through natural wear-out and replacement. In this sense, the MURS is the minimum that a homeowner could do to their house over the analysis period assuming that standards in the future will require at least the current level of efficiency.

Figures 4-3 and 4-4 show example annual energy use and cash flow diagrams, respectively, for both the MURS and a post-retrofit scenario. As seen in Figure 4-3, the annual energy use of the MURS decreases at two points in the analysis period when the existing equipment below the minimum standard wears out and is replaced with the more efficient minimum standard equipment. For the post-retrofit scenario, equipment and enclosure measures decrease the annual energy uses relative to the MURS. All existing equipment below the minimum standard is replaced at the beginning of the analysis period, so the annual energy use does not change from

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[12] To obtain the equivalent annual cost in terms of dollars at the beginning of the analysis period.

year to year. Unlike the MURS, the post-retrofit scenario has loan costs related to financing the retrofit. Both the post-retrofit scenario and the MURS have costs related to replacements, utility bills, and residual values, though they are different as a result of the retrofit and replacement schedule.

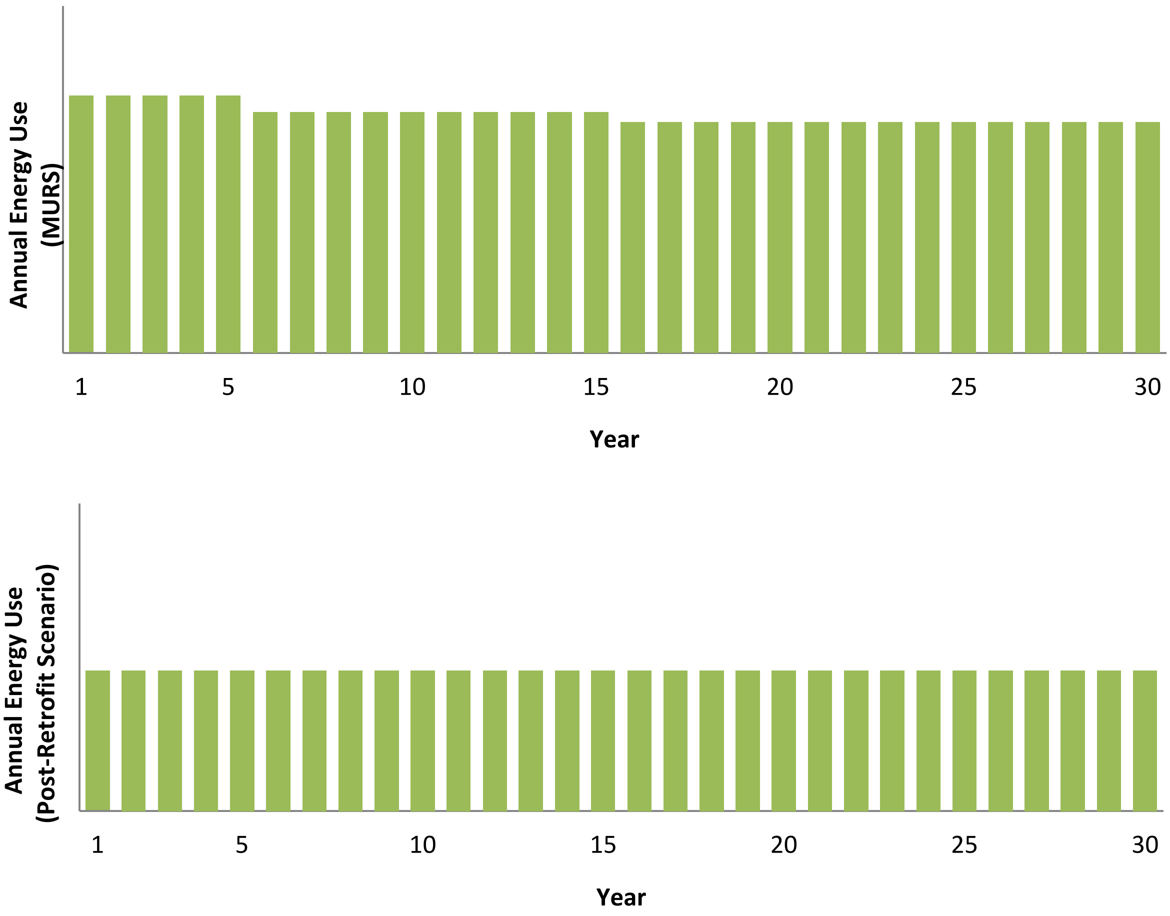

Figure 4-3. Example annual energy uses for MURS (top) and post-retrofit scenario (bottom)

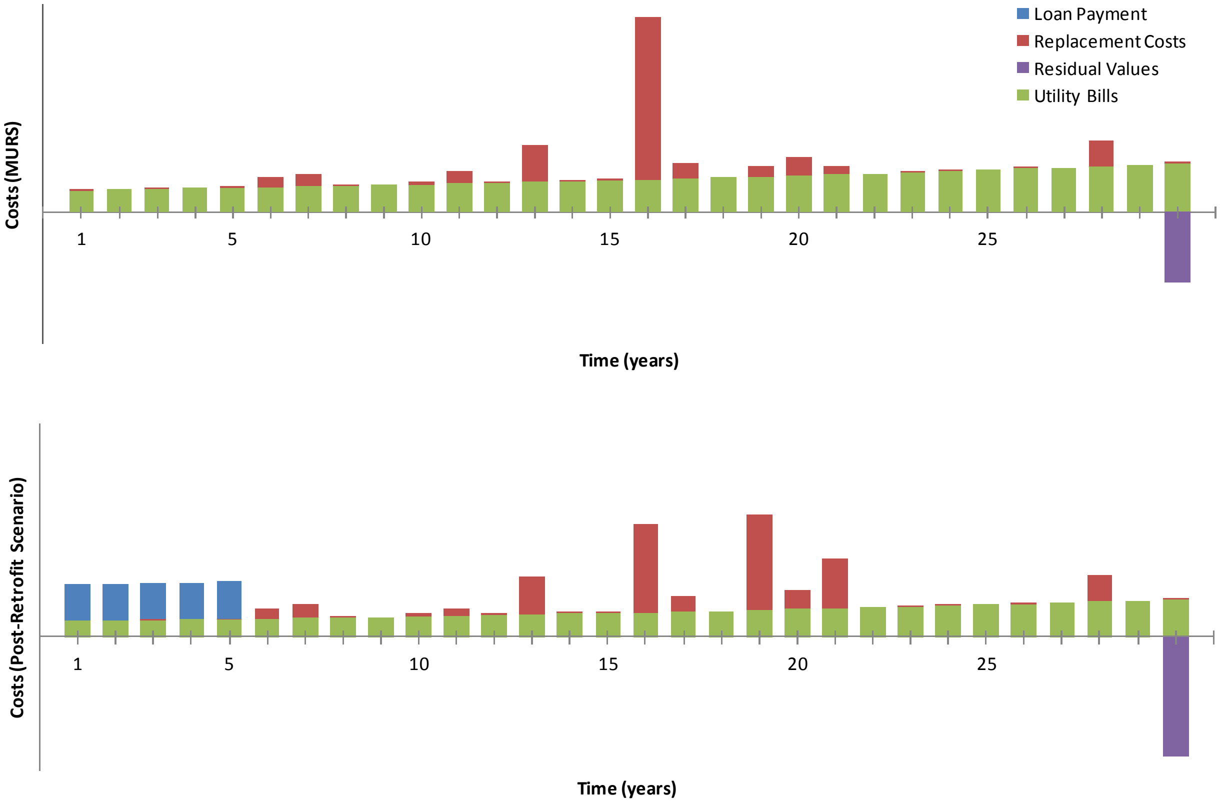

Figure 4-4. Example cash flows for MURS and post-retrofit scenario

Figures 4-5 and 4-6 show the AEU and EAC for both the example MURS and the example post-retrofit scenario. As seen in Figure 4-5, significant average energy savings (AES, difference in AEU) is achieved through the retrofit. Figure 4-6 shows that although the post-retrofit scenario incurs loan costs, its EAC is less than that of the MURS because of decreased utility bill costs.

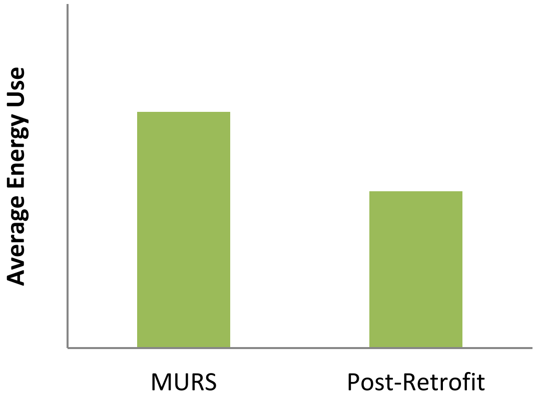

Figure 4-5. Average energy use (AEU) for MURS and post-retrofit scenario

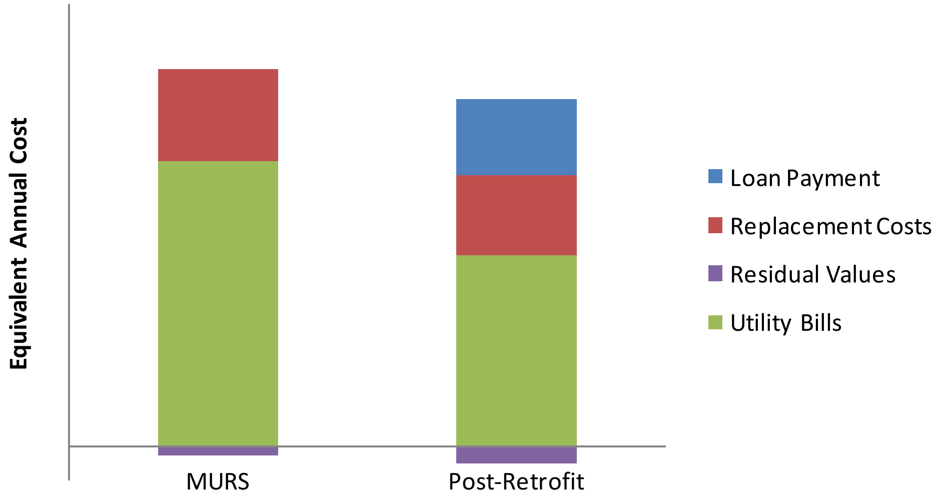

Figure 4-6. Equivalent annual cost (EAC) for MURS and post-retrofit scenario

4.4 Optimization

The metric for the optimization algorithm used in BEopt to determine optimal new construction building designs was modified based on the AEU and EAC. Christensen et al. (2006) give a detailed description of the sequential search algorithm—the following is a general description of the optimization:

A. Optimization starts with the reference scenario. Annual building energy simulations are performed to determine annual energy uses and cash flows for that scenario, from which AEU and EAC are computed.
B. For each iteration, the optimization individually investigates each possible measure (e.g. R-30, R-40, R-50) within a category (e.g., attic insulation) as a unique scenario. Each category/measure combination represents a different scenario for which simulations are performed, annual energy uses and cash flows are determined, and AEU and EAC are calculated.
C. The objective functions *J*(*AEU*) and *K*(*EAC*,*AEU*) for the optimization are:

$$J(AEU) = AEU_{previous} - AEU_{current}, \tag{4-7}$$

$$K(EAC, AEU) = \frac{EAC_{previous} - EAC_{current}}{AEU_{previous} - AEU_{current}}, \tag{4-8}$$

where "previous" refers to the optimal point for the last iteration and "current" refers to the scenario under consideration. For the first iteration, the previous values are those for the reference scenario. Each category/measure scenario is then evaluated against the previous scenario. The following logic is used to progress through the optimization:

1. If *J*(*AEU*) for all scenarios investigated in the iteration is negative, then the optimization is complete (maximum savings achieved). When one or more scenarios are positive, proceed to step 2.
2. For those category/measure scenarios where *J*(*AEU*) is positive, select the scenario with maximum value of *K*(*EAC*, *AEU*) as the "optimal" scenario for the iteration. This is the scenario with the largest equivalent annual cost savings per unit of energy savings.
3. Repeat steps 1 and 2 using the optimal scenario from the last iteration as the previous scenario in Equations 4-7 and 4-8. Evaluate the objective functions for all scenarios in this iteration and all scenarios in the previous iterations. Select the next optimal point and repeat step 3 until the optimization is complete.

The optimization process uses the sequential search technique to determine optimal retrofit packages. One benefit of this technique is that ECMs are analyzed together, which accounts for their energy and cost interactions over the analysis period. For example, window replacements are simulated both in the context of the existing HVAC equipment as well as minimum HVAC equipment upgrades in the future. Because scenarios are evaluated from all previous iterations, the optimization can "look back" and determine if it should divest in one technology and reinvest that money in a different technology. For example, as more enclosure measures are included in the retrofit, the optimal HVAC equipment efficiency may step down because the reduced loads make it increasingly difficult to recover the cost premium of more efficient equipment.

Figure 4-7 shows example optimization results. The vertical axis is the incremental equivalent annual cost (IEAC, 2010 dollars) relative to the MURS. The horizontal axis is the AES of the retrofit scenario relative to the MURS. The starting point on the optimization curve (point A) is simply the MURS scenario. Thus, there is zero IEAC and AES. The red points are example scenarios from the first iteration of an optimization. Point B is selected as the optimal point for this iteration, and then the blue points are investigated in the second iteration. When selecting the optimal point in the second iteration, all previous points (red and blue) are considered. Point C is selected in the second iteration, and the yellow points are investigated for the third iteration. Considering all previous points again when selecting the optimal point for the third iteration (red, blue, and yellow), point D is chosen. This process continues (represented as grey points) until no further energy savings can be achieved. The line connecting the optimal points is the least-cost curve, which can be plotted and compared to least-cost curves for other optimizations.

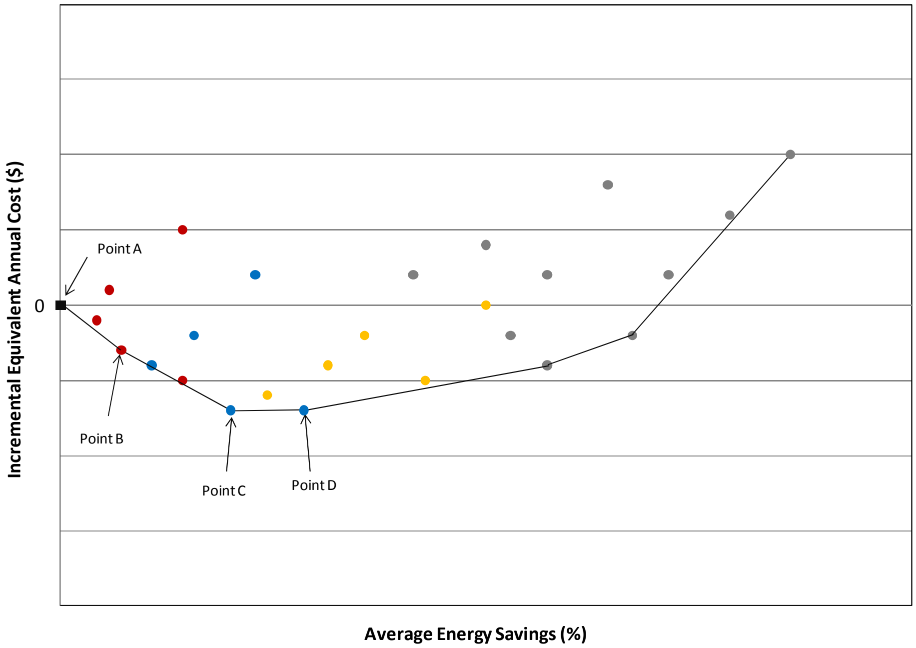

Figure 4-7. Example of optimization results

Although the results of an optimization can be displayed using a curve, the least-cost curve is made up of discrete points representing discrete retrofit packages. Also, significant uncertainty can exist in the cost and energy savings for each scenario, so in reality points near the least-cost curve may be equally acceptable solutions. In the end, selecting optimal retrofit packages involves judgment considering uncertainty in the results as well as other intangible differences such as difficulty in implementing each retrofit package because of on-site circumstances and the effects of each retrofit scenario on occupant comfort, occupant health, safety, building durability, and so on.

