OPTIMIZATION OF WHOLE HOUSE RETROFIT PACKAGES FOR TARGETING 50% ANNUAL ENERGY USE REDUCTIONS IN PRE-1978 CHICAGOLAND HOMES

BY

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LIST OF ABBREVIATIONS

Abbreviation	Definition
ACEEE	American Council for an Energy-Efficient Economy
ACH	Air Changes per Hour
AERC	Annualized Energy Related Cost
AFUE	Annual fuel utilization efficiency
AIA	American Institute of Architects
ASHP	Air-Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BA	Building America
BEopt	Building Energy Optimization
BEoptE+	Building Energy Optimization with EnergyPlus simulation engine
EC2	Elastic Compute Cloud
CCCAP	City of Chicago Climate Action Plan
CDD	Cooling Degree Days
CHES	Chicago Home Energy Savers
CNT	Center for Neighborhood Technology
COP	Coefficient of Performance
DOE	United States Department of energy
DSIRE	Database of State Incentives for Renewable Energy
EF	Energy Factor
ELA	Effective Leakage Area

Enh	Thermally Enhanced
EPA	United States Environmental Protection Agency
EPW	EnergyPlus Weather Data
EUI	Energy Use Intensity
GHG	Green House Gas
GSHP	Ground-Source Heat Pump
HCBA	Historic Chicago Bungalow Association
HDD	Heating Degree Days
HSPF	Heating and Seasonal Performance Factor
HVAC	Heating, Ventilation and Air Conditioning
IHP	Illinois Home Performance with ENERGY STAR
IP	Inch-Pound
Iter Pt	Iteration Point
LBNL	Lawrence Berkley National Laboratory
LED	Light-Emitting Diode
MEEA	Midwest Energy Efficiency Alliance
MEL	Miscellaneous Electrical Load
MSHP	Mini-Split Heat Pump
NREL	National Renewable Energy Laboratory
OAT	Outdoor Air Reset
OSB	Oriented Strand Board
PARR	The Partnership for Advanced Residential Retrofit
PV	Photovoltaic

RH	Relative Humidity
SDHW	Solar Domestic Hot Water
SEER	Seasonal Energy Efficiency Ratio
WAP	Weatherization Assistance Program
U.S.	United States
ZNE	Zero Net Energy

ABSTRACT

New standards and guidelines for energy consumption for the various building sectors in the United States are being developed by organizations such as the US Department of Energy and others. These typically include goals for all existing residential buildings to pursue deep energy retrofits that reduce their energy consumption by at least 50% relative to the regional average for the 2005 stock of that particular building type by the year 2030. To better inform these energy savings goals, this work relies on whole building energy simulation and optimization to construct a "tool-box" of prescriptive deep energy retrofit solutions that can be applied to a large portion of a subset of the housing stock responsible for a significant portion of residential energy use in the Chicagoland area: existing single-family detached homes built prior to 1978.

Ten typology groups of pre-1978 single-family homes were considered for energy retrofit package optimization with a target of 50% annual site energy reductions. Simulations were conducted as a two-step process using sequential search optimization functions in BEopt and EnergyPlus as the simulation engine. First, optimizations of the building enclosure for each typology were performed and the combined highest efficiency, least cost packages were applied to the base models. Second, optimizations based on the modified base models were performed using several heating, ventilation and air-conditioning (HVAC) system options, and an optimal cost-effective package was chosen for each typology based on maximizing annual energy reductions, payback periods, and modified internal rates of return (MIRR). Results reveal that prescriptive deep energy retrofit solutions can indeed be defined for each typology that achieve at least 50% site energy reductions, largely through common envelope retrofit measures for all groups and either upgrades to existing HVAC system efficiency or a conversion to mini-split heat pump (MSHP) systems. A scaling analysis suggests that widespread application of the prescriptive deep energy retrofit solutions described herein to the entire Chicagoland residential building stock could save between $400 and $1300 on energy costs per year per home, depending on typology, summing to a total of approximately $280 million per year in savings across all Chicagoland homes.

CHAPTER 1

INTRODUCTION

The residential sector is responsible for approximately 59% of the overall natural gas consumption in the Cook County and Chicagoland areas (CNT Energy, 2009). Single-family homes built prior to 1978 make up 82% of the single-family residential building population and are represented by over 900,000 homes (CNT Energy, 2009). These homes are notorious for being poorly insulated, having poor air sealing, and containing low-efficiency heating and air-conditioning equipment, and are thus found to be highly energy intensive relative to other home types.

Recent concerns for energy conservation and sustainability of buildings have initiated propositions from numerous national organizations targeting a minimum building energy usage reduction of 50% in existing residential buildings and new residential buildings to be zero net energy ready by the year 2030 (Architecture 2030, 2011; Adelaar, Pasini, de Buen, & Selkowitz; U.S. Department of Energy). These goals create both a challenge and opportunity for the subset of older Chicagoland homes built prior to 1978. The purpose of this work is to respond to this unique opportunity by combining building energy simulation and optimization tools with knowledge of this particular subset of Chicagoland single-family homes to develop prescriptive deep energy retrofit solutions targeting a 50% reduction in site energy usage that can be applied to or installed for this portion of the residential sector in the Chicagoland area and potentially be implemented on a larger scale. The motivations and intentions for this work are to provide the knowledge of potential energy and annualized monetary savings to homeowners; to provide information to government officials and other decision makers that may offer insight for future energy conservation projects or incentives; and ultimately to pave a pathway toward a more sustainable Chicagoland area.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Motivation and History of Deep Energy Retrofit Programs for the Residential Sector

In recent years, topics of climate change, energy conservation and greenhouse gas (GHG) emissions reductions have been of major concern for the building construction community of the United States (U.S.) as well as around the world, leading to an increase in the number of organizations dedicated to finding sustainable energy solutions. In 2002, architect Edward Mazria established Architecture 2030, a non-profit, non-partisan, and independent organization in response to the climate change crisis (Architecture 2030, 2011). The organization then issued the 2030 Challenge in 2006, asking the global built environmental to adopt the following (Architecture 2030, 2011):

- All new construction and major renovations are to be designed to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 60% below the regional (or country) average/median for that building type.
- At a minimum, an equal amount of existing building area shall be renovated annually to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 60% of the regional (or country) average/median for that building type.
- The fossil fuel reduction standard for all new buildings and major renovations shall be increased to 70% in 2015, 80% in 2020, 90% in 2025, and carbon-neutral in 2030 (using no fossil fuel GHG emitting energy to operate).