5.0 Example Analysis

The analysis method described in Section 4 was implemented in BEopt and used to conduct a retrofit example analysis on a 1960s-era house in eight different U.S. cities. This section presents the results for the eight cities, which span most IECC climate zones. Although the example analysis applied realistic pre-retrofit conditions and retrofit measures (refer to Appendix A for details), inputs and results do not represent the U.S. housing stock as a whole. This example analysis demonstrates how the analysis method can be used to generate recommendations for individual retrofit measures and packages of measures specific to a building, its occupants, and its location. Appendix B discusses the sensitivity of example analysis results to the general, financial, occupant, and building assumptions.

As described in Section 4.3, the analysis determines EAC for each retrofit scenario, considering the costs over the analysis period related to the initial loan (used to finance the retrofit), future replacements, utility bills, and residual values (negative costs). Table 5-1 lists the assumed values of key financial parameters.

Table 5-1. Assumed Values for Key Financial Parameters

Financial Parameter	Value
Analysis Period (years)	30
Inflation Rate (%)	3
Real Discount Rate (%)	3
Real Fuel Escalation Rate (%)	0
Annual Effective Loan Interest Rate (%)	7
Loan Period (years)	5

Houses in each city are single-level, 1,280 ft^2 ranches and are identical except for a climate appropriate foundation, the location of the ductwork, shingle solar reflectance, and exterior finish. Table 5-2 lists the IECC climate zone,[13] foundation type, duct location, and energy tariffs[14] for each city considered (ordered according to IECC climate zone).

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[13] EnergyPlus weather files (.epw), obtained from processing typical meteorological year (.TM3) weather data, were used to drive the simulations: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.

[14] Gas: http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm (used 2008 year, 10.29 therms/Mcf conversion factor).

Electricity: http://www.eia.doe.gov/cneaf/electricity/esr/table5.html.

Table 5-2. Cities, Climate Zones, Foundations, Duct Location, and Energy Tariffs for Each City

City[a]	IECC Climate Zone	Foundation Type	Location of Ducts	Electricity ($/kWh)	Gas ($/therm)
Houston, Texas	2	Slab	Attic	0.1304	1.34
Phoenix, Arizona	2	Slab	Attic	0.1027	1.71
Atlanta, Georgia	3	Vented Crawl Space	Vented Crawl Space	0.0993	1.80
San Diego, California	3	Slab	Attic	0.1381	1.24
Seattle, Washington	4	Vented Crawl Space	Vented Crawl Space	0.0754	1.27
Washington, D.C.	4	Unconditioned Basement	Unconditioned Basement	0.1304[b]	1.34[b]
Chicago, Illinois	5	Unconditioned Basement	Unconditioned Basement	0.1107	1.17
Minneapolis, Minnesota	6	Unconditioned Basement	Unconditioned Basement	0.0974	1.10

[a] Cities are listed in order of IECC Climate Zone.

[b] Standard values in BEopt do not reflect current published values because of incomplete data availability at the time of entry.

Table 5-3 gives a high-level description of the retrofit measures with associated costs[15] and relevant pre-retrofit conditions. Enclosure measures are first, followed by air distribution, HVAC equipment, water heating, appliances, and lighting. The MURS is the pre-retrofit building modeled over the analysis period, except that the SEER 10 AC is replaced with SEER 13 at wear-out and the old refrigerator (739 kWh/yr) is replaced with a standard refrigerator (514 kWh/yr, $585) at wear-out. Existing equipment in the home is assumed to have half of its useful lifetime remaining. For example, the assumed useful lifetime of refrigerators is 19 years, so the existing refrigerator in the pre-retrofit house has 9.5 years of useful lifetime remaining. Again, Appendix A gives more details about the pre-retrofit home (including assumed lifetimes of equipment) and retrofit measures.

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[15] Costs were taken from the National Residential Efficiency Measures Database (NREL 2010). The current version of the database can be found at http://www.nrel.gov/ap/retrofits/index.cfm.

Table 5-3. Retrofit Measures, Properties, and Costs

Measure	Pre-Retrofit	Post-Retrofit	Measure Cost (2010$)
Air Seal (~55% Improvement, Including Mechanical Ventilation)	0.0009 SLA	0.0004 SLA + Mech. Vent.[a]	$2,880
Insulate and Air Seal Attic Floor (IECC Climate Zones 1-4)	R-11, 0.0009 SLA	R-38, 0.0007 SLA	$2,075
Insulate and Air Seal Attic Floor (IECC Climate Zones 5-8)	R-19, 0.0009 SLA	R-49, 0.0007 SLA	$2,215
Drill-and-Fill Wall	Uninsulated	R-13 cavity	$2,545
Close, Condition and Insulate Crawl Space	Vented, nACH = 2.0 Uninsulated	Sealed, nACH = 0.35, Wall = R-13	$3,840
Insulate Basement Wall, Basic (unfinished)	Uninsulated Wall	½ Wall, 1-in. polyiso, R-6	$700
Insulate Basement Wall, Advanced (finished)	Uninsulated Wall	Full Wall, 1-in. XPS w/ gypsum, R-6.4	$2,765
Replace Windows	Single-Pane[b]	Standard (IECC 2009) or ENERGY STAR®	$25/ft^2 $33/ft^2
Seal Ducts	R-1, 15% Leakage	R-1, 8% Leakage	$890
Seal and Insulate Ducts	R-1, 15% Leakage	R-6, 8% Leakage	$1,800
Replace AC	SEER 10	SEER 13 or SEER 16	See Table 5-4
Replace Furnace	AFUE 80	AFUE 92.5	See Table 5-4
Replace Tank Water Heater With ENERGYSTAR Tankless Water Heater	Tank, EF = 0.59	Tankless, EF = 0.82[c]	$1,825
Replace Tank Water Heater with ENERGY STAR Tank Water Heater	Tank, EF = 0.59	Tank, EF = 0.67	$1,500
Replace Refrigerator	Old, 739 kWh/yr	Standard (514 kWh/yr) or ENERGY STAR (411 kWh/yr)	$585 $674
Replace Clothes Washer	MEF = 1.41, WF = 8.6	MEF = 2.47, WF = 3.9	$648
Replace Lamps (%Incandescent:%CFL:%LFL)	66:21:13	43:44:13 or 32:55:13	CFL = $0.17/W

[a] Exhaust-only mechanical ventilation according to ASHRAE 62.2-2007 (ASHRAE 2007), including infiltration credit (see Appendix A for details).

[b] The ratio of the total window area to the exterior wall area of the living space is 17.8% both pre- and post-retrofit, which corresponds to 205 ft^2 of window area.

[c] Tankless water heater energy factor is derated by 8% in BEopt analysis according to California's Title 24-2008 (CEC 2010).

Table 5-4 details the heating and cooling equipment sizes and costs. Note that, consistent with the climate, the AC size in San Diego is the smallest (2 tons)—cities in warmer climates have 5 ton units.[16] The furnace is the smallest in San Diego (30 kBtu/h) and the largest in Minneapolis

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[16] AC sizes were capped at 5 tons because this is the largest available single unit in the market.

(80 kBtu/h). The costs increase linearly with the size of the equipment, as defined by the National Residential Efficiency Measures Database (NREL 2010).

Table 5-4. Air Conditioner and Furnace Sizes and Costs per Location

City	**AC Size** (tons)	**AC Retrofit** ($) **(AC MURS)** ($)	**Furnace Size** (kBtu/h)	**Furnace Retrofit** ($) **(Furnace MURS)** ($)
Houston, Texas	5	8,820 (7,560)	50	1,650 (800)
Phoenix, Arizona	5	8,820 (7,560)	40	1,320 (640)
Atlanta, Georgia	5	8,820 (7,560)	60	1,980 (960)
San Diego, California	2	3,530 (3,025)	30	990 (480)
Seattle, Washington	4	7,060 (6,050)	50	1,650 (800)
Washington, D.C.	5	8,820 (7,560)	60	1,980 (960)
Chicago, Illinois	4	7,060 (6,050)	70	2,310 (1,120)
Minneapolis, Minnesota	5	8,820 (7,560)	80	2,640 (1,280)

5.1 Individual Retrofit Measures

Table 5-5 lists the predicted average annual source energy savings (%) for individual retrofit measures applied to the example analysis house in the different cities. Note that the energy savings listed are valid only when a single measure is implemented in the house; if more than one measure is implemented, the calculated savings are not necessarily additive because there can be interactions between measures (e.g., installing a more efficient furnace reduces the amount of energy that can be saved by enclosure improvements such as efficient windows). Some of the important results are as follows:

- Drill-and-fill insulation in the walls saves the most energy in most locations. The exceptions are sealing and insulating ducts in Houston and closing the crawl space in Seattle.
- Because space conditioning in San Diego is not very significant, the house there saves less energy from enclosure measures than in the other locations. For the same reason, replacing appliances, lighting, and water heating saves more energy in San Diego (as a percentage).
- Because of the substantial cooling load in Phoenix, the house there benefits significantly from replacing the AC with a higher efficiency unit.

- With its high heating loads, Minneapolis benefits most from drill-and-fill, window replacement, attic insulation, and upgrading to a more efficient furnace.
- Sealing and insulating ducts delivers significant energy savings in each city.

Table 5-5. Predicted Average Annual Source Energy Savings (%) for Individual Retrofit Measures

Retrofit Measure	Houston	Phoenix	Atlanta	San Diego	Seattle	DC	Chicago	Minneapolis
Drill and Fill	8.8	13.5	8.9	9.1	10.0	9.8	10.5	10.8
Attic Ins./Attic Seal	6.5	6.0	8.2	5.3	9.2	9.1	7.5	7.9
4 ft Basement Ins.	—	—	—	—	—	3.1	3.9	4.2
8 ft Basement Ins.	—	—	—	—	—	5.1	6.5	7.0
Close Crawl Space	—	—	7.9	—	12.0	—	—	—
Standard Window	8.2	9.2	6.5	3.4	6.3	7.5	8.0	8.4
ENERGY STAR Window	8.3	9.4	7.3	3.9	8.7	8.1	9.6	10.1
Max Air Seal	1.7	1.3	2.3	0.5	3.0	3.6	5.1	5.9
Seal Ducts	3.8	4.0	2.3	1.7	2.2	2.1	2.1	2.3
Seal and Ins. Ducts	9.3	11.4	5.0	6.3	6.1	4.8	5.4	5.4
Tank Water Heater (gas, EF = 0.67)	1.5	1.2	1.5	2.2	1.4	1.4	1.2	1.1
Tankless Water Heater (gas, EF = 0.82)	3.0	2.4	2.9	4.3	2.6	2.6	2.2	2.0
Lighting (44% CFL)	0.9	0.7	0.7	1.0	0.5	0.6	0.5	0.4
Lighting (55% CFL)	1.3	1.1	1.0	1.6	0.7	0.9	0.7	0.6
SEER 13 AC	2.7	3.9	1.8	1.4	0.4	1.3	0.7	0.6
SEER 16 AC	5.8	9.7	4.8	3.2	1.3	3.6	1.9	1.5
92.5 AFUE Furnace	2.6	1.3	4.5	2.5	6.9	5.7	7.3	7.8
Standard Refrigerator	0.5	0.4	0.4	0.5	0.2	0.3	0.2	0.2
ENERGY STAR Refrigerator	1.1	0.9	0.9	1.3	0.5	0.7	0.5	0.5
ENERGY STAR Clothes Washer	1.8	1.4	1.8	2.6	1.7	1.7	1.5	1.4

Table 5-6 shows the predicted IEAC (2010 dollars) for the individual retrofit measures implemented in each location. A negative IEAC indicates that the retrofit scenario has a lower life-cycle cost than the MURS. There are many observations worth making about this table:

- Drill-and-fill insulation and lighting upgrades reduce EAC in every location considered.
- An upgraded furnace reduces EAC in the colder climates, but not in San Diego, Phoenix, and Houston.
- Adding 4 feet of basement insulation, adding 8 feet of basement insulation, and closing the crawl space reduce EAC in each applicable location.
- An AC upgrade is not cost-effective in any location considered. Note that the AC upgrade, as with all equipment replacements in this example analysis, must justify replacing the existing equipment, which has half of its useful life remaining.
- Duct sealing and insulation reduces EAC everywhere but San Diego.
- As previously mentioned, measures can deliver other benefits beyond energy savings, and a higher associated cost could be justified by these benefits.

Table 5-6. Predicted Incremental Equivalent Annual Cost (2010$) for Individual Retrofit Measures

Retrofit Measure	Houston	Phoenix	Atlanta	San Diego	Seattle	DC	Chicago	Minneapolis
Drill and Fill	–70	–198	–122	–16	–120	–155	–171	–181
Attic Ins./Attic Seal	–23	–33	–104	37	–99	–136	–82	–95
4 ft Basement Ins.	—	—	—	—	—	–54	–68	–77
8 ft Basement Ins.	—	—	—	—	—	–7	–31	–45
Close Crawl Space	—	—	–23	—	–83	—	—	—
Standard Window	100	82	132	215	131	81	58	47
ENERGY STAR Window	183	165	195	294	158	145	100	85
Max Air Seal	116	119	78	145	75	44	13	–8
Seal Ducts	–33	–39	–9	22	–2	–6	–8	–13
Seal and Ins. Ducts	–92	–153	–32	8	–45	–33	–48	–50
Tank Water Heater (gas, EF = 0.67)	61	54	45	62	58	50	60	62
Tankless Water Heater (gas, EF = 0.82)	–6	–21	–34	–2	–8	–24	–5	0
Lighting (44% CFL)	–21	–17	–13	–19	–8	–12	–14	–13
Lighting (55% CFL)	–30	–24	–18	–28	–11	–17	–20	–18
SEER 13 AC	118	90	153	163	147	162	131	174
SEER 16 AC	132	55	186	213	202	202	165	230
92.5 AFUE Furnace	37	30	–30	21	–78	–63	–71	–71
Standard Refrigerator	7	10	13	9	17	14	12	14
ENERGY STAR Refrigerator	0	7	13	3	22	14	12	14
ENERGY STAR Clothes Washer	–7	1	–5	–8	1	–5	–7	–4

5.2 Optimization

The optimization approach described in Section 4.4 determined least-cost packages of measures at different levels of energy savings for each location. Figures 5-1 through 5-8 and Tables 5-7 through 5-14 show a series of least-cost curves and tables with the packages determined from the optimization for each location, respectively. The Houston results are discussed in Section 5.2.1 as an example of what information can be obtained from the optimization results. Section 5.2.2 includes a high-level summary of all results.

5.2.1 Example Discussion of Optimization Results for One City

Table 5-7 shows the incremental EAC and AES values for the retrofit packages considered in Houston. Each point on the plot in Figure 5-1 represents a different retrofit package. The dark line is the least-cost curve, which connects the optimal packages determined from the optimization. Many packages are close to the least-cost curve. Because of uncertainty in the EAC and AES values calculated for each package, some of these packages near the least-cost curve may in reality deliver equivalent or better results than those on the least-cost curve. The minimum-cost package, represented by the lowest point in the graph, reduces the EAC by about $185 and represents an average source energy savings of 30%.

The packages that define the least-cost curve in Figure 5-1 can be seen in Table 5-7. AES values are listed next to optimal packages in Figure 5-1 (1, 1, 11, 18, 19, etc.) appear in the left column of Table 5-7 in increasing value of AES. The first point on the least-cost curve delivering energy savings is obtained by upgrading the lighting to 44% CFL. Because this is a single measure, it is also shown in Tables 5-5 and 5-6. Although many other measures in those tables deliver higher savings individually, they are not selected as the first point because they deliver less decrease in EAC per unit of energy savings (have a more positive slope) than the 44% CFL measure. The next package on the least-cost curve is 55% CFL lighting (instead of 44% CFL). After that, the next package is sealing and insulating the ducts, leading to a combined AES of 11%. For the rest of the optimization, each measure that is added to the previous package to obtain another point on the least-cost curve remains part of the next package as the energy savings increases, except for the window upgrade (one can install either standard or ENERGY STAR windows, but not both). The minimum cost package (30% AES) has drill-and-fill wall insulation, attic insulation/air seal, duct seal/insulation, tankless water heater, 55% CFL lighting, ENERGY STAR refrigerator, and ENERGY STAR clothes washer.

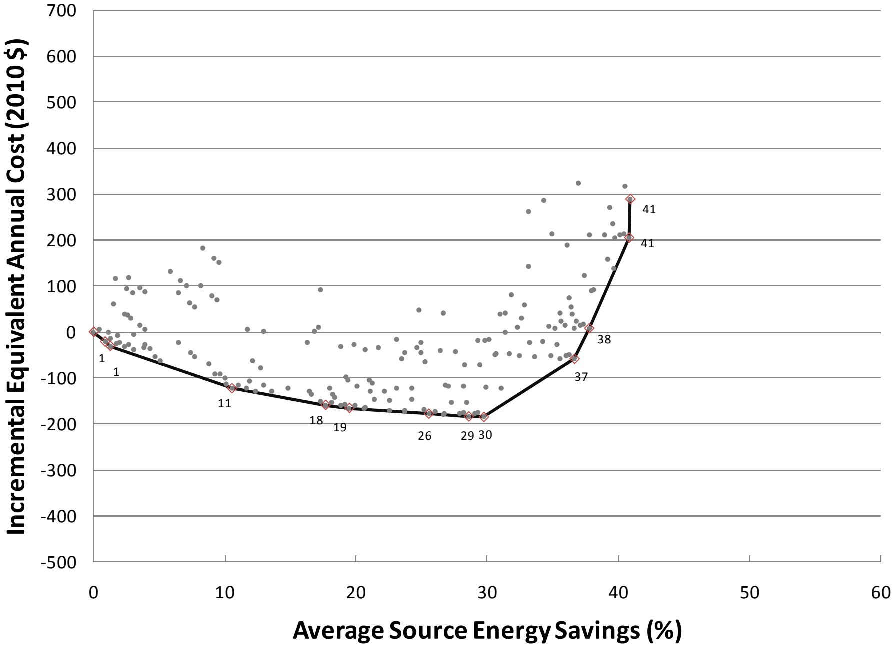

Figure 5-1. Incremental EAC at different levels of energy savings for Houston

Table 5-7. Least-Cost Packages at Different Energy Savings for Houston

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
1	−21													X							
1	−30														X						
11	−122										X				X						
18	−159	X									X				X						
19	−165	X									X				X						X
26	−178	X	X								X				X						X
29	−184	X	X								X		X		X						X
30	−185	X	X								X		X		X					X	X
37	−59	X	X				X				X		X		X					X	X
38	8	X	X				X				X		X		X			X		X	X
41	204	X	X				X				X		X		X		X	X		X	X
41	288	X	X					X			X		X		X		X	X		X	X

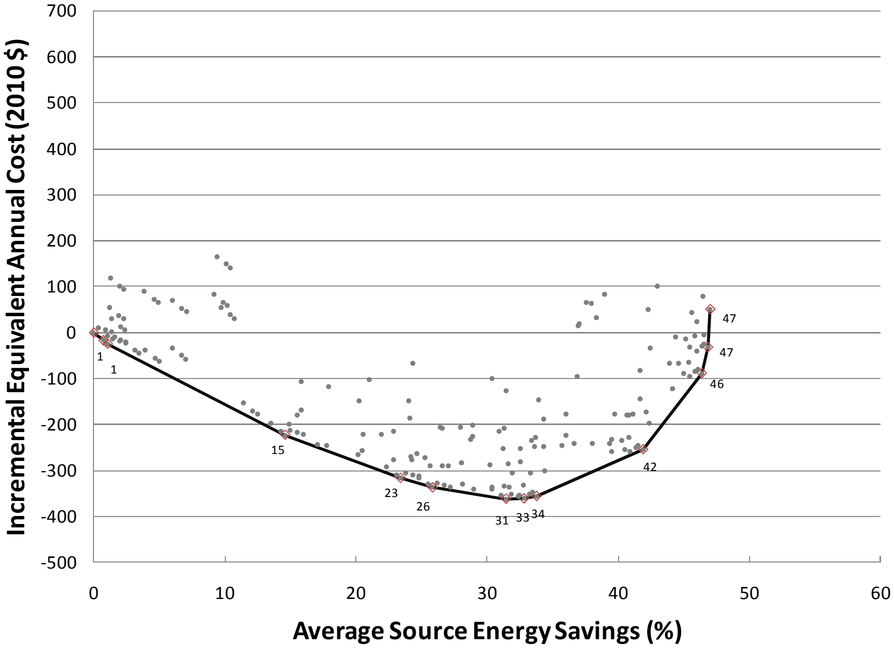

Figure 5-2. Incremental EAC at different levels of energy savings for Phoenix

Table 5-8. Least-Cost Packages at Different Energy Savings for Phoenix

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
1	−17													X							
1	−24														X						
15	−222	X													X						
23	−316	X									X				X						
26	−337	X									X		X		X						
31	−361	X	X								X		X		X						
33	−361	X	X								X		X		X						X
34	−356	X	X								X		X		X					X	X
42	−254	X	X				X				X		X		X					X	X
46	−88	X	X				X				X		X		X		X			X	X
47	−31	X	X				X				X		X		X		X	X		X	X
47	51	X	X					X			X		X		X		X	X		X	X

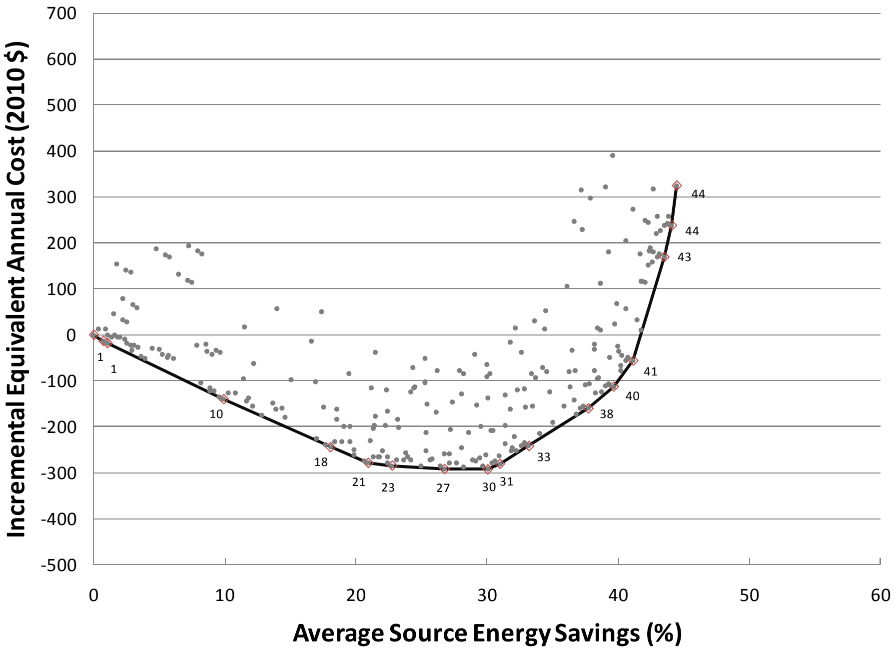

Figure 5-3. Incremental EAC at different levels of energy savings for Atlanta

Table 5-9. Least-Cost Packages at Different Energy Savings for Atlanta

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
1	−13													X							
1	−18														X						
10	−140	X													X						
18	−244	X	X												X						
21	−279	X	X										X		X						
23	−284	X	X										X		X						X
27	−292	X	X								X		X		X						X
30	−293	X	X			X							X		X						X
31	−281	X	X			X							X		X					X	X
33	−242	X	X			X							X		X			X		X	X
38	−160	X	X			X	X						X		X					X	X
40	−113	X	X			X	X						X		X			X		X	X
41	−56	X	X			X	X				X		X		X			X		X	X
43	169	X	X			X	X				X		X		X		X	X		X	X
44	238	X	X			X		X			X		X		X		X	X		X	X
44	325	X	X			X		X	X		X		X		X		X	X		X	X

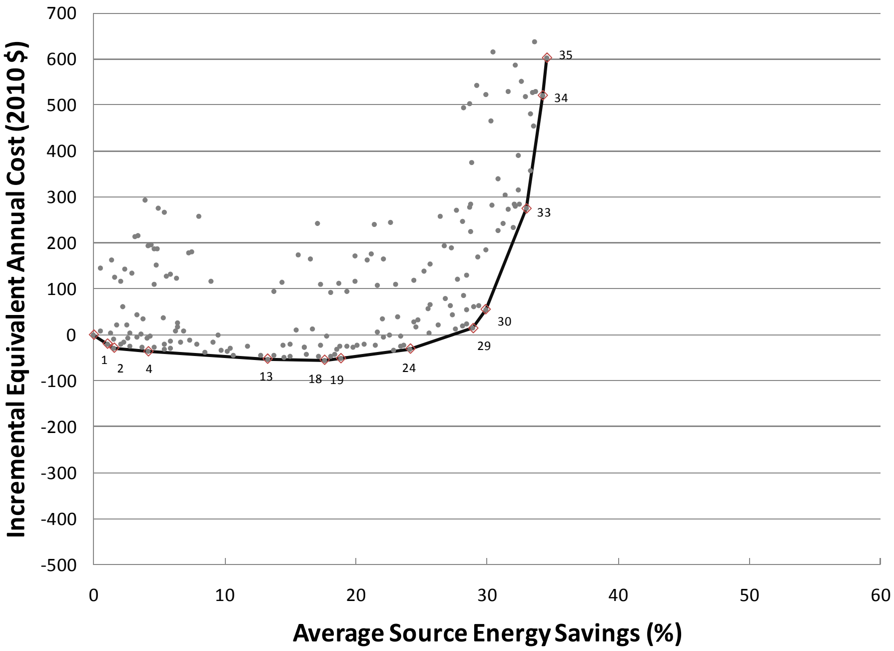

Figure 5-4. Incremental EAC at different levels of energy savings for San Diego

Table 5-10. Least-Cost Packages at Different Energy Savings for San Diego

AES (%)	**IEAC (2010 $)**	**Drill and Fill**	**Attic Ins./Attic Seal**	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	**Standard Window**	**ENERGY STAR Window**	**Max Air Seal**	**Seal Ducts**	**Seal and Ins. Ducts**	**Tank Water Heater (gas, EF = 0.67)**	**Tankless Water Heater (gas, EF = 0.82)**	**Lighting (44% CFL)**	**Lighting (55% CFL)**	**SEER 13 AC**	**SEER 16 AC**	**92.5 AFUE Furnace**	**Standard Refrigerator**	**ENERGY STAR Refrigerator**	**ENERGY STAR Clothes Washer**
1	−19													X							
2	−28														X						
4	−36														X						X
13	−52	X													X						X
18	−55	X											X		X						X
19	−51	X											X		X					X	X
24	−30	X									X		X		X					X	X
29	14	X	X								X		X		X					X	X
30	55	X	X								X		X		X			X		X	X
33	275	X	X				X				X		X		X			X		X	X
34	521	X	X				X				X		X		X		X	X		X	X
35	603	X	X					X			X		X		X		X	X		X	X

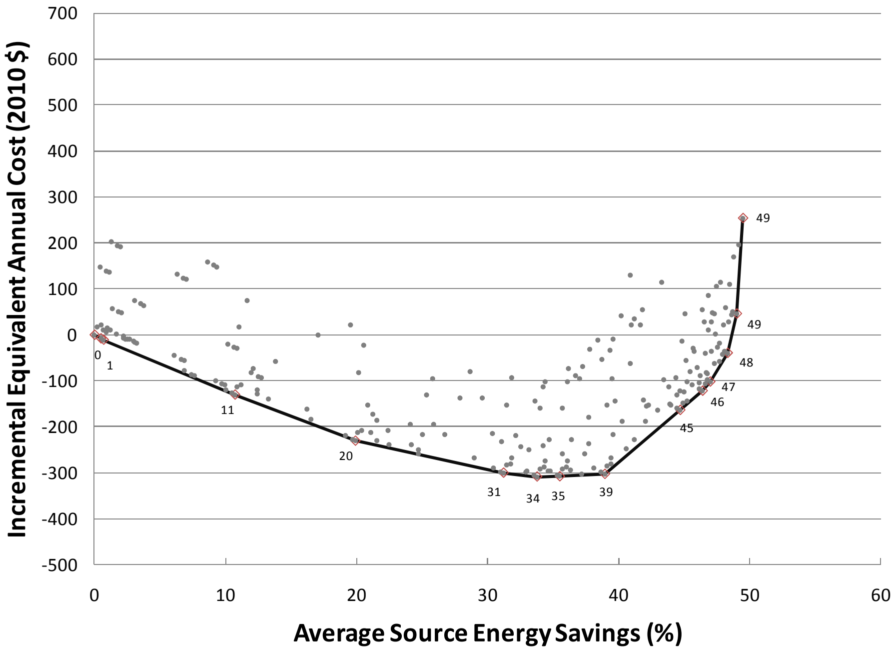

Figure 5-5. Incremental EAC at different levels of energy savings for Seattle

Table 5-11. Least-Cost Packages at Different Energy Savings for Seattle

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
0	−8													X							
1	−11														X						
11	−130	X													X						
20	−231	X	X												X						
31	−300	X	X			X									X						
34	−309	X	X			X							X		X						
35	−308	X	X			X							X		X						X
39	−303	X	X			X							X		X			X			X
45	−164	X	X			X	X						X		X			X			X
46	−122	X	X			X		X					X		X			X			X
47	−102	X	X			X		X					X		X			X		X	X
48	−39	X	X			X		X			X		X		X			X		X	X
49	46	X	X			X		X	X		X		X		X			X		X	X
49	254	X	X			X		X	X		X		X		X		X	X		X	X

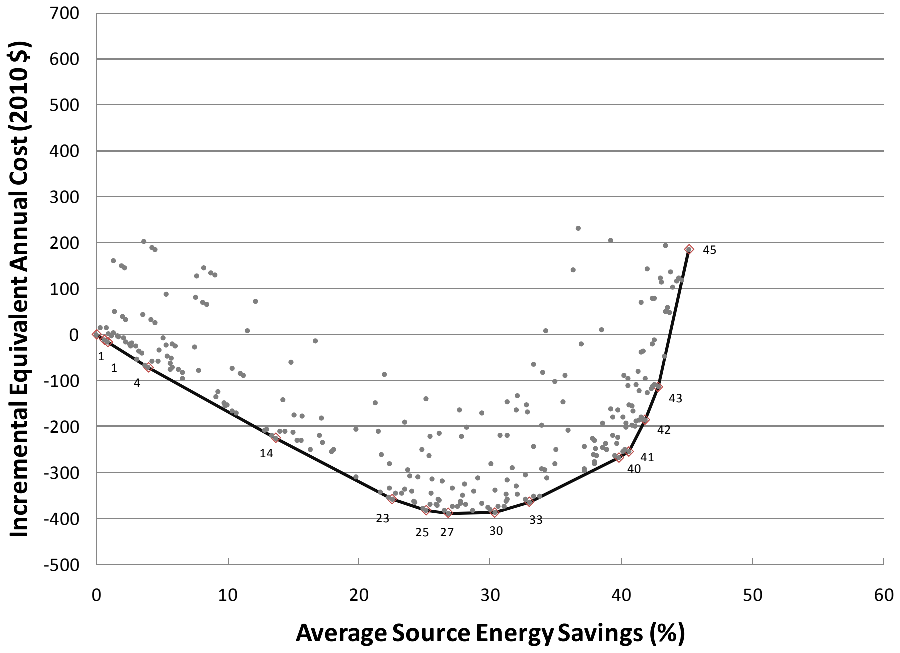

Figure 5-6. Incremental EAC at different levels of energy savings for Washington, D.C.