This may be accomplished through the implementation of innovative sustainable design strategies, generating on-site renewable energy, and/or purchasing off-site renewable energy up to 20% (Architecture 2030, 2011). The first organization to adopt the 2030 Challenge was the American Institute of Architects (AIA) (Architecture 2030, 2011). Among other adoptive organizations are the United States Green building Council (USGBC), The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Congress for New Urbanism, American Solar Energy Society (ASES), Society of Building Science Educators, Association of Collegiate Schools of Architecture, National Wildlife Federation, and several others (Architecture 2030, 2011). In May of 2006, Architecture 2030 worked with Chicago's Mayor Richard M. Daley and others to introduce "Resolution #50- Adopting the '2030 Challenge' for All Buildings" to the U.S Conference of Mayors which was unanimously approved the following month (Architecture 2030, 2011).

AIA later adapted their interpretation of the challenge, increasing the target of an energy reduction of 50% relative to the regional average for the 2005 stock of that particular building type by the year 2030 (Adelaar, Pasini, de Buen, & Selkowitz). As of May of 2010, 126 programs distributed across the United States were identified in the Database of State Incentives for Renewable Energy (DSIRE) to be programs that promote a whole home approach to energy conservation, providing access to whole-house audit and support for numerous energy efficiency solutions including but not limited to insulation and weather sealing (LeBaron & Rinaldi, 2010). Figure 1 illustrates the breakdown of the number of programs by region.

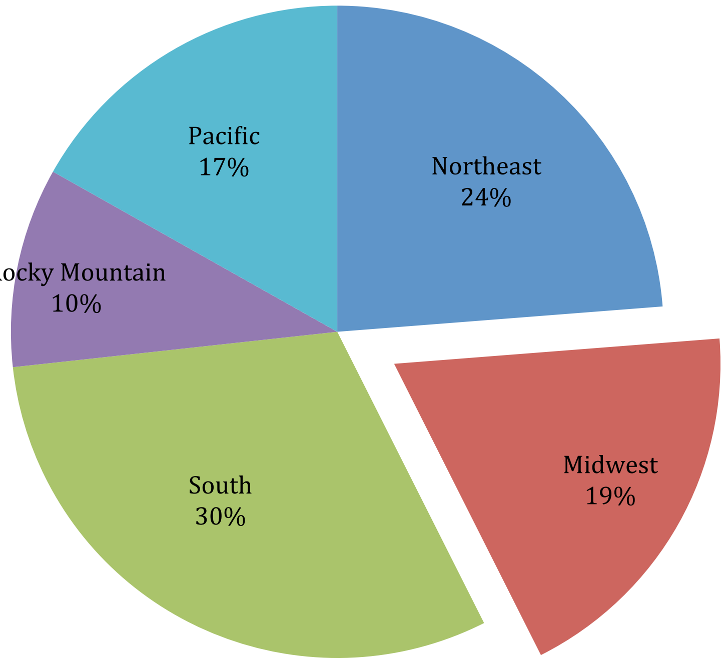


Figure 1. Whole home energy conservation programs in the U.S. Database of State Incentives for Renewable Energy (DSIRE) by region (LeBaron & Rinaldi, 2010)

Out of the 126 programs, the twelve states that make up the Midwest had 24, of which a majority of the programs were in were in Missouri, Iowa and Minnesota (LeBaron & Rinaldi, 2010). According to DSIRE, Illinois only has one energy retrofit program: U.S. Department of Energy (DOE) Weatherization Assistance Program (WAP) which is committed to enabling low-income families to reduce their energy bills by installing energy-efficiency measures in the homes of qualifying homeowners free of charge (North Carolina Solar Center, 2013; United States Department of Energy, 2012). The listing does not specify whether or not WAP is considered to be a whole home energy retrofit program.

Contrary to the reporting of whole home energy retrofit programs by DSIRE, there are several local organizations and programs that focus on residential energy efficiency. For more than 15 years, the Building America (BA) program, a national program that is part of the U.S. Department of Energy Office of Energy, Efficiency and Renewable Energy, Building Technologies Office, has been committed to conducting the necessary research to improve new and existing residential energy efficiency, and accelerate the development of reliable and effective whole house efficiency measures in order to maximize energy savings (Rowley, Kerr, & Brand, 2012; U.S. Department of Energy). The national goal of BA is to demonstrate how cost-effective strategies can reduce home energy use by up to 50% for both new and existing homes in all climate regions by 2017 (U.S. Department of Energy). BA has a Chicago based team, The Partnership for Advanced Residential Retrofit (PARR), which for the last five years has led large, comprehensive residential retrofit programs that serve as a foundation for residential retrofit research in cold climates (Rowley, Kerr, & Brand, 2012). PARR also represents a broad spectrum of residential building stakeholders including Elevate Energy, formerly Center for Neighborhood Technology (CNT) Energy, whose mission is to design and implement efficiency programs that lower costs, protect the environment, and ensure the benefits of energy efficiency reach those who need them most (Spanier, Scheu, Brand, & Yang, 2012; Elevate Energy)

Another national program administered by the DOE in conjunction with the U.S. Environment Protection Agency (EPA) is the Home Performance with ENERGY STAR program (U.S. Environment Protection Agency, 2014; Baker, Yee, & Brand, 2013). The Home Performance with ENERGY STAR program connects homeowners to qualified contractors and energy auditors who assess the energy performance of existing homes and provide whole house solutions to improve comfort, indoor air quality, and energy efficiency (U.S. Environment Protection Agency, 2014). In November 2011, the Midwest

Energy Efficiency Alliance (MEEA), another organization partner to DOE, EPA, and other agencies in their efforts to accelerate the adoption of energy-efficient programs, led the development of the version of Home Performance with ENERGY STAR in Illinois, or Illinois Home Performance (IHP) (Baker, Yee, & Brand, 2013; Yee, Milby, & Baker, 2014; Midwest Energy Efficiency Alliance , 2014). Like the national program from which it derived, IHP functions as a process as well as a set of contractor and performance standards, used by a variety of utility and nonprofit residential programs across Illinois, including ComEd (local electricity provider), Nicor Gas (local natural gas provider), the Historic Chicago Bungalow Association (HCBA), and others (Baker, Yee, & Brand, 2013).

In 2008, the City of Chicago released the Climate Action Plan (CCCAP), which in part identified residential energy building energy retrofits as having the potential to substantially reduce the city's total emissions (Ludwig & Isaacson, 2010). One of the goals of the plan includes energy retrofitting 40% of Chicago's housing stock, about 400,000 units, to achieve a 30% energy savings per home by 2020 (Ludwig & Isaacson, 2010). Elevate Energy created the Chicagoland Whole Home energy Savers (CHES) pilot program designed to test the tangibility the CCCAP targets by taking a "whole home" approach and combining gas and electric home energy retrofits (Ludwig & Isaacson, 2010).

Though the target for the CCCAP is 30% energy savings, the goal for this work is to optimize retrofit solutions that reach 50% site energy savings relative to the regional average/median for the pre-1978 single-family residential building stock in the

Chicagoland area in order to elevate local goals to be more consistent with those in Architecture 2030 and other efforts.

2.2 Chicagoland's Pre-1978 Housing Stock

The Chicagoland region consists of seven counties with more than 3.3 million single-family homes, representing 63% of the population of single-family homes in Illinois (Spanier, Scheu, Brand, & Yang, 2012). Of the seven counties, Cook County is the most housing dense, having 1.1 million single family homes (Spanier, Scheu, Brand, & Yang, 2012). For the remainder of this work, the term 'Chicagoland' refers to the Cook County area only. The median built year of the single family housing stock in Cook County is 1956 which predates the year, 1978, when the requirement of installing insulation in buildings was written into energy code (Spanier, Scheu, Brand, & Yang, 2012) and more than 30% of the total housing stock in Cook County was built in 1939 or earlier (CNT Energy, 2009). Therefore, this large number of older existing homes presents both a unique challenge and opportunity for energy saving retrofits.

One of Chicago's most defining residential building typologies is the Chicago Bungalow. Between 1900 and 1940, more than 80,000 were built (Knight, 2004). The current single-family home building stock is still highly influenced by this building boom, with uninsulated wood frame and solid masonry buildings built pre-1942 being the predominant type of housing construction in the Chicagoland area (Spanier, Scheu, Brand, & Yang, 2012). The typical bungalow was recently found to consume roughly 25% more energy than the median of homes in the Chicagoland area (Spanier, Scheu, Brand, & Yang, 2012).

2.3 Residential Retrofit in the Chicagoland Area

BA's Chicago based team, PARR, in line with their stated goals, performed a characterization of the top 15 single-family housing type groups in the Chicagoland area, focusing only on the Cook County area. The groups were characterized based on data collected from the Cook County assessors, utility billing history, and prior energy efficiency programs. A sample of 432,605 homes, representing 39% of the population of nearly 1.1 million homes in the Cook County-Chicagoland area, was left after the clearing the data of addresses with missing data and high-energy use outliers (Spanier, Scheu, Brand, & Yang, 2012). Using The Building Energy Optimization (BEopt) simulation software and local cost data, PARR worked to optimize retrofit packages targeting a 30% source EUI reduction and devise the three most prospective (ranked by cost effectiveness of energy savings) building types for eventual implementation of the appropriate packages in the field (Spanier, Scheu, Brand, & Yang, 2012). The prospects were determined by three important criteria: largest potential for cost-effective retrofit, highest EUI, and frequency of housing type (Spanier, Scheu, Brand, & Yang, 2012). The 15 groups considered include:

- Group 1: Brick, 1978-Present, 1 to 1.5 stories (no split level);
- Group 2: Brick, 1978-Present, Split level (1.5 stories);
- Group 3: Brick, 1978-Present, 2 stories;
- Group 4: Brick, 1942-1978, 1 to 1.5 stories (no split level);
- Group 5: Brick, Pre-1978, Split level (1.5 stories);
- Group 6: Brick, 1942-1978, 2 stories;

- Group 7: Brick, Pre-1942, 1 to 1.5 stories (no split level). Note that Group 7 represents Pre-1942 Chicago bungalow style architecture and is shown to have the highest mean site Energy Use Intensity (EUI) of all the groups;
- Group 8: Brick, Pre-1942, 2 stories;
- Group 9: Frame, 1978-Present, 1 to 1.5 stories (no split level);
- Group 10: Frame, All years, Split level (1.5 stories);
- Group 11: Frame, 1978-Present, 2 stories;
- Group 12: Frame, 1942-1978, 1 to 1.5 stories (no split level);
- Group 13: Frame, 1942-1978, 2 stories;
- Group 14: Frame, Pre-1942, 1 to 1.5 stories; and
- Group 15: Frame, Pre-1942, 2 stories

Based on information from the property assessor and energy data from CNT Energy, PARR modeled the buildings in BEopt under three scenarios (Spanier, Scheu, Brand, & Yang, 2012):

- 'As-built': to establish a common baseline for all groups based on year of construction.
- 'Today': to apply typical upgrades in insulation, infiltration and HVAC systems made over time by the homeowner to match the EUI energy data provided for each group.
- 'Upgrade': to use the optimization routines in BEopt and determine the potential energy savings through upgrade.

Since, optimizations involved only a few parameters for each group (i.e. infiltration, attic insulation, and the efficiencies of space and water heating systems)

PARR was not able to observed a EUI savings of 30% in any of the groups after their prescribed BEopt upgrades were applied to the models. However, Groups 7, 12 and 14 (all built prior to 1978) were found by PARR to have the greatest potential for energy reduction, and were estimated to experience a reduction in source EUI of 28%, 11%, and 9% respectively (Spanier, Scheu, Brand, & Yang, 2012).