Table 5-12. Least-Cost Packages at Different Energy Savings for Washington, D.C.

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
1	−12													X							
1	−17														X						
4	−72			X											X						
14	−225	X		X											X						
23	−358	X	X	X											X						
25	−382	X	X	X									X		X						
27	−388	X	X	X									X		X						X
30	−388	X	X	X									X		X			X			X
33	−364	X	X	X							X		X		X			X			X
40	−268	X	X	X			X				X		X		X			X			X
41	−255	X	X	X			X				X		X		X			X		X	X
42	−186	X	X		X		X				X		X		X			X		X	X
43	−114	X	X		X		X		X		X		X		X			X		X	X
45	185	X	X		X			X	X		X		X		X		X	X		X	X

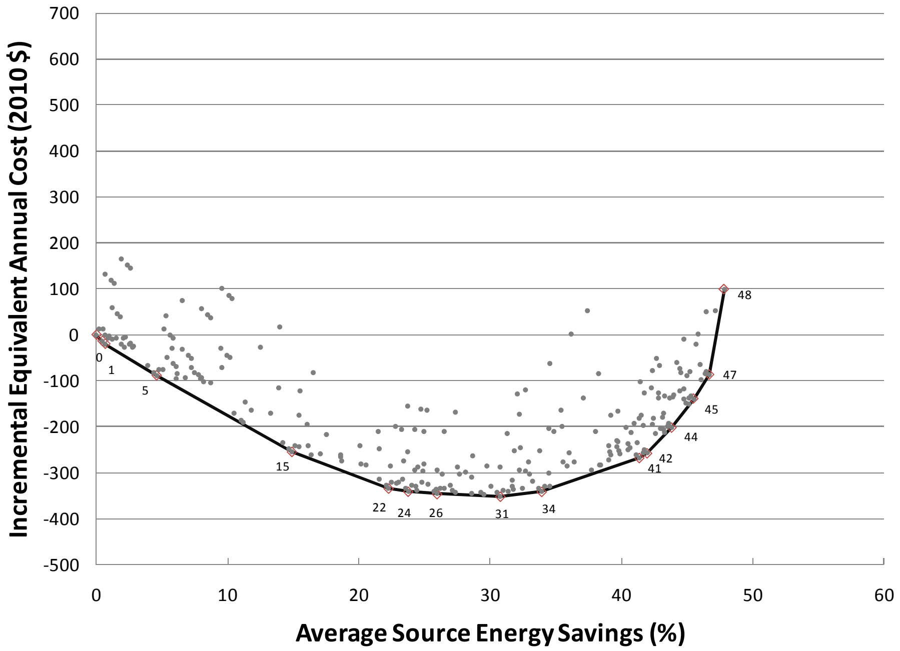

Figure 5-7. Incremental EAC at different levels of energy savings for Chicago

Table 5-13. Least-Cost Packages at Different Energy Savings for Chicago

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
0	−14													X							
1	−20														X						
5	−88			X											X						
15	−254	X		X											X						
22	−333	X	X	X											X						
24	−340	X	X	X											X						X
26	−346	X	X	X									X		X						X
31	−351	X	X	X									X		X			X			X
34	−341	X	X	X							X		X		X			X			X
41	−267	X	X	X			X				X		X		X			X			X
42	−257	X	X	X			X				X		X		X			X		X	X
44	−201	X	X	X			X		X		X		X		X			X		X	X
45	−138	X	X		X		X		X		X		X		X			X		X	X
47	−86	X	X		X			X	X		X		X		X			X		X	X
48	98	X	X		X			X	X		X		X		X		X	X		X	X

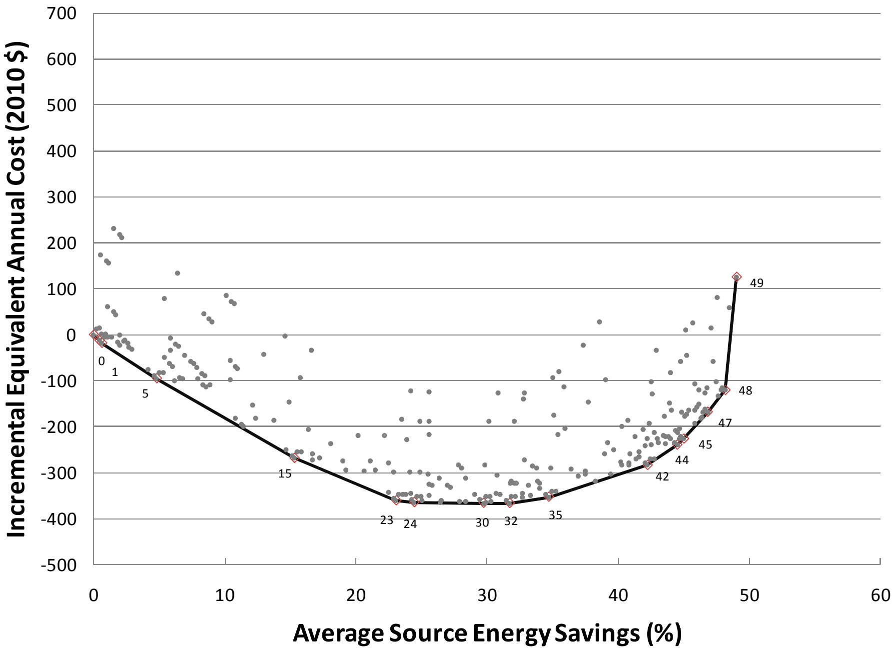

Figure 5-8. Incremental EAC at different levels of energy savings for Minneapolis

Table 5-14. Least-Cost Packages at Different Energy Savings for Minneapolis

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
0	−13													X							
1	−18														X						
5	−95			X											X						
15	−268	X		X											X						
23	−361	X	X	X											X						
24	−364	X	X	X											X						X
30	−366	X	X	X											X			X			X
32	−366	X	X	X									X		X			X			X
35	−353	X	X	X							X		X		X			X			X
42	−284	X	X	X			X				X		X		X			X			X
44	−240	X	X	X			X		X		X		X		X			X			X
45	−226	X	X	X			X		X		X		X		X			X		X	X
47	−168	X	X		X		X		X		X		X		X			X		X	X
48	−121	X	X		X			X	X		X		X		X			X		X	X
49	125	X	X		X			X	X		X		X		X		X	X		X	X

5.2.2 Summary of Optimization Results

To summarize the results obtained from the optimization for the eight cities, Table 5-15 shows the AES and incremental equivalent annual cost (IEAC) for minimum-cost packages and for packages on the least-cost curve that are closest to neutral cost.[17] The AES values for the minimum-cost packages range from 18% (San Diego) to 34% (Seattle) and the IEAC values range from –$388 (Washington, DC) to –$55 (San Diego). Averaged over the cities considered in this analysis, the minimum cost package achieves 30% AES at an IEAC of –$289. The AES values for the nearest to neutral cost packages[18] range from 29% (San Diego) to 48% (Seattle and Minneapolis).

Table 5-15. Minimum-Cost and Nearest to Neutral Cost Packages on Least-Cost Curve

Location	**Minimum Cost**		**Nearest to Neutral Cost**	
	AES (%)	**IEAC** (2010$)	**AES** (%)	**IEAC** (2010$)
Houston, Texas	30	–185	38	8
Phoenix, Arizona	33	–361	47	–31
Atlanta, Georgia	30	–293	41	–56
San Diego, California	18	–55	29	14
Seattle, Washington	34	–309	48	–39
Washington, D.C.	30	–388	43	–114
Chicago, Illinois	31	–351	47	–86
Minneapolis, Minnesota	32	–366	48	–121

Table 5-16 shows how measures are incorporated sequentially in the packages on the least-cost curve with increasing levels of average energy savings. Some observations are as follows:

- CFL lighting is always the first measure to be adopted.
- CFL lighting, drill-and-fill wall insulation, tankless water heater, and 4-ft basement insulation/close crawl space (where appropriate) are in the minimum-cost package for each city.
- Attic sealing and insulation is in every minimum-cost package except in San Diego, where space conditioning loads are smaller.
- Furnace upgrade is selected in Washington D.C., Chicago, and Minneapolis for the minimum cost packages.
- Window replacement, AC replacement, 8-ft basement insulation (where appropriate), tank water heater upgrade, duct sealing (no added insulation), and maximum air sealing are not included in any minimum cost package.

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[17] Note the least-cost curve is defined by a set of discrete retrofit packages. There is no guarantee any of the discrete packages delivers an IEAC of exactly $0.

[18] Targeting the nearest to neutral cost point may be an opportunity to accomplish significant savings when considered before any retrofit is performed. Once a retrofit package is implemented to the minimum cost point, there can be a significant cost barrier to get to larger energy savings.

Table 5-16. Order Measures Are Added to Packages on Least-Cost Curve to Minimum Cost Point

	Packages to Minimum Cost Point							
Location	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Houston, Texas	Lighting (44% CFL)	Lighting (55% CFL)	Seal and Insulate Ducts	Drill-and-Fill	ENERGY STAR Clothes Washer	Attic Sealing and Insulation	Tankless Water Heater	ENERGY STAR Refrigerator
Phoenix, Arizona	Lighting (44% CFL)	Lighting (55% CFL)	Drill-and-Fill	Seal and Insulate Ducts	Tankless Water Heater	Attic Sealing and Insulation	ENERGY STAR Clothes Washer	
Atlanta, Georgia	Lighting (44% CFL)	Lighting (55% CFL)	Drill-and-Fill	Attic Sealing and Insulation	Tankless Water Heater	ENERGY STAR Clothes Washer	Seal and Insulate Ducts	Close Crawl Space[a]
San Diego, California	Lighting (44% CFL)	Lighting (55% CFL)	ENERGY STAR Clothes Washer	Drill-and-Fill	Tankless Water Heater			
Seattle, Washington	Lighting (44% CFL)	Lighting (55% CFL)	Drill-and-Fill	Attic Sealing and Insulation	Close Crawl Space	Tankless Water Heater		
Washington, D.C.	Lighting (44% CFL)	Lighting (55% CFL)	4-ft Basement Insulation	Drill-and-Fill	Attic Sealing and Insulation	Tankless Water Heater	ENERGY STAR Clothes Washer	92.5 AFUE Furnace
Chicago, Illinois	Lighting (44% CFL)	Lighting (55% CFL)	4-ft Basement Insulation	Drill-and-Fill	Attic Sealing and Insulation	ENERGY STAR Clothes Washer	Tankless Water Heater	92.5 AFUE Furnace
Minneapolis, Minnesota	Lighting (44% CFL)	Lighting (55% CFL)	4-ft Basement Insulation	Drill-and-Fill	Attic Sealing and Insulation	ENERGY STAR Clothes Washer	92.5 AFUE Furnace	Tankless Water Heater

[a] The seal and insulate ducts measure added in the previous package on the least-cost curve is not included in the minimum cost package (see Table 5-9). Closing the crawl space brings the ducts inside the thermal enclosure and therefore reduces the benefit of duct sealing and insulation.

6.0 Conclusions

This report describes a method for analyzing potential energy efficiency retrofits of existing houses. The method uses an optimization scheme that considers average energy use (determined from building energy simulations) and equivalent annual cost to recommend optimal retrofit packages specific to the building, occupants, and location. Energy savings and incremental costs are calculated relative to a MURS, which accounts for efficiency upgrades that would have been made in the absence of a retrofit because of equipment wear-out and replacement with current minimum standards.

In the illustrative example, the method was applied to analyze the retrofit of a 1960s-era house in eight U.S. locations. Retrofit measures were defined considering safety and durability, in addition to cost-effectiveness. Financial considerations were developed to be consistent with the specific needs of retrofitting existing houses; measure costs were determined using the National Residential Efficiency Database (NREL 2010). A least-cost curve was presented for each location, from which optimal retrofit packages were highlighted at various levels of energy savings, including the minimum cost package and the package nearest to neutral cost.

The main conclusions of the example analysis presented in Section 5 follow:

- Results were specific to assumptions in the following categories (as described in Appendix B): general (analysis period, MURS, etc.), financial (retrofit financing and measure costs), occupant, and building. Results should not be interpreted as “average” for U.S. housing stock.
- For the 1,280 ft^2, 1960s-era home and the specific set of retrofit measures considered in the analysis, minimum cost packages varied in average energy savings from 18% in San Diego to 34% in Seattle.
- The nearest to neutral cost package provided significant additional savings beyond the minimum-cost package.

Issues such as complexity of the retrofit package, on-site conditions, and effect on occupant comfort were not considered and may justify certain measures that were not included in optimal packages, as well as eliminate measures that were. Together, the analysis method and example analysis presented in this report are an introduction to retrofit optimization; improvements to the analysis method and additional studies considering a comprehensive range of building types, locations, and retrofit measures are needed. Future efforts related to the analysis method and example analysis are presented in Sections 6.1 and 6.2, respectively.

6.1 Analysis Method Future Work

Despite the advances made to address the issues outlined in Section 4, several additional issues and areas of future improvement were identified while developing and implementing the analysis method.

- Financing replacements in the future—The current analysis method assumes that all future replacements are paid for in cash. In reality, financing may be used for larger replacements such as heating and cooling systems.