Earlier this year, other members of PARR (Yee, Milby, & Baker, 2014) reported on an expansion of the previous research conducted by Spanier et al. (2012) in order to compare differences between the optimal retrofit packages and actually installed measures. Yee et al. (2014) investigated 800 homes that were involved in the IHP process, which could be categorized under one of 12 of the 15 Chicagoland residential archetypes earlier established PARR (Spanier, Scheu, Brand, & Yang, 2012), and the homeowner-chosen retrofit measure packages associated with each of the homes. The actual retrofit packages were then compared to the BEopt optimized packages developed by Spanier et al. and it was found that the scope of IHP retrofit measures were unmatched by BEopt suggested measures; IHP homes received more retrofit measures than BEopt optimizations suggested, on average. Also, IHP options focused more on enclosure improvements while BEopt was focused more on the installation of improvements in HVAC equipment (Yee, Milby, & Baker, 2014). This difference made it difficult to accurately compare the two methods; hence, homes from select groups (the three archetypes found to have the most potential by Spanier et al.; groups 7, 12,and 14) fitted with IHP implemented retrofits were replicated in BEopt and their results were compared to their corresponding in-field retrofit packages.

From this investigation, an important observation was made: A large difference in costs between the actual retrofit packages and results from BEopt replicates of the same homes was revealed. BEopt cost-optimized packages costs were found to be conservative as they were more costly than actual retrofit package costs. Moreover, payback periods were found to be lower for the BEopt recommended packages than they were for IHP measures (Yee, Milby, & Baker, 2014). BEopt default costs are pulled from the National Residential Efficiency Database and such a significant difference between modeled and actual measures indicates that these figures are different from actual market costs for measures available to IHP participants (Yee, Milby, & Baker, 2014), which suggests that BEopt users should adapt usage of the software (e.g., by modifying costs associated with certain parameters) in order to accurately reflect actual market costs.

Additionally, Yee et al. concluded that BEopt optimized retrofit packages may be at higher risk for missed energy saving opportunities, as IHP retrofit measures were found to experience greater EUI reductions than BEopt recommendations, albeit primarily because for most housing archetypes in IHP, the homes received more measures than BEopt- recommended cost-optimal measure packages (Yee, Milby, & Baker, 2014). More importantly, one of the most important conclusions of the study conducted by Yee et al. is that making a connection between home categorization and standardized retrofit measure packages provides an opportunity to streamline the process for single-family home energy retrofits and maximize both energy savings and cost effectiveness (Yee, Milby, & Baker, 2014). The combination of these studies, despite their sometimes conflicting results, also suggest that building energy simulation and optimization software can still play a role in informing standardized retrofit packages for energy-intensive homes.

2.4 Optimization Methods

Analysis through simulation typically involves many uncertainties and "what if" scenarios, as different input conditions may output different optimal results. The heating and cooling thermal loads of a building are significantly influenced by many design parameters such as building size and shape, orientation, enclosure and roof construction; and can influence the characteristics of the HVAC mechanical systems such as type, efficiency and operation settings. Performing parametric analyses with an energy optimization program is often based on assessing the impact of a limited number of parameters, potentially missing important interactive effects which may not lead to the best optimization selection of design features that can both minimize energy use and cost while maintaining certain constraints on parameters such as desirable indoor thermal comfort conditions or budget. The use of energy simulation software coupled with optimization algorithms has been shown to improve the computational efficiency and accuracy with which optimal energy efficiency packages are discovered (Bichiou & Krarti, 2011).

For example, Bichiou and Krarti (2011) used three optimization algorithms to select the best combinations of several building enclosure, HVAC System design and operation option parameters that optimize energy consumption and life cycle costs using the DOE-2 simulation engine (Bichiou & Krarti, 2011). The three optimization algorithms included:

- Genetic Algorithm, based on the concept of evolutionary natural selection processes (Electromagnetic Optimization by Genetic Algorithms, 1999);
- Particle Swarm Optimization, based on a global stochastic search method whereby candidate solutions are treated as particles moving in a large search-space; and
- Sequential Search, based a gradient descent search technique whereby cost functions are checked one at a time and in sequence (this is also the method used by the Building Energy Optimization (BEopt) energy analysis software, explained in a later portion of this subsection).

Using the BA benchmark model (Hendron, 2006) of a two-story single-family residential building, and reference building characteristics, hypothetically located in Chicago, Illinois, Bichiou and Krarti performed simulations to select optimal design solutions including:

- HVAC optimization only, assuming that the building enclosure features are defined,
- Full optimization, in order to design both building enclosure and HVAC system features,
- Sequential optimization of first the building enclosure characteristics and then of the HVAC system features to assess any interactive effects between building enclosure and HVAC system, and
- Optimization based on reducing annual total energy use or cost rather than life cycle costs.

After conducting series of simulations mentioned above, Bichiou and Krarti concluded that similar optimal solutions were achieved by all three of the optimization algorithms. However, it was found that full optimization provides slightly more accurate results but with typically more computational efforts than sequential optimization approach with the building envelope features are first selected and then the HVAC system options are optimized (Bichiou & Krarti, 2011) Moreover, it was found that simulations utilizing the sequential search method were the most calculation time intensive of the three optimization algorithms, and that the Genetic Algorithm approaches were shown to provide least cost solutions with the least computational requirements for most scenarios.

2.5 The Use of BEopt for Retrofit Optimization

BEopt is an open source energy analysis program developed by a team at the National Renewal Energy Laboratory in support of U. S. Department of Energy Building America program goals to develop market-ready energy solutions for new and existing homes. It calls upon either the DOE-2 or EnergyPlus simulation engines and utilizes a sequential search technique to automate optimal building solutions along the path to ZNE (NREL BEopt Development Team, 2014; Christensen, Anderson, Horowitz, Courtney, & Spencer, 2006). In the section to follow, a description of the software and a summary of its capabilities detailed in a number of references authored by the NREL BEopt Development team and Christensen et al. is discussed (NREL BEopt Development Team, 2014; Christensen, Anderson, Horowitz, Courtney, & Spencer, 2006).

Figure 2 illustrates the simulations processes and communications between the two simulation engines and BEopt.