- Fuel price projection—The current analysis method assumes that fuel prices increase with inflation. Price projection (e.g., EIA[19] forecasting) could be included in future studies.
- HVAC equipment size—When HVAC equipment is replaced after or at the same time as other efficiency measures, it may be possible to downsize the equipment. In the current analysis method, equipment is not resized.
- Impact of retrofits on occupant behavior—Occupants may "take back" energy savings expected from a retrofit by changing their behavior to achieve more comfort. Or they may save additional energy because retrofits to the enclosure increase radiant temperatures and reduce drafts, allowing occupants to maintain comfort at more efficient thermostat settings. Future analysis methods could include validated models for the effect of retrofits on occupant behavior.
- Optimization in the future—The current analysis method makes recommendations only for a retrofit package implemented at the beginning of the analysis period, assuming all later replacements meet the current minimum standard or the existing efficiency, whichever is more efficient. Optimization could also be performed for retrofits after the beginning of the analysis period, such that the optimal package is a retrofit plan for the analysis period. An example optimal package could be drill-and-fill now, add foam sheathing at time of siding replacement, and upgrade to SEER 18 AC at time of SEER 10 AC wear-out.
- Performance degradation—The performance of building components can degrade with time. For example, without proper maintenance, an AC will become less efficient with time owing to problems such as loss of charge and fouling of the heat exchangers. This could affect both the energy savings of retrofit packages (e.g., degradation of new equipment over time) and the energy use of the existing building (e.g., already degraded equipment). More information is needed about the performance degradation of enclosure and equipment components to include this effect in the analysis.
- Standards forecasting—The current analysis method replaces all equipment below the current minimum standard with current minimum standard at the time of wear-out. Taken a step further, all equipment could be replaced with at least the future minimum standard, where forecasting is required to estimate the future standards.

6.2 Example Analysis Future Work

In general, the results in the example analysis presented in Section 5 reflect a long-term view of costs and energy savings—although the loan period was 5 years, replacement costs and utility bill cost savings over the 30-year analysis period were considered. Some homeowners may require a shorter time horizon, for example, when they plan to move and do not expect to recover the value of the retrofit at time of sale, or they are primarily concerned with year-to-year cash flow during the loan period and cannot afford to invest in retrofit measures for 5 years that are justified by energy savings over 30 years, or both. In these scenarios, the analysis period should be shortened to ensure the investment is justified by the energy savings that occur before the homeowner moves or the homeowner experiences a positive cash flow during the loan period (energy savings over loan period justifies loan payments). Alternatively, a longer term loan

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[19] See http://www.eia.doe.gov/oiaf/forecasting.html.

approaching the length of the analysis period could produce positive cash flow for the homeowner immediately. Future analyses should consider a variety of homeowner perspectives and financing mechanisms.

A more accurate characterization of the U.S. housing stock (sufficient for building energy modeling) is needed to build a statistically representative set of house descriptions in each climate region. This will involve developing representative house descriptions from identified existing datasets or from characterization data collected in the future. Applying the analysis method described in this report to these representative models would allow for extrapolating individual results to average potential energy savings for the U.S. housing stock, and generate climate and building-type specific recommendations for optimal individual retrofit measures and packages of measures. Other possible improvements for future studies include the following:

- Adjust retrofit costs city by city, similar to energy costs.
- Add more house types (e.g., two-story houses). Ideally, the house types analyzed should be representative of the locations considered, including assumptions related to fuel types.
- Add retrofit measures, including those for safety and health of the occupants (e.g., combustion air for the atmospherically vented appliances).
- Investigate different metrics, financial mechanisms, and loan terms to cover a wider range of possibilities.

Finally, efforts continue at NREL to assess and improve the accuracy of analysis tools by developing new and improved models and validating software predictions against measured data. Energy use and savings predictions in this and future studies should be compared to measured use and savings from laboratory tests, field tests, and pre- and post-retrofit utility bill analysis.

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Appendix A. Pre- and Post-Retrofit Performance Assumptions for Example Analysis

This appendix describes the technical retrofit measure definitions and the assumptions used in the example analysis. The relevant cost data were taken from the National Residential Efficiency Measures Database, v1.0.0beta (NREL 2010). As described in Section 5, the example analysis of the 1280 ft^2, 1960s-era house illustrates the analysis method presented in Section 4. Accordingly, the pre-retrofit assumptions are not meant to be "average" for the U.S. housing stock, and the post-retrofit assumptions may not represent the only viable retrofit options for the example house.

A.1 Enclosure Components

A.1.1 Crawl Spaces

Pre-Retrofit Performance Assumptions—Crawl spaces are often designed as a vented assembly with an earthen floor and may contain mechanical services for the house (e.g., furnace, ductwork, plumbing). Moisture management is a critical consideration when retrofitting crawl spaces.

Seattle and Atlanta were modeled with uninsulated, vented crawl spaces. An important modeling input in BEopt for vented crawl spaces is the air changes per hour (ACH) within the space. Open crawl space natural ventilation rates can vary widely from house to house, depending on the characteristics of the building, the vents, the surrounding buildings and vegetation, the weather, and so on. Some ACH values from the literature are:

- 0.67 ACH (ASHRAE 2001)
- 0.4–1.7–2.5 ACH (Kurnitski 2000)
- 2–8 ACH (Trethowen 1994)
- 3.5–5 ACH (Karagiozis 2005)
- 1 ACH (Lstiburek 2008).

The BEopt default value of 2 ACH used in this analysis falls within the range of values presented in the literature, but more research is needed to determine average natural infiltration levels or to develop more detailed algorithms for predicting crawl space natural ventilation rates on at the hourly or sub-hourly timescale.

The characteristics of the pre-retrofit crawl space are:

- Naturally vented, BEopt default 2 ACH
- Ducts in unconditioned crawl space (duct leakage into space)
- Uninsulated crawl space ceiling and walls
- No vapor barrier on crawl space floor.

Post-Retrofit Performance Assumptions—Building code generally requires crawl space ventilation (natural or mechanical) unless it has all of the following characteristics (Lstiburek 2004):

- A vapor barrier installed on the crawl space floor
- Insulation installed on the exterior crawl space walls
- Conditioned crawl space.

Although the intent of crawl space ventilation requirements in building code is primarily to control moisture, building scientists have demonstrated that in certain climates (such as hot humid areas in the Southeast), natural ventilation can actually increase the moisture in the crawl space (Lstiburek 2004, Davis et al. 2005). An alternative approach is closing and conditioning the crawl space according to the general requirements stated previously. Specific requirements for closing crawl spaces depend on local building code. Example specifications can be found in the literature (Dastur et al. 2005, Lstiburek 2004).

For the purposes of this energy analysis, the natural ventilation rate of the closed crawl space is assumed to be 0.35 ACH.

The retrofit option included in this study is based on a previous field study (Davis et al. 2005). The following list contains the major characteristics of the retrofit; smaller details may be included when determining cost (such as adding a crawl space drain).

- Install vapor barrier on crawl space floor
- Install vapor barrier on crawl space exterior walls
- Air seal where appropriate
- Install 2 inches of R-13 foil-faced polyisocyanurate (polyiso) foam on exterior crawl space walls, leaving a 3-inch gap between crawl space floor (to prevent wicking) and a 3-inch gap between the top sill (for termite inspection)
- Add supply duct that provides conditioned air to space when heating, ventilating, and air-conditioning (HVAC) system runs.

For the retrofit described, it is assumed no problems exist in the crawl space related to combustion safety, radon, mold, rot, insects, flooding, and drainage. Additionally, it is assumed that the conditioned air from the HVAC system adequately removes moisture from the crawl space (no additional dehumidification is needed). The insulation is modeled in BEopt as covering the entire crawl space wall, so the insulation R-value is derated to R-11.4 to approximate the effect of the 3-inch gaps in insulation. Because of modeling constraints in DOE2.2[20], the supply duct airflow into the crawl space is not modeled explicitly. The amount of conditioned air entering the crawl space through the supply duct (~30 cfm) would, however, be small compared to the duct leakage into the crawl space (e.g., 10% supply side leakage with a 2,000-cfm HVAC

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[20] DOE2.2 is a detailed building energy simulation program and was the primary simulation engine underlying BEopt analysis for this report. For more information on the DOE2 software please visit http://www.doe2.com/.

system flow rate corresponds to 200 cfm of conditioned air entering the crawl space when the air handler is running).

Other crawl space retrofits such as insulating the underside of the floor joists with rigid insulation were not considered in this analysis. This type of retrofit may necessitate moving the mechanical equipment into the attic, which in turn may require closing and conditioning the attic space. Future analyses may include this combination of options.

Lifetime—The assumed lifetime for this measure is greater than the 30-year analysis period. Some maintenance of the vapor barrier may be required, depending on how frequently people enter the space.

A.1.2 Basements

Pre-Retrofit Performance Assumptions—An uninsulated, unconditioned basement is assumed for the pre-retrofit case in Chicago, Minneapolis, and Washington, DC. BEopt models basements with zero exposed above-grade wall sections. This results in an ACH of zero. The unconditioned basement also has zero cavity insulation between the floor joists above the basement.

Post-Retrofit Performance Assumptions—It may not be appropriate to insulate all basement walls because of moisture concerns. The current analysis assumes that the basement does not have a history of moisture issues. If evidence or knowledge of such problems exists, a perimeter drain may be needed (BSC 2007a). The high cost[21] associated with removing sections of the slab floor, installing the drainage system, and repouring concrete mean an undertaking of this magnitude would not necessarily be motivated solely by the energy saving potential. This scenario is not considered in the current analysis.

There are a number of recommended retrofit options for insulating existing basement walls where there are no known moisture problems, as shown in Table A-1 (BSC 2007a, Yost and Lstiburek 2002). The options involve using either fire-rated polyiso or extruded polystyrene (XPS). Other insulation systems used in basement applications, such as “blankets” with impermeable surfaces, have proven to be problematic (Aldrich and Zuluaga 2006, Yost and Lstiburek 2002) and are not recommended. XPS must be protected with at least a 15-minute thermal barrier (e.g., 0.5-in. gypsum board) (BSC 2007a). This essentially means the insulation retrofit turns an unfinished basement into a finished basement, thereby adding a significant benefit to the project beyond the energy savings alone. Secondary benefits occur with many other retrofit measures as well, though often in less direct ways. For example, improvements to the above-grade enclosure may be economically justified on the energy savings associated with them but the homeowner enjoys the added benefit of improved comfort. These benefits are not accounted for in the current analysis because they are difficult to monetize.

The current analysis only includes the 0.5-in. wall polyiso and 1–in. XPS with furring strip options. The half-wall polyiso option does not result in a finished basement and can be considered an energy-only measure. Because the 1–in. XPS with furring strips option does not

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[21] Yost and Lstiburek (2002) note: “The cost of accomplishing [moisture flow and airflow control] can be difficult and frequently expensive. In many older homes and some newer homes basements cannot be insulated safely and inexpensively. The cost of properly insulating a basement while controlling moisture should be compared with the cost of constructing additional quality living space above grade.”

result in wall cavities, running services (e.g., electrical) through the wall is not possible and therefore the result is a less-finished option than the framed options.

Table A-1. Summary of Proposed Basement Wall Measures and Costs

Measure	Effective (Nominal) R-value[a]	Estimated Total Cost (evaluated for our test house)[b]
Half wall (4-ft) application of 1-in. fire-rated polyiso	R-6 (R-6)	$700
1–in. XPS fastened w/furring strips covered with gypsum sheathing (rough finish, no paint)	R-6.4 (R-5)	$2,760
2–in. XPS fastened w/furring strips covered with gypsum sheathing	R-11.4 (R-10)	$3,490
1–in. XPS plus frame wall with gypsum sheathing	R-6.7 (R-5)	$3,600
2–in. XPS plus frame wall with gypsum sheathing	R-11.7 (R-10)	$4,330
1–in. XPS plus frame wall, gypsum sheathing, R-13 fiber glass batts	R-16.6 (R-18)	$4,730
2–in. XPS plus frame wall, gypsum sheathing, R-13 fiber glass batts	R-21.6 (R-23)	$5,450

[a] The effective R-value was calculated using the simple parallel paths method and published material properties (ASHRAE 2005). A 16% framing factor was used for furred assemblies (1 × 3 in. furring strips, 16–in. on centers [O.C.]), and an 18% framing factor was used for stud assemblies (2 × 4 in., 16–in. O.C., including top and bottom plates).

[b] Costs taken from RSMeans (RSMeans, 2010). Gypsum considered taped and finished but not painted.

Lifetime—The assumed lifetime for this measure is greater than the 30-year analysis period.

A.1.3 Wall Insulation

Pre-Retrofit Performance Assumptions—It is assumed that the example analysis house is 2×4 stick-built with no wall insulation. Joint Appendix IV of Title 24 (CEC 2005) indicates a U-value of 0.356 Btu/ h·ft²·°F for a 16 in. O.C. wall with no cavity insulation. This leads to an overall R-value of the wall, including the film coefficients of 2.8 Btu/ h·ft²·F. The pre-retrofit wall in BEopt has an R-value of 2.2 excluding gypsum board and film coefficients. Including the expected R-values of drywall (~R-0.5) and the film coefficients yields a total assembly R-value close to the CEC Title 24 definition of an empty cavity wall.

Post-Retrofit Performance Assumptions—The nominal levels of dense pack cellulose cavity insulation are assumed to be the maximum attainable (R-13) for an empty 2×4 cavity (3.5 in. deep) (Greenfiber 2010). Our analysis is conservative in that it does not take into account the air-sealing benefits of dense pack insulation (Lstiburek 2010b).

Lifetime—The assumed lifetime for this measure is greater than the 30-year analysis period.

A.1.4 Whole House Air Sealing

Pre-Retrofit Performance Assumptions—The Lawrence Berkeley National Laboratory (LBNL) has done extensive work quantifying air leakage in U.S. homes, e.g., Chan et al. (2005), Sherman and Dickerhoff (1998), and Sherman and McWilliams (2007). These data (~100,000 houses) were used by McWilliams and Jung (2006) in the development of a statistical model to estimate the normalized leakage of a home using the following variables: climate zone, age, floor area, number of stories, whether or not the home has been previously improved for energy efficiency, whether or not the home is considered "low income," and foundation type. The output of this model, normalized leakage (NL), can be used in the calculation of BEopt inputs (i.e., either whole-house SLA [specific leakage area] or natural ACH [nACH]). For example, using a 1,280 ft2 home built in 1960, located in a cold climate with an unconditioned basement and assuming the home has not been previously air-sealed nor is considered low income, the total SLA is calculated to be 0.0010 (ACH50 = 21.6, nACH = 0.92). The SLA increases in dry climates (0.0012) and decreases for humid climates (0.0007). The assumed total SLA for the retrofit analyses done to date for all climates, 0.0009 (18.6 ACH50), appears to be within the range estimated by the McWilliams and Jung model.

Other, more general references (Tiller and Creech 2006) show the typical infiltration rates for existing homes to be between 10 and 50 ACH50. The assumed value for the retrofit analysis is within this general range.

Post-Retrofit Performance Assumptions—The analysis includes two measures that affect the infiltration rate of the house: an attic and air seal (20% reduction) and an aggressive air seal with exhaust-only mechanical ventilation (55% reduction with 75% of ASHRAE 62.2 or 32 cfm[22]).

Retrofit data for air sealing reveal a wide range of likely outcomes. Sherman and Dickerhoff (1998) found that air sealing retrofits resulted in an average reduction in leakage of 25%. Improvements to a "typical" home of approximately 45% (calculated from the nACH values referenced) are cited by ENERGY STAR (EPA 2010c). This analysis assumes a comprehensive whole house air sealing retrofit beyond what is "typical."