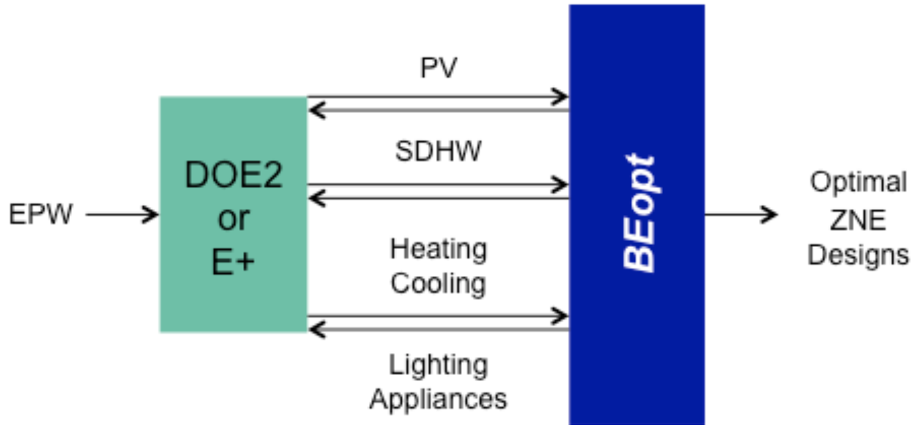


Figure 2. The BEopt simulation process (NREL BEopt Development Team, 2014)

BEopt software users can select pre-defined options in various building and occupant behavior parameters and options to consider for optimization. These options can be modified and new custom options can also be added if necessary to improve accuracy of the resulting models. The chosen simulation engine uses EnergyPlus Weather (EPW) data for a user-defined location in order to simulate selected parameters (e.g. photovoltaic (PV), solar domestic hot water (SDHW), heating and cooling systems, and lighting appliances) under realistic, location-specific conditions (See Fig. 2). There are currently three modes of analysis (NREL BEopt Development Team, 2014):

- 'Design Mode' – allows users to perform a single set of building design simulations for analysis.
- 'Parametric Mode' – allows users to quickly perform traditional parametric analyses of all possible combinations of the selected building and occupant behavior parameters and options.

- ‘Optimization Mode’ – sequentially searches selected building and occupant behavior options for the lowest cost building designs at various levels of energy savings up to ZNE.

The sequential search method used by BEopt in Optimization Mode involves searching all selected building and occupant behavior parameters for the most cost-effective option at each sequential point along the path to ZNE (NREL BEopt Development Team, 2014; Christensen, Anderson, Horowitz, Courtney, & Spencer, 2006). Starting with the reference building, simulations are performed to evaluate all selected options for improvement (one at a time) in the building enclosure and equipment. Based on the results, the most cost-effective option is selected as an optimal point on the path and included in an updated building configuration (NREL BEopt Development Team, 2014). The process is repeated until the desired point (user defined source or site energy, or GHG reduction value) is reached as illustrated in Figure 3 with a basic summary of an explanation found in the latest BEopt Help Guide to follow (NREL BEopt Development Team, 2014).

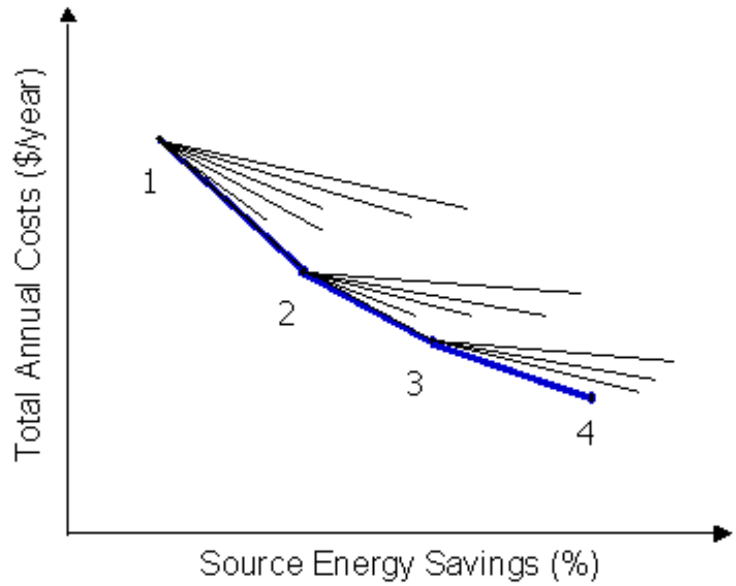


Figure 3. Example of a typical output resultant of the Sequential Search technique (NREL BEopt Development Team, 2014; Christensen, Anderson, Horowitz, Courtney, & Spencer, 2006)

In Figure 3, Iteration points (or "Iter Pt") 1, 2, 3, and 4 represent a unique building configuration or optimal iteration point. The slope of each line extending from the points represents another possible energy efficiency measure for BEopt to evaluate terminating at other iteration points. The iteration with the steepest downward slope provides the most energy savings for the least amount of investment. From this new iteration point, the remaining options are evaluated to find the next optimal point and so on until all possible configurations are exhausted or the simulation target is met.

The next section describes the methods and procedures for the work herein based on the use of BEopt optimizations for defining deep-energy retrofit packages for the pre-1978 subset of Chicagoland homes. While it is understood that the term "optimization" generally refers to the process of finding a solution that represents a global minimum for a defined function, which could be done in BEopt with an exhaustive simulation of all possible combinations of outputs based on chosen parameters in ‘Parametric Mode’ (albeit with high computational costs), the use of the term “optimization” for the purposes of this work refers to the process of simulating across a group of chosen parameters in order to find the least-cost solution using the sequential search methods in ‘Optimization Mode’ in BEopt.

CHAPTER 3

METHODS AND PROCEDURES

The approach for the analyses herein is divided into two major tasks: defining model inputs and BEopt modeling. These activities are discussed in the following subsections.