Air sealing retrofits considered in this analysis do not result in an outdoor air ventilation rate below the acceptable level as specified in the most recent version of ASHRAE Standard 62.2 (ASHRAE 2007).[23] For a three-bedroom, 1,280 ft^2 house, ASHRAE 62.2-2007 specifies a continuous outdoor air flow rate of 42.8 cfm. The natural pre-retrofit infiltration rate is 131 cfm. A 55% reduction of the pre-retrofit natural rate results in a post-retrofit natural rate of 59 cfm. As per 62.2-2007, "When excess infiltration has been measured….the rates in Section 4.1 may be decreased by half of the excess of the rate calculated….that is above the default rate". Therefore, if the excess rate is 59 – 42.8 = 16.2 cfm, one half is 8.1 cfm resulting in a ventilation rate requirement as per 62.2-2007 of 42.8 – 8.1 = 34.7 cfm. The use of 75% of 62.2-2007, or 32 cfm (display variable from BEopt), is appropriate for approximating energy usage due to exhaust-only mechanical ventilation.

Lifetime—The assumed lifetime for this measure is greater than the 30-year analysis period.

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[22] The exhaust-only mechanical ventilation option in BEopt assumes a fan energy of 0.3 W/cfm (e.g. 10 W for 32 cfm).

[23] An updated version is scheduled to be released September 2010 (ASHRAE 2010).

A.1.5 Attic Insulation and Air Sealing

Pre-Retrofit Performance Assumptions—Initial levels of insulation (R-19 in Chicago and Minneapolis, R-11 in all others) are assumed because adding insulation to attic is an easy retrofit that took place in many houses that were built in the 1960s.

Post-Retrofit Performance Assumptions—Final levels of insulation are taken from the U.S. Environmental Protection Agency's (EPA's) "Recommended insulation levels for retrofitting existing wood-framed buildings" (EPA 2010b). Chicago and Minneapolis are retrofitted to R-49 and all other cities are retrofitted to R-38. Blown cellulose is the assumed material, although other insulation products such as fiberglass insulation are equally acceptable options.

Before performing an attic insulation retrofit, air-sealing the attic floor is recommended to prevent air leakage from the conditioned zone of the house. Failure to do so could result in health, safety, and durability issues. A number of references are available to guide and inform this work, including:

- The EPA's "A Do-It-Yourself Guide to Sealing and Insulating with ENERGY STAR" (EPA 2007a)
- Building Science Corporation's document on attic air sealing, including details: "Guide to Attic Air Sealing" (Lstiburek 2010a)
- Building America's "Best Practices Series" on air sealing (Baechler and Love 2010).

The analysis assumes a 20% whole-house infiltration reduction from air sealing the attic floor.

Lifetime—The assumed lifetime for this measure is greater than the 30-year analysis period.

A.1.6 Windows

Pre-Retrofit Performance Assumptions—The Residential Energy Consumption Survey (RECS) includes specific questions characterizing the type of windows installed in the survey homes. According to the RECS microdata (EIA 2009), 60% of 1960s-era homes have single-pane windows. In this particular vintage, slightly less than 50% have had a full window replacement during the life of the house at the time of the survey. These data show that a reasonable fraction of 1960s-era homes have single pane windows today, as assumed in the example analysis. The properties of this window type were derived from the National Residential Efficiency Measures Database (v1.0.0beta, NREL 2010) and represent the single-pane, clear, wood frame assembly (shown in bold in Table A-2).

Table A-2. Single-Pane Window Options From the National Residential Efficiency Measures Database

Window Type	U-Factor	SHGC
Single-Pane, Clear, Aluminum Frame	1.27	0.75
Single-Pane, Tinted, Aluminum Frame	1.27	0.64
Single-Pane, Clear, Vinyl Frame	0.89	0.64
Single-Pane, Clear, Wood Frame	**0.89**	**0.64**
Single-Pane, Tinted, Vinyl Frame	0.89	0.54
Single-Pane, Tinted, Wood Frame	0.89	0.54

Post-Retrofit Performance Assumptions—Our analysis assumes full window replacement, though other retrofit options exist (EfficientWindows 2010). Windows should be installed to carefully manage bulk water entry into and air leakage across the enclosure. Details for managing these risks can be found in several Building America publications (BSC 2007b, 2009, IBACOS 2003). Full window replacement will likely reduce the air leakage associated with the fenestration components of the enclosure. The air leakage associated with windows and doors, as a percentage of total air leakage, is typically between 6% and 22% (ASHRAE 2005). Because of a lack of data quantifying air leakage reductions associated with window replacement, the current analysis does not account for these effects.

The retrofit window options (see Table A-3) are in part based on the 2009 IECC (IECC 2009) and ENERGY STAR (EPA 2010a). Modifications were made to reflect the current market conditions and to ensure consistency with the Building America House Simulation Protocol (Hendron and Engebrecht 2010).

Table A-3. Retrofit Window Options

Standard	Houston	Phoenix	Atlanta	San Diego	DC	Seattle	Chicago	Minneapolis
IECC Climate Zone	2	2	3	3	4	4	5	6
IECC U-value	0.40	0.40	0.40	0.40	0.35	0.35	0.35	0.35
IECC SHGC	0.30	0.30	0.30	0.30	0.35	0.35	0.35	0.35
ENERGY STAR U-value	0.40	0.40	0.35	0.35	0.32	0.30	0.30	0.30
ENERGY STAR SHGC	0.27	0.27	0.30	0.30	0.40	0.50	0.50	0.50

Lifetime—The assumed lifetime for this measure is greater than the 30-year analysis period.

A.2 HVAC Equipment and Distribution

A.2.1 Air Conditioning

Pre-Retrofit Performance Assumptions—As of 2007, 51.8% of U.S. homes had central AC systems, and 12.8% had heat pumps (DOE 2010). In the same year, the following numbers of units were sold (DOE 2010):

- Split system central AC = 3.58 million
- Single package central AC = 0.34 million
- Split heat pump = 1.57 million
- Single package heat pump = 0.20 million.

Because of their high saturation level and sales, split system central AC systems were considered in this analysis for the pre-retrofit building and the space cooling retrofit options.

As of January 23, 2006, the national minimum standard for split system central AC is SEER 13 (CFR 2002; DOE 2010). The pre-retrofit AC used in our analysis is the BEopt standard SEER 10 option. The minimum replacement AC is the BEopt standard SEER 13 option.

Post-Retrofit Performance Assumptions—Federal tax credits (as of June 2010) for central AC systems require a minimum SEER 16 (EER 13) (CEE 2009, DOE 2010). The highest tier efficiency level for split system central AC under the CEE Residential Central Air Conditioner and Heat Pump Initiative is also SEER 16 (EER 13) ((DOE 2010, EPA 2010d). The BEopt SEER 16 (EER 11.61) standard option is considered as a potential retrofit in our analysis.

Lifetime—A previous literature review of AC lifetimes shows (DOE 2010):

- *Appliance Magazine*: 11 year average for residential central AC
- Air-Conditioning, Heating and Refrigeration Institute: 12–15 years
- DOE (2010) study: 19 years.

The BEopt default lifetime of 18 years was used in this analysis.

A.2.2 Gas Furnace

Pre-Retrofit Performance Assumptions—Indoor gas furnaces are the most common type of residential space heating equipment (DOE 2006). The National Appliance Energy Conservation Act (NAECA) was passed in 1987 and established a minimum annual fuel utilization efficiency (AFUE) of 78% for gas furnaces effective January 1, 1992 (DOE 2006, LBNL 2010). The AFUE of 78% remains the national minimum standard. According to the Department of Energy (DOE 2006), "Most of the [indoor] gas furnaces on the market have an efficiency of 80 percent AFUE."

An 80% AFUE gas furnace is assumed for the pre-retrofit building. The BEopt 80% AFUE standard option is selected for the pre-retrofit furnace in our analysis.

Post-Retrofit Performance Assumptions—Condensing gas furnaces accounted for approximately one-third of sales as of 2006 and ranged in efficiency from about 90% to 94% AFUE (DOE 2006). The analysis considers a 92.5% AFUE condensing gas furnace retrofit option. The BEopt 92.5% AFUE standard option is selected for the post-retrofit furnace in our analysis.

Lifetime—The average lifetime used by the U.S. Department of Energy (DOE 2006) for an indoor gas furnace is 20 years. The BEopt default furnace lifetime of 20 years was used in the analysis.

A.2.3 Air Distribution System

Pre-Retrofit Performance Assumptions—Many studies have been done to quantify duct leakage in U.S. homes. These tests do not always use the same methods or metrics (e.g., cubic feet per minute or percent fan flow) and have limited sample sizes. Additionally, some tests do not distinguish between supply and return leakage fractions. BEopt requires supply and return leakage, as well as supply and return leakage at the air handler unit (AHU), as a percentage of total fan flow.

ASHRAE Standard 152 was introduced in 2004 and includes two methods for measuring duct leakage in the field (Modera 2005).

Francisco et al. (1998) observed 20% supply (± 4% stdev) and 20% return (±17% stdev) leakage to the outside pre-retrofit (n = 6, Pacific Northwest). This was reduced to ~7% supply (±4% stdev) and 6% return (±5% stdev) leakage to the outside through retrofit measures (~70% reduction). This study used a combination of blower door, duct leakage, and register flow measurements in its calculations.

Jump et al. (1996) measured duct leakage (n = 24 houses in Sacramento) using a flow subtraction technique (leakage = total AHU flow – Σ register flows). Average supply leakage pre- and post-retrofit was 18% and 8% (±8/8% stdev). Average return leakage pre- and post-retrofit was 17% and 13% (±10/9% stdev) (~40% reduction).

Karins et al. (1997) investigated duct leakage (n = 25 units in nine multifamily buildings in New York) using the flow subtraction technique and duct leakage measurements (supply side only). Pre-retrofit supply leakage ranged from 14% to 35% using the flow subtraction technique and 18% to 35% using the duct leakage test. This was reduced to 0-6% post retrofit using the flow subtraction and 14% to 30% using the duct leakage test. Pre-retrofit return leakage was large at 56% to 83% and was reduced to 11% to 51%. This study shows the possible variability in results when using or comparing different testing techniques.

Yuill and Musser (1997) studied retrofit effectiveness for duct leakage using whole house and duct pressurization at different levels such that the results could be used for curve fitting (n = 5, Pennsylvania). The authors note that there were variable pressures in the duct system that could have “significantly impacted” the results of their test (p. 265). The results are not presented in such a way to identify leakage as a percentage of system flow. The average post-retrofit reduction in leakage was 16% (ignoring one outlier point, entire sample range is 5%–93% leakage reduction).

Erinjeri et al. (2007) performed a comprehensive statistical review of duct leakage measurements taken using three different test methods (variations on blower door methods to evaluate leakage to outside) in homes in Louisiana (n = 39, 32, or 35, depending on test and comparison). Results are presented in absolute terms (i.e., cubic feet per minute of leakage) with no further information about a particular system that would allow for the comparison of the test results to BEopt inputs. The authors note that, however, assuming a system size of 3 tons (with 400 cfm/ton), the average total duct leakage in Louisiana homes is 29%.

Walker et al. (1996) used the flow subtraction technique to measure duct leakage (pre- and post-retrofit) in two apartment buildings in New York where the retrofit was performed on visible duct sections in the basement only. Large, obvious leaks (e.g., disconnected ducts) were repaired before the retrofit. Average supply leakage pre-retrofit was 34% and was improved to 22%. Average return leakage pre-retrofit was 82% and improved to 57%.

Walker et al. (2009) measured leakage at the AHU cabinet in a laboratory setting. The results indicated a leakage rate of 5% of total system flow.

Siegel et al. (2002) describe a useful comparison of duct leakage in new construction using the test procedure defined in ASHRAE Standard 152. They found an average supply side leakage to the exterior of 6% and an average return side leakage to the outside of 5% (total supply and return leakages were 9% and 8%, respectively).

The BEopt inputs used in the analysis are 10% supply leakage and 5% return leakage (inclusive of cabinet leakage). The literature has a large range of results, and assuming 15% total duct leakage is toward the conservative end of the range.

Francisco and Palmiter (1998) and Jump et al. (1996) have the most descriptive results for single family houses. Their results show supply leakage greater than return leakage. This observation is consistent with the BEopt inputs used in this analysis.

Post-Retrofit Performance Assumptions—Post-retrofit duct leakage assumes a 50% reduction to 4.4% and 3.6% supply and return leakage, respectively. A ~50% reduction in duct leakage is possible (see Francisco and Palmiter, 1998) but could be toward the upper range of what is commonly achieved in the field (see Jump et al. 1996; Yuill and Musser 1997; Walker et al 1996).

Lifetime—The assumed lifetime for this measure is greater than the 30-year analysis period.

A.3 Domestic Water Heating Equipment

A.3.1 Replacement of Standard Gas With ENERGY STAR Gas Water Heater

Pre-Retrofit Performance Assumptions—The BEopt standard efficiency water heater (energy factor [EF] = 0.59, 40-gal tank) was chosen for the pre-retrofit house and corresponds to the minimum NAECA efficiency level (DOE 2009). The assumed cost for replacing this water heater with the same model was $930.

Post-Retrofit Performance Assumptions—The standard gas storage water heater is replaced with a higher efficiency gas storage water heater of the same volume meeting ENERGY STAR requirements effective September 1, 2010 (EPA 2010e). The ENERGY STAR performance requirements are EF ≥ 0.67, first hour rating (FHR) ≥ 67 gal/h. BEopt inputs for this water heater were developed using the method presented in Burch and Erickson (2004).

Lifetime—The 11-year default BEopt lifetime was used for storage tank water heaters.

A.3.2 Replacement of Standard Gas With ENERGY STAR Tankless Water Heater

Pre-Retrofit Performance Assumptions—The BEopt standard efficiency water heater (EF = 0.59, 40 gal) was chosen for the pre-retrofit house and corresponds to the minimum NAECA efficiency level (DOE 2009). The assumed cost for replacing this water heater with the same model was $930.

Post-Retrofit Performance Assumptions—The standard gas storage water heater is replaced with a gas tankless water heater meeting ENERGY STAR requirements effective September 1, 2010 (EPA 2010e). The ENERGY STAR performance requirements are EF ≥ 0.82, gallons per minute (gpm) ≥ 2.5 over a 77°F temperature rise. The nominal EF is derated in BEopt according to CEC (2010).

Lifetime—The 20-year default BEopt lifetime was used, which agrees with DOE (2009).

A.4 Appliances and Lighting

A.4.1 Lighting

Pre-Retrofit Performance Assumptions—The pre-retrofit lighting inputs are consistent with the Building America House Simulation Protocol (Hendron and Engebrecht 2010). Specifically, it is assumed that 21% of the lighting in the house is compact fluorescent lamps (CFLs) and 13% linear fluorescent lamps (LFLs). All other lighting is incandescent.

Post-Retrofit Performance Assumptions—The EERE US Lighting Market Characterization (Navigant 2002) references a study from Grays Harbor, Washington, where a detailed inventory of light fixtures indicated that ~50% of all sockets could receive CFLs (Jennings et al. 1996). Using the data from Appendix D of Navigant (2002) and noting that CFLs typically replace general service lamps (GSLs) only, the potential for CFLs as a percentage of installed lamps was calculated to be approximately 80% (Table A-4). This level of penetration may not, however, be feasible (e.g., because of dimming requirements), nor is it necessarily cost-effective to install CFLs in parts of the house with low hours of use. Additional data from Navigant (2002) report the average hours of use in each room. These data were combined with Table A-4 data for interior, conditioned spaces to determine retrofit package options; i.e., when considering interior, high-use spaces, what fraction of installed capacity makes sense for CFL installations? The results are shown in Table A-5. Package A includes the top five most lit rooms by annual hours of use (Navigant 2002): kitchen, utility room, living room, dining room, and family room. Package B adds to Package A the sixth most lit room by hours, the bathroom, and Package C adds the seventh most lit room by hours, the hall. Packages B and C are used in this analysis.