3.1 Model Inputs: Defining Representative Home Characteristics

Representative pre-1978 homes and their important characteristics were first defined as model inputs in this work. The housing typology groups and their baseline energy usage characteristics were gathered from PARR (Spanier, Scheu, Brand, & Yang, 2012). These include 10 of the 15 the typology groups from the PARR report (all pre-1978):

- Group 4: Brick, 1942-1978, 1 to 1.5 stories (no split level);
- Group 5: Brick, Pre-1978, Split-level (1.5 stories);
- Group 6: Brick, 1942-1978, 2 stories;
- Group 7: Brick, Pre-1942, 1 to 1.5 stories (no split level);
- Group 8: Brick, Pre-1942, 2 stories;
- Group 10: Frame, All years, Split level (1.5 stories);
- Group 12: Frame, 1942-1978, 1 to 1.5 stories (no split level);
- Group 13: Frame, 1942-1978, 2 stories;
- Group 14: Frame, Pre-1942, 1 to 1.5 stories; and
- Group 15: Frame, Pre-1942, 2 stories

The following general assumptions defined by PARR were applied to the appropriate models and cases (Spanier, Scheu, Brand, & Yang, 2012):

- Lot size and distance to neighbors were based on homeowner input from the PARR research team and information of a standard city and suburban lot.
- The heating setpoint was set at 70ºF and cooling setpoint was set at 72ºF.
- Windows were modeled as double–clear (window plus storm window) in all cases. Note that there is not a 'Double-Clear' window option in the BEopt version used for this work. A custom option was created based on the same parameter from a previous version, BEopt version 1.0.
- Mechanical ventilation was modeled as 'none' for pre 1942 and 'spot ventilation' for the other vintages (i.e., spot exhaust fans such as kitchen and bathrooms). This parameter option was also not included in the newest version of BEopt and was created based on BEopt version 1.0 parameter with the same name.
- Average current appliances were chosen for the models, as they were only significant in evaluating the energy use in the 'Today' Scenario.
- Other Electrical Loads were set at '1.00'.

As-built case assumptions for Pre-1942 construction are as follows (Spanier, Scheu, Brand, & Yang, 2012):

- Brick walls pre-1942 are double brick construction. The layers from outside to inside are: 4 inch brick, 1 inch airspace (the weep space, largely mortar and bricks connecting the inside and outside layer), an inside brick layer, wood lath with no insulation in the spaces, and 5/8 inch drywall simulating plaster. A structural brick wall was not a default option for this parameter. A custom option was made based on Concrete Masonry Unit (CMU) structured walls (6” hollow CMU) but with physical specifications of brick. Costs associated with these options were carried over from the CMU base.

- Wood frame walls pre-1942 were modeled from the outside to inside as siding, sheathing, 2x4 uninsulated walls, and 5/8 inch drywall simulating plaster on the interior wall.
- Roofs and ceilings in both types of houses were modeled as uninsulated. Bungalows were modeled with finished attic space in the upper half story. Interzonal knee walls were modeled with no insulation and the roof above the living space was also modeled with no insulation in the As-built scenario.
- Basements were uninsulated. Crawl spaces and slabs are uncommon in Chicago construction.
- Enclosure airtightness assumptions were as shown: ‘very leaky’ for 1 story and ‘leaky’ for 2 stories. These assumptions were made based on the opinion of an expert panel without validation from field data other than the close match of the ‘Today’ case with field energy use intensity (Spanier, Scheu, Brand, & Yang, 2012). The infiltration options in the version of BEopt used for this work are based on air changes per hour (ACH) values. New Infiltration parameter options were created based on previous BEopt version 1.0 in order to reflect options chosen by PARR, which are based on effective leakage area (ELA) values. The ratios for very leaky, leaky, typical, tight, tighter, and tightest (respectively) are: 0.0009, 0.0007, 0.0005, 0.00036, 0.00018, and 0.009.
- No clothes dryer was included—line drying is the assumption.

- Boilers were the most common for pre-1942 construction and 65% efficiency was assumed.
- No cooling was included in the As-built case.
- Pre-1942 gas water heating was assumed with an energy factor (EF) of 0.48.

The assumptions for 1942-1978 construction are as follows (Spanier, Scheu, Brand, & Yang, 2012):

- For brick walls, 1 inch of R-3 (IP) fiberglass was added between the furring strips. Note that all insulation R-values reported throughout are given in inch-pound (IP) units unless stated otherwise.
- For wood frame and interzonal walls, an R-7 fiberglass batt was the typical insulation for that era.
- Ceiling and interzonal floor insulation was assumed to be R-11.
- Infiltration for 1 story was upgraded to leaky and 2 stories to typical.
- Furnaces replaced boilers in the average house in this time frame; an AFUE of 70% was assumed.
- In the As-built case, cooling was not assumed for this vintage.
- The gas water heater was assumed to have the same 0.48 EF as pre-1942.

The ‘Today’ case assumptions were used to model the houses to reflect common energy upgrades typically made to houses over time. Note that the terms ‘today’ and ‘existing’ are used synonymously in the context of building scenario, case, or condition throughout this paper. For Pre-1942 construction, the upgrade assumptions include (Spanier, Scheu, Brand, & Yang, 2012):

- An attic insulation increase to R-7.
- A gas dryer was added (no longer line drying).
- Cooling was added—with an EER of 10 representing window air conditioners.
- Boiler efficiency was increased to 80%, representing a 1980's boiler.

For 1942-1978 construction the following assumptions for the today case include (Spanier, Scheu, Brand, & Yang, 2012):

- Attic insulation increased to R-19.
- Furnace efficiency was increased to 78% AFUE.
- Central cooling was added with a SEER of 10.

Special case assumptions were applied to improve the accuracy of the 'Today' model for groups 4, 7, and 14. Unless noted otherwise, the following assumptions are based on those made by PARR (Spanier, Scheu, Brand, & Yang, 2012):

- For group 4, a majority of houses in this group had slab floor construction (no basement) which best fit the EUI, therefore, slab construction was modeled in this case and this case only.
- For Group 7, a floored attic assumed for the 'As-built' scenario was not changed for the 'Today' case because insulation beneath the floor is not typical for floored attics. Also, short knee-walls were considered to be inaccessible and thus uninsulated.
- Group 14 was considered to have a full-unfinished attic, having a floored attic modeled in the As-Built case. R-3 insulation was added to reflect the average insulation that would be added if the attic were partially finished for the 'Today' model.

PARR's 'As-Built' and 'Today' scenarios for each of the groups were replicated in "Design Mode' to the best of abilities with a goal for the replicate 'Today' scenarios to be within a deviation range of 20% of the CNT mean numbers for three energy use categories (i.e. source EUI, electricity, and gas consumption). Tables 1, 2, and 3 list the PARR results along with the CNT mean numbers, replicate 'Today' results and deviation allowance ranges targeted for this thesis for each of the 10 groups according to the three energy use categories. From the tables it is observed that all groups are within their target deviation allowances.

Table 1. Annual source EUI and deviation allowances

Source EUI (kBtu/SF-yr)					
Group	CNT Mean	PARR 'Today'	Replicate 'Today'	Target Range	
				-20%	20%
4	192.3	196.4	183.3	154	231
5	198.2	195.1	194.5	159	238
6	147.7	155.2	147.8	118	177
7	227.8	224.7	204.3	182	273
8	169.3	177.1	175.8	135	203
10	199.1	193.9	184.0	159	239
12	199.0	191.0	162.0	159	239
13	172.0	163.9	161.4	138	206
14	222.9	216.4	196.4	178	267
15	164.8	168.6	172.5	132	198

Table 2. Annual electricity usage and deviation allowances

Electricity usage (kWh/yr)					
Group	CNT Mean	PARR 'Today'	Replicate 'Today'	Target Range	
				-20%	20%
4	8,859	9,254	9,053	7,087	10,631
5	9,643	9,227	9,532	7,714	11,572
6	11,714	11,534	11,533	9,371	14,057
7	8,927	8,725	8,239	7,142	10,712
8	11,062	10,608	10,241	8,850	13,274
10	9,321	8,772	8,599	7,457	11,185
12	8,483	8,257	7,190	6,786	10,180
13	9,802	9,367	9,513	7,842	11,762
14	9,050	8,624	8,328	7,240	10,860
15	11,348	10,870	10,654	9,078	13,618

Table 3. Annual gas usage and deviation allowances

Gas usage (Therms/yr)					
Group	CNT Mean	PARR 'Today'	Replicate 'Today'	Target Range	
				-20%	20%
4	1,212	1215.7	1,088	970	1,454
5	1,344	1350.6	1,389	1075	1,613
6	1,553	1712.9	1,661	1242	1,864
7	1,442	1430.6	1,324	1154	1,730
8	1,757	1940.9	2,023	1406	2,108
10	1,480	1473.6	1,415	1184	1,776
12	1,268	1204.6	1,035	1014	1,522
13	1,467	1395.6	1,408	1174	1,760
14	1,608	1578.7	1,670	1286	1,930
15	1,913	2034.9	2,217	1530	2,296

3.2 BEopt Modeling

It was not disclosed in the PARR report whether the DOE-2 or EnergyPlus simulation engine was used, however, it is presumed that the version of BEopt used in the report was one of BEoptE+ versions 1.0-1.4 or BEopt versions 1.0-1.3 (with DOE2 simulation engine) given that these were the available versions at the time the study was conducted. Moreover, newer releases have since then been deployed; hence, the newest version, BEopt version 2.2.0.2 with the EnergyPlus 8.1.0 simulation engine, was used for the modeling purposes of this thesis. Although the EnergyPlus simulation engine requires more computation time than DOE-2, it was chosen for this work as it allows for exploration of technologies that are not offered in the DOE-2 engine (e.g., ground source heat pumps) and has more capabilities (NREL BEopt Development Team, 2014).

There are many subtle differences between BEopt v2 and BEopt v1; the most critical differences being those involving several building and energy parameters. Therefore, careful considerations and modifications of a few parameters were necessary in order to replicate PARR's reference models accurately. As previously mentioned the assumptions reported by PARR for each group were modeled in retrofit 'Design Mode' in BEopt and replicate 'Today' scenarios were only considered to be acceptable when the results for each of the energy categories fell within the 20% deviation range as indicated in the previous subsection (See Tables 1-3). After this criterion was met each group was then simulated in 'Optimization Mode' to analyze the separate HVAC scenarios (explanation of this process to follow).

Initially, full optimization of all the appropriate parameters for each of the groups was intended. However, a full simulation trial was done and it was determined that the simulation could take an extremely long period of time to complete. Therefore, each of the group models were first simulated for optimal building enclosure retrofits using the corresponding PARR 'Today' scenario HVAC system assumptions with the target set to calculate the least cost building enclosure component package across all parameter options BEopt considered appropriate. BEopt cannot run an optimization with options selected across mutually exclusive categories, thus, multiple simulation cases involving the different system configurations were performed. The resultant enclosure package was then used to optimize the separate HVAC system cases where appropriate, namely boiler and room A/C combinations, furnace and central A/C combinations, mini-split heat pump systems (MSHP) and electric baseboard combinations, and ground-source heat pump systems (GSHP). This layered approach to address passive strategies first (i.e. reducing heating and cooling loads) and then building efficiency is commonly used in the building energy design/retrofit industry and was shown to be effective in Bichiou & Krarti (2011). It also reduced the complete optimization simulation run time to under 48 hours per group.

Parameter options that BEopt deemed inappropriate and for which costs would not be calculated if selected for optimization are denoted by an exclamation mark next to the option on the options selection screen (see Figure 4). These options were not selected for modeling purposes unless the calculations of costs associated with the implementation of the options were not necessary (i.e. for use in the 'Today' scenario).

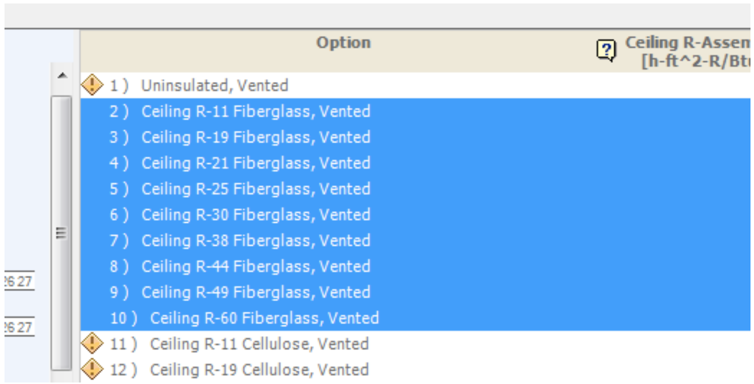


Figure 4. Screenshot of BEopt option list illustrating appropriate vs. inappropriate options

All parameters and options selected for the modeling and optimization of all groups, scenarios, and cases (i.e. 'Today', Enclosure, and all HVAC cases) are to be assumed to be BEopt default without modification to any specifications, properties, and costs associated with such parameter options unless otherwise stated. Default costs were kept for all parameters despite research conducted by Yee et al. (2014) reporting that BEopt cost calculations can be considered conservative for the following reasons:

- The study conducted by Yee et al. (2014) was published after the simulations for this work were concluded and reported herein.
- Although the discrepancies in parameter option costs affect variables associated with those costs such as annualized energy related costs (AERC), initial costs, payback periods, and Modified Internal Rate of Return, it does not affect the potential energy savings for any of the groups.
- BEopt costs were shown to be overestimated and can be considered as conservative pricing.