Table A-4. GSL and CFL Summary by Room

Area	Number of Lamps (total)	Number of GSLs	Number of CFLs
Bathroom	6.88	6.14	0.04
Bedroom	9.94	9.40	0.09
Closet	0.77	0.72	0.01
Dining Room	1.23	1.16	0.01
Family Room	2.38	1.79	0.04
Garage	4.23	1.87	0.03
Hall	5.12	4.82	0.03
Kitchen	5.11	2.68	0.14
Living Room	5.97	5.38	0.22
Office	1.16	0.86	0.03
Other	2.05	1.00	0.01
Outdoor	4.06	2.50	0.05
Utility Room	1.81	1.36	0.08
Total	**50.71**	**39.69**	**0.78**
% of Total		**78%**	**2%**

Source: Adapted from Navigant (2002).

Table A-5. Lighting Retrofit Options

Package	Number of Lamps (total)	Number of GSLs	Percentage of GSLs
A	16.5	12.38	29%
B	23.38	18.52	44%
C	28.50	23.34	55%

Source: Adapted from Navigant (2002).

Lifetime—Lamps are aggregated in BEopt and a common, effective lifetime is calculated. Individual lamp lifetimes came from ENERGY STAR (EPA 2007b). Table A-6 shows the packages and their associated lifetimes.

Table A-6. Lighting Options and Lifetimes

Timing	Lamp Distribution (%CFL:%LFL:%Incandescent)	Effective Lamp Lifetimes (years)
Pre-Retrofit	21:13:66	3.98
Post-Retrofit	44:13:43	6.21
Post-Retrofit	55:13:32	7.57

A.4.2 Refrigerator

Pre-Retrofit Performance Assumptions—The “Below Standard, Large (20 ft^3)” refrigerator in the National Residential Efficiency Measures Database (v1.0.0beta, NREL 2010) was assumed for the pre-retrofit building and has a rated annual energy consumption of 739 kWh/yr.

Post-Retrofit Performance Assumptions—Two refrigerator options were evaluated for the retrofit:

1. Standard option: The “Standard, Large (20 ft^3)” refrigerator in the National Residential Efficiency Measures Database was evaluated and has a rated annual energy consumption of 514 kWh/yr.
2. ENERGY STAR: The “ENERGY STAR, Large (20 ft^3)” refrigerator in the National Residential Efficiency Measures Database was evaluated and has a rated annual energy consumption of 411 kWh/yr.

Lifetime—The BEopt default lifetime of 19 years was used in the analysis.

A.4.3 Clothes Washer

According to the ENERGY STAR website (EPA 2010f), as of January 1, 2011, the minimum federal standard for clothes washers is modified energy factor (MEF) ≥ 1.26 and water factor (WF) ≤ 9.5, and the ENERGY STAR requirements are MEF ≥ 2.0 and WF ≤ 6.0.

Pre-Retrofit Performance Assumptions—A 3.5 ft^3 top-loading clothes washer with MEF = 1.41 and WF = 8.6 was assumed for the pre-retrofit building. The assumed cost of replacing this clothes washer with the same model is $500.

Post-Retrofit Performance Assumptions—A 3.7 ft^3, MEF = 2.47, WF = 3.9, top-loading clothes washer was evaluated as an ENERGY STAR retrofit option.

Lifetime—A lifetime of 13 years was assumed in the analysis.

Appendix B. Sensitivity of Example Analysis Results

B.1 Introduction

The example analysis results (Section 5) for the individual retrofit measures and packages of retrofit measures are sensitive to:

- General assumptions
    - Analysis approach (hourly simulations, life-cycle cost)
    - Length of analysis period
    - Minimum upgrade reference scenario (MURS)
- Financial assumptions
    - Discount rate
    - Loan interest rate and length
    - Fuel prices and fuel escalation rate
    - Retrofit and replacement costs
    - Residual values
- Occupant assumptions
    - Same occupants year to year
    - Behavior of occupants
- Building assumptions
    - Basic building features (geometry, foundation type, fuel type, etc.)
    - Pre-retrofit enclosure and equipment characteristics
    - Retrofit enclosure and equipment characteristics.

Results should be interpreted with the understanding that alternative assumptions could produce different values for incremental equivalent annual cost (IEAC) and average energy savings (AES), as well as lead to different optimal packages of retrofit measures. This appendix discusses sensitivity to key assumptions and gives some examples.

B.2 General Assumptions

As discussed in Section 5, NREL researchers developed an analysis method to determine optimal retrofit packages and estimate energy savings specific to the building, occupants, and location. This approach uses annual building energy simulations to determine energy savings over the analysis period relative to a MURS. The equivalent annual cost of the retrofit is calculated relative to the MURS considering retrofit costs, replacement costs, utility bill costs, and residual values using a life-cycle cost analysis approach. The example analysis results are therefore sensitive to the building energy simulation program used to perform the simulations (BEopt with DOE-2.2 engine), the approach used to perform the economic analysis, the length of the analysis period, and the assumptions related to the MURS.

A development version of BEopt with the DOE-2.2 simulation engine was used to complete the annual building energy simulations. The results depend on the specific algorithms and default assumptions associated with the DOE-2.2 engine, as well as many "background" inputs and assumptions in BEopt that are not part of the DOE-2.2 engine, but also not part of the user-selected inputs. A version of BEopt using EnergyPlus as the simulation engine has been developed, though further testing is needed before the example analysis simulations can be run using the EnergyPlus version of BEopt. Eventually, optimizations should be performed using both the DOE-2.2 and EnergyPlus versions of BEopt to investigate the sensitivity or results to the underlying simulation engine and other background inputs and assumptions.

A life-cycle-cost analysis determined the financial implications of different retrofit scenarios. Inherent in this analysis approach is the assumption of a time horizon (analysis period) over which cash flows and annual energy uses are calculated. Therefore, the choice of a life-cycle-cost analysis and the 30 year time horizon affects the results presented in Section 5. Alternative methods such as simple payback based on first costs and first-year energy savings may lead to different prioritizations of individual measures and different recommendations for retrofit packages.

The MURS is the baseline for calculating incremental EAC and average energy savings. Thus, all results presented in Section 5 are sensitive to the MURS assumptions. Other analysis approaches may calculate energy savings relative to the pre-retrofit building and assume that level of energy savings extends over a number of years. Using the MURS as the baseline ensures that no credit is taken for energy savings that would have otherwise occurred through equipment wear-out and replacement, as required by the current minimum standards. Forecasting standards into the future and including those forecasts in the MURS would tend to reduce the average energy savings predictions because the reference scenario would have a more efficient building, on average.

B.3 Financial Assumptions

We made several financial assumptions to complete the example analysis. Assumptions related to the discount rate, inflation, loan interest rate/length, fuel prices/escalation, retrofit costs, replacement costs, and residual values all affect the EAC (used as a metric in the optimization) and therefore affect the results for both individual measures and packages of measures.

A 6.1% nominal discount rate was used in Section 5 to convert the time-series cash flows into present worth. Figure B-1 shows the Chicago optimization results[24] for nominal discount rates of 3%, 5%, and 10%. As seen in Figure B-1, the AES at minimum cost decreases as the discount rate increases.[25] This is in part because energy efficiency upgrades are competing with more lucrative alternative investment options at higher rates of return.

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[24] The sensitivity analysis in this appendix was performed with preliminary input assumptions that are slightly different from the ones used in the main body of the document.

[25] Plots in this appendix are taken directly from the BEopt output screen, where “Annualized Energy Related Costs” on the y-axis are the annualized utility bills costs of the MURS plus the IEAC (in current dollars).

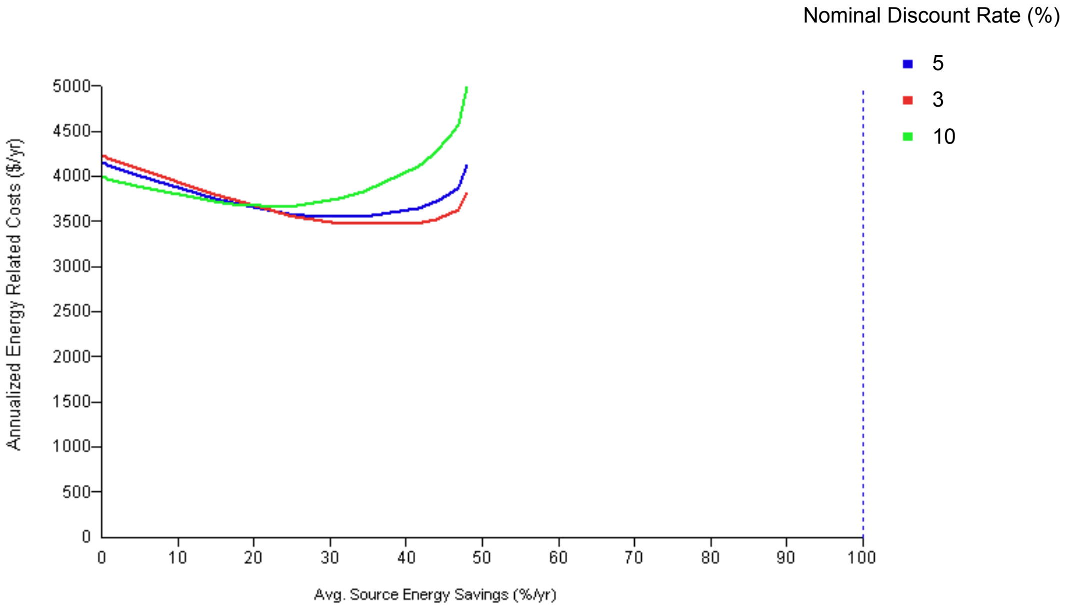

Figure B-1. Chicago optimization results as a function of nominal discount rate

The inflation rate affects the future costs of utility bills and replacements, as well as the residual values, which are based on the inflated cost of the component or equipment at the end of the analysis period. A 3% inflation rate was assumed for the example analysis. Figure B-2 shows Chicago optimization results for inflation rates of 0%, 3%, and 5%. The annualized energy related costs at 0% AES (y-intercept) are the annualized utility bill costs of the MURS. Both annualized utility bills of the MURS (y-intercept) and the AES at minimum cost increase as the inflation rate increases.

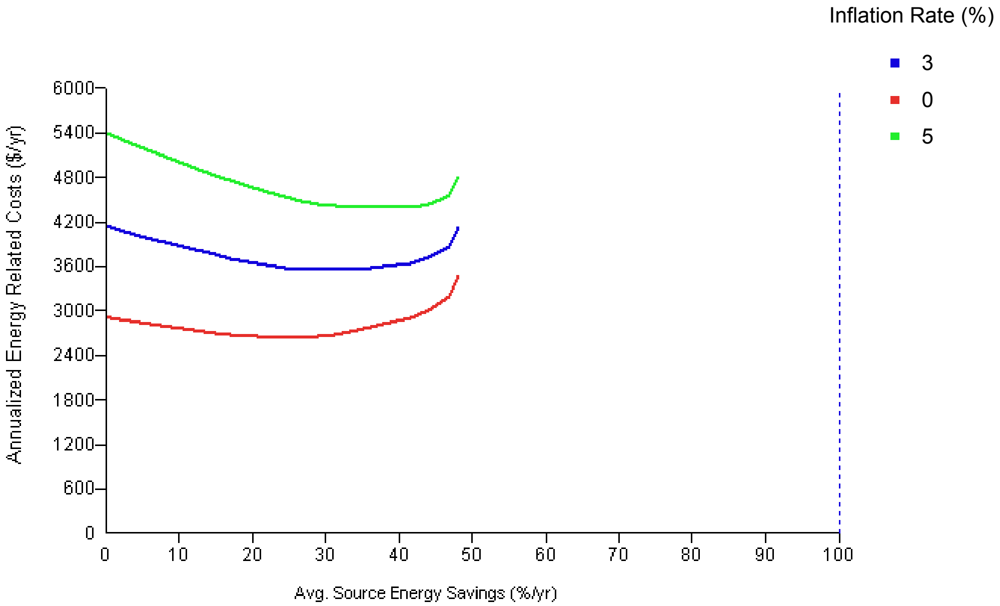

Figure B-2. Chicago optimization results as a function of inflation rate

A 5-year loan having an annual effective interest rate of 7% was assumed for the example analysis. Table B-1 shows the optimization results for Chicago assuming a 20-year loan with the annual effective interest rate of 7%. Compared to the results for the 5-year loan (Table 5-13), the packages on the least-cost curve and their associated AES are identical. The only difference is that the IEAC values for packages in the 20-year scenario are greater than those in the 5-year loan period.

Table B-1. Least-Cost Packages at Different Energy Savings for Chicago (20-year loan)

AES (%)	IEAC (2010 $)	Drill and Fill	Attic Ins./Attic Seal	4 ft Basement Ins.	8 ft Basement Ins.	Close Crawl Space	Standard Window	ENERGY STAR Window	Max Air Seal	Seal Ducts	Seal and Ins. Ducts	Tank Water Heater (gas, EF = 0.67)	Tankless Water Heater (gas, EF = 0.82)	Lighting (44% CFL)	Lighting (55% CFL)	SEER 13 AC	SEER 16 AC	92.5 AFUE Furnace	Standard Refrigerator	ENERGY STAR Refrigerator	ENERGY STAR Clothes Washer
0	−14													X							
1	−20														X						
5	−86			X											X						
15	−247	X		X											X						
22	−321	X	X	X											X						
24	−326	X	X	X											X						X
26	−326	X	X	X									X		X						X
31	−326	X	X	X									X		X			X			X
34	−311	X	X	X							X		X		X			X			X
41	−224	X	X	X			X				X		X		X			X			X
42	−212	X	X	X			X				X		X		X			X		X	X
44	−152	X	X	X			X		X		X		X		X			X		X	X
45	−83	X	X		X		X		X		X		X		X			X		X	X
47	−27	X	X		X			X	X		X		X		X			X		X	X
48	173	X	X		X			X	X		X		X		X		X	X		X	X

The loan interest rate affects the cost of financing the initial retrofit, with higher values increasing the IEAC of individual measures and packages of measures. Figure B-3 shows the Chicago optimization results for loan interest rates of 3%, 5%, 7%, 10%, and 20%. The results shown in Figure B-3 indicate that the AES and minimum-cost increases as the interest rate of the loan decreases.

For the example analysis, the nominal fuel escalation rate was identical to the inflation rate at 3%. The fuel escalation rate affects the price of energy (dollars per therm, dollars per kilowatt-hour) over the analysis period. Figure B-4 shows Chicago optimization results for nominal fuel escalation rates of 3%, 5%, 7.5%, and 10%. The annualized utility bill costs of the MURS (y-intercept) increase as the fuel escalation rate increases. As the fuel escalation rate increases, however, the AES at minimum cost increases and the incremental EAC at minimum cost decreases. In other words, the retrofit scenarios become more cost-effective the higher the fuel escalation rate because future utility bill cost savings are larger and help justify more investment in energy efficiency now.

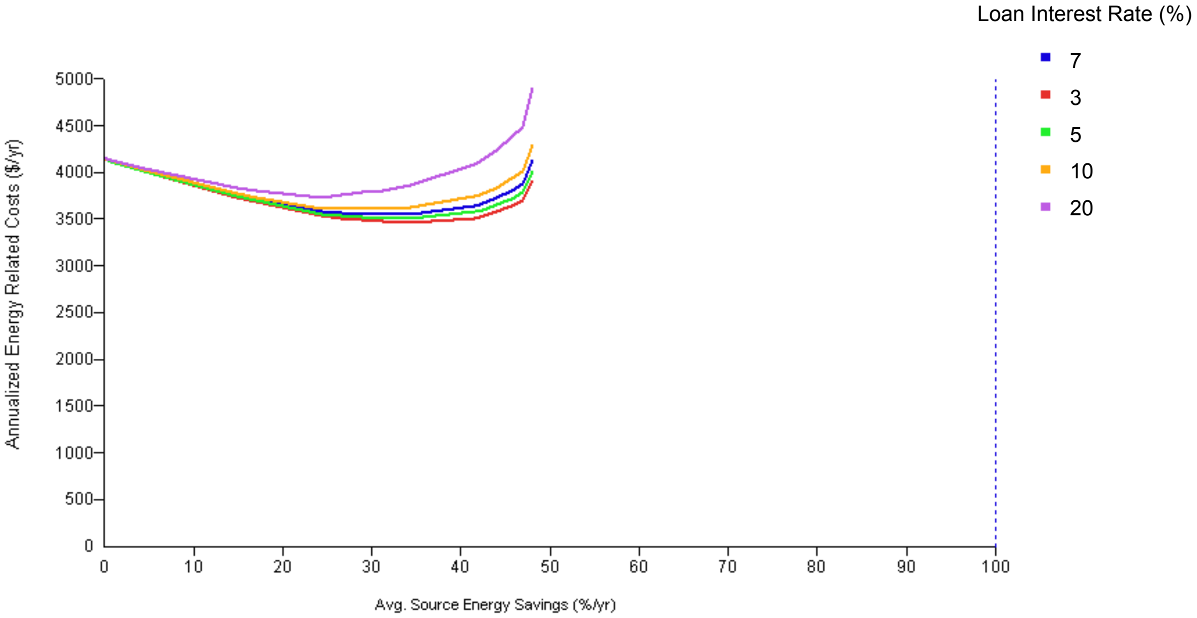

Figure B-3. Chicago optimization results as a function of annual effective loan interest rate

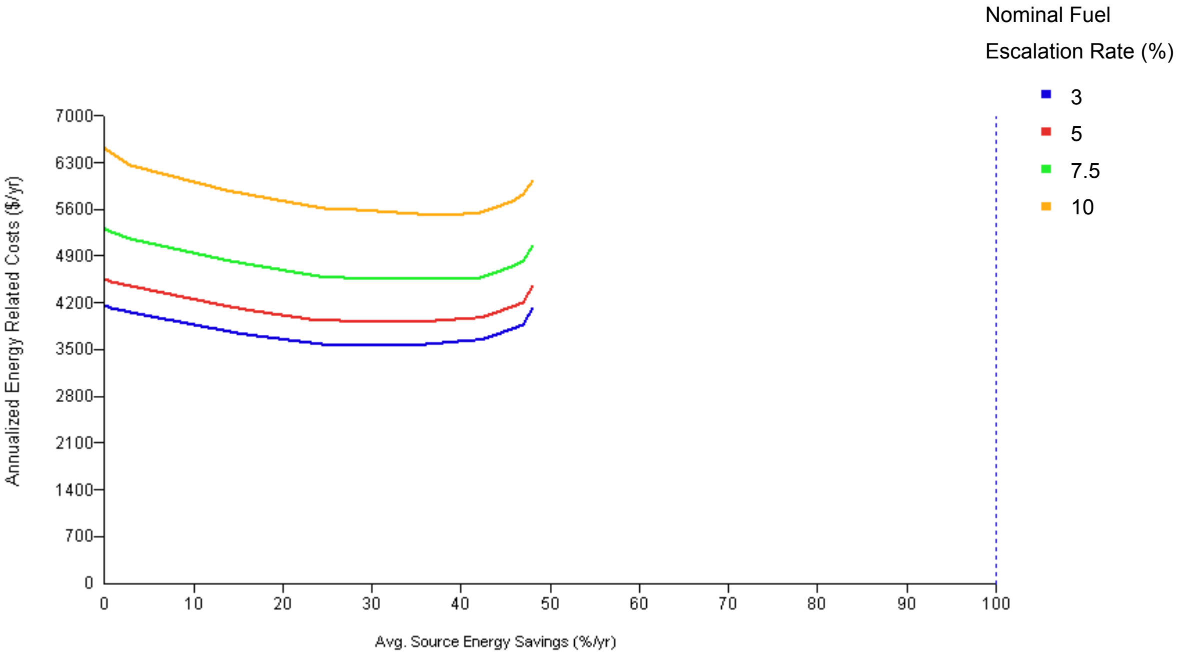

Figure B-4. Chicago optimization results as a function of nominal fuel escalation rate

The most obvious financial assumptions in the example analysis of Section 5 are the costs of retrofits measures and replacements. Costs for enclosure and equipment upgrades/replacements were taken from the National Residential Efficiency Measures Database (v1.0.0beta, NREL 2010). Costs for particular measures are typical and national, and therefore they do not vary city by city in the analysis. The specific cost of a retrofit can vary greatly depending on the location, existing conditions in the building, the availability of contractors, rebates, and so on. It is also important to note that the measures database is a dynamic entity and that the quality of the cost data improves over time as new information becomes available and as markets adapt to new technologies and deployment efforts.

Financial assumptions related to residual values also affect the results of the example analysis. Because the analysis period is 30 years, the real discount rate is 3%, and the inflation rate is 3%, the effect of the residual values is diminished compared to analyses taking place over shorter time horizons or with smaller real discount rates.

B.4 Occupant Assumptions

Occupant behavior for the example analysis was the same every year and was based on the standard assumptions outlined in the Building America House Simulation Protocol (Hendron and Engebrecht 2010). In reality, occupant behavior could change from year to year depending on specific events (e.g., kids leaving for college) or could change gradually over time (e.g., less use of basement with aging of occupants). Occupant behavior is a very significant driving force for energy use: space conditioning loads are highly dependent on thermostat operation, and other end uses such as domestic hot water, appliances, lighting, and miscellaneous electric loads are known to vary greatly depending on occupant behavior. Figure B-5 shows Chicago optimization results for occupants having high energy use thermostat set points, “Benchmark” energy use set points, and low energy use set points. As expected, the annualized utility bill costs of the MURS (y-intercept) is highest for the high energy use set point case and lowest for the low energy use set point case. Higher AES and lower IEAC are achievable at minimum cost for the high energy set point case than the lower energy set point case. These results demonstrate the significant effect that occupant behavior has on the energy and cost savings achievable through energy retrofit.

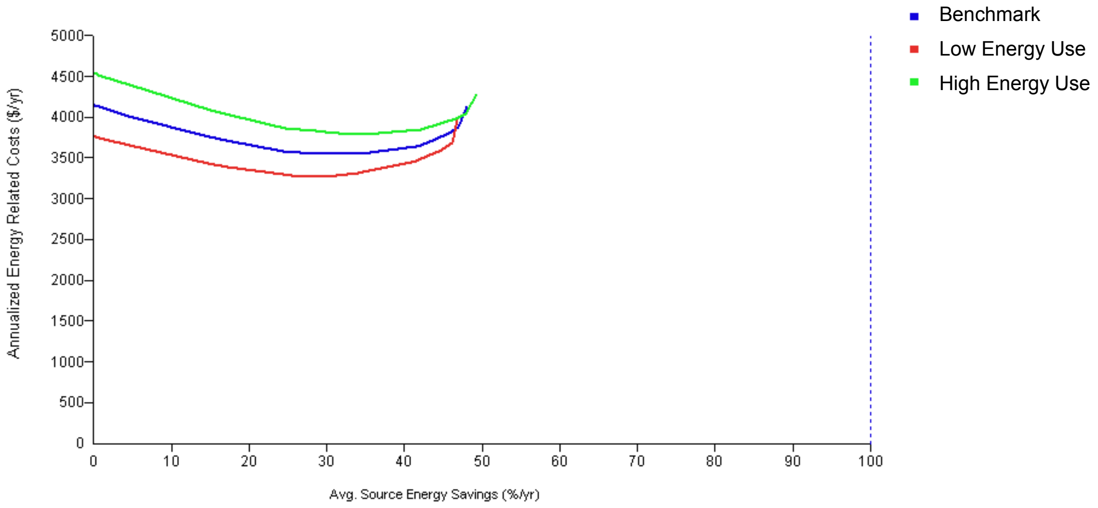

Figure B-5. Chicago optimization results as a function of thermostat set point

Another key assumption in the example analysis is that occupant behavior does not change as a result of the retrofit.[26] Occupants can, however, “take back” energy savings in exchange for more

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[26] The only exception for the example analysis is lighting; 10% of the energy savings resulting from using CFLs is taken back by assuming longer hours of operation.

comfort. For example, occupants in a leaky, poorly insulated home may set their thermostat to 65°F to keep monthly gas bills below $250. Retrofitting the building may lead to gas bills per month of $180 for a 65°F thermostat set point, but the occupants may choose to raise the set point to 68°F to increase comfort at the expense of reduced energy savings. Alternatively, more energy may be saved than expected because retrofits to the enclosure increase radiant temperatures and reduce drafts, allowing occupants to maintain comfort at more efficient thermostat settings. More research is needed to quantify the impact of energy efficiency improvements on occupant behavior.

B.5 Building Assumptions

Researchers made several assumptions in the example analysis regarding the building characteristics before and after the retrofit, as well as the building characteristics for the MURS. These characteristics are needed for the annual building energy simulations and for estimating the costs of each the retrofit and future replacements.

Basic features of the building, such as the geometry, fuel types, age, etc. were fixed from city-to-city. Other features such as the foundation type and exterior finish were varied depending on city. As described in Section 5, building assumptions (pre-retrofit and retrofit) are meant to be realistic for the 1960s-era house, but will not necessarily yield “typical” or “national average” results for average energy savings, EAC, and optimal retrofit packages.

To demonstrate the sensitivity of results to building assumptions, consider the attic insulation/air-seal retrofit: for Chicago R-19 insulation was assumed for the pre-retrofit building and R-30 was added as the retrofit. Figure B-6 shows the average energy savings of the attic insulation/air seal retrofit in Chicago as a function of the pre-retrofit insulation level (assuming the post-retrofit R-value is always R-49). At a pre-retrofit insulation level of R-49, the only energy savings is gained from air sealing the attic floor. As the pre-retrofit insulation level decreases, the AES increases gradually until reaching about R-20, at which point AES values begin to increase dramatically. In general, the higher the pre-insulation R-value the less sensitive AES predictions are to that input. Figure B-6 demonstrates the idea that small errors in the characterization of pre-retrofit R-values (when very little insulation exists) can lead to large errors in AES predictions because of the high sensitivity.

The example analysis results are also sensitive to the description of the retrofit: continuing with the previous example, other attic post-retrofit insulation levels could be investigated and would yield different average energy savings and equivalent annual cost results. Figure B-7 shows the attic insulation/air seal energy savings for Chicago as a function of the post-retrofit R-value (assuming the pre-retrofit R-value is always R-19). As seen in Figure B-7, at a post-retrofit R-value of R-19 (no insulation added), the energy savings is gained from air sealing the attic floor. As the post-retrofit R-value increases, the AES increases quickly and then begins to level off at higher post-retrofit R-values. Figure B-7 demonstrates the idea of “diminishing returns”: the amount of additional energy savings per additional unit of insulation decreases as higher overall insulation levels are attained.

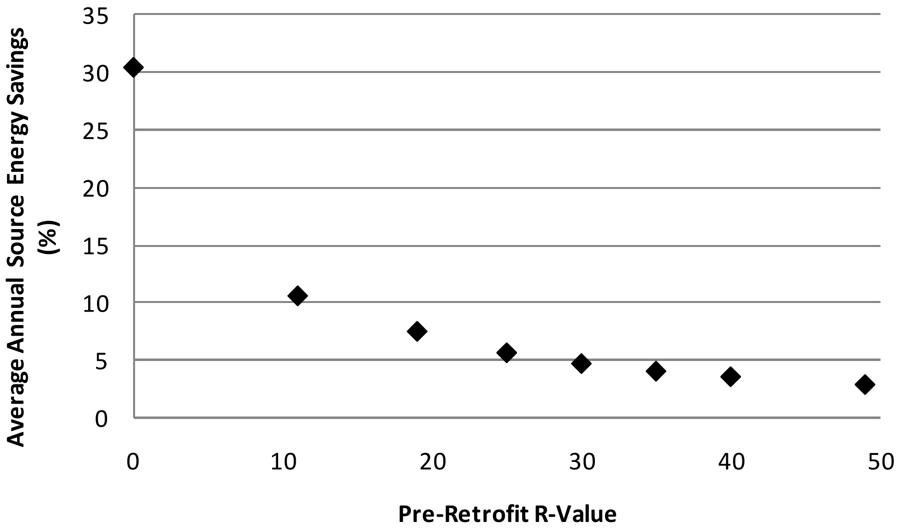

Figure B-6. Attic insulation/air seal energy savings as a function of pre-retrofit insulation level (Chicago)

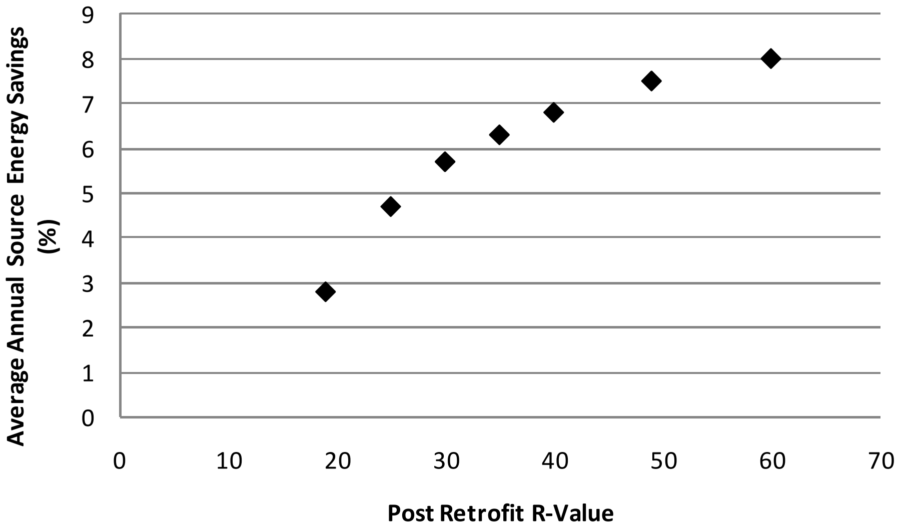

Figure B-7. Attic insulation/air seal energy savings as a function of post-retrofit R-value (Chicago)

Figures B-6 and B-7 showed the sensitivity of average energy savings predictions to building assumptions. Although not shown here, optimization results are also sensitive to building assumptions related to the pre-retrofit building, the retrofit, and the MURS.

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