For reference, original BEopt files and inputs for all groups can be found and downloaded at the following web address:

http://built-envi.com/portfolio/chicagoland-housing-retrofits/

In addition to the existing condition assumptions, the following parameters and options deemed eligible by BEopt were chosen for the 'Enclosure' optimization simulations for each group (where appropriate):

- Exterior Wall (Wood Stud) – Frame exterior wall construction only. All options for this parameter that were deemed appropriate by BEopt were chosen for optimization were options which had higher thermal resistance over the existing case and included most default 2x4, 16-inch (in) on center (o.c.) options insulated with either fiberglass batt, cellulose (blown-in), fiberglass (blown-in), or spray foam insulation. Insulation R-values ranged from R-7 (fiberglass batts) up to R-23 (spray foam).
- Exterior Wall (Brick) – Brick exterior wall construction only. BEopt does not have default double brick walls options, therefore, new CMU options for the weep space plus 4 inch interior brick were created based off existing 6-in hollow CMU options. All specifications for the masonry (i.e. block thickness, material conductivity and density) were modified to reflect the specifications of brick but all labor and material costs associated with the original default options were kept as is for the new brick options. These options include the double brick wall insulated with either of the following insulations within the interior side furring cavity: R-3 fiberglass batt (2-in furring cavity), R-10 XPS (2-in furring cavity), R-

13 closed cell spray foam (2-in furring cavity), R-12 polyiso (2-in furring cavity), or R-19 fiberglass batt within a 2x6, 24-in o.c. furring cavity.

- Wall Sheathing – Frame exterior wall construction only. The following insulations were chosen for optimization as being installed between the exterior finish and the frame wall: R-5 XPS, R-10 XPS, R-15 XPS, R-6 Polyiso, and R-12 Polyiso.
- Exterior Finish – All colors for the appropriate finish were chosen (i.e. light or medium/dark brick for brick constructed homes, and light or medium/dark wood siding for frame constructed homes).
- Interzonal Walls – All eligible options for 2x4 16-in o.c. interzonal walls were chosen. This included walls insulated with either fiberglass batt, cellulose (blown-in), fiberglass (blown-in), or spray foam insulation. Insulation R-values ranged from R-7 (fiberglass batts) up to R-23 (spray foam).
- Unfinished Attic – In groups where unfinished attic space was present, all eligible BEopt options were chosen. Options varied from group to group and were dependent mainly on vintage and existing insulation and were considered appropriate if they represented an improvement in thermal resistance. Selected options include but were not limited to options with insulation installed in either the attic floor space (ceiling of the finished space), within the cavity space between 2x6 rafters (roof), or both ceiling and roof (in few cases). Insulation in the form of vented, blown-in fiberglass; vented, blown-in cellulose; fiberglass batt; or closed cell spray foam in the ceiling space, and/or closed cell spray foam

in the roof were chosen with R-values range from R-11 to R-60 for both types of insulation.

- Finished Roof – In groups where finished attic space was present all eligible options (higher R-values than the existing) included the existing insulation (R-19 blown-in fiberglass within 2x6 rafters) both alone and in combination with XPS having the R-value of 15, 20, or 25.
- Roof Material – For all groups, the options chosen for roof material included ‘Asphalt shingles’ in all default colors: dark, medium, light, or white or cool colors.
- Radiant Barrier – For all groups, both the available options for this parameter were chosen; ‘none’ (the existing condition), or ‘double-sided, foil’
- Unfinished Basement – All default options for insulating and finishing of the basements interior perimeters were chosen for all groups.
- Interzonal Floor – Interzonal Floors can be defined as floors that separate conditioned from unconditioned space (e.g. the floor separating the unfinished attic from the conditioned space below, or the ceiling area/floor area between the unconditioned garage and conditioned living space above) In models of groups for which interzonal floors were present all default options were selected for optimization of this parameter.
- Window Type – For all groups, all eligible window options were chosen for optimization. Included are all double or triple pane; low, medium, or high gain low-e coated; insulated or non-metal frame; air or argon filled configurations. An

option for back windows to have a high solar heat gain coefficient (SHGC) was included among the options chosen for optimization.

- Air Leakage – Options selected for the air leakage parameter was dependent on group vintage and number of stories. Only the existing condition and the option that represented a single step up were chosen for each group (e.g. very leaky and leaky, leaky and typical, or typical and tight) as two-step upgrades were not assumed to be realistic for the pre-1978 vintage (Spanier, Scheu, Brand, & Yang, 2012). For the version of BEopt used to model the groups for this work, air leakage options were based on ACH values. Custom options were created based on options from a former version (BEopt 1.0) in order to resemble the options used by PARR based on ELA.
- Mechanical Ventilation – The selection of options for this parameter were also dependent on group vintage. For pre-1942 groups all default options were selected but for 1942-1978 all options except those that implement 'supply' ventilation were selected for optimization.

After the corresponding optimal Enclosure package was implemented to the model a second set of optimizations were performed for each group. The following options were selected according to HVAC system type for optimization and comparison along side the options of the existing scenario (where appropriate):

- Central A/C – (Furnace-Central A/C optimization only) Options that represented improvements to the existing system's efficiency were deemed eligible by BEopt. Among the selected are all default options with SEER equal to or higher than 10.

- Room A/C – (Pre-1942 groups only; Boiler-Room A/C optimization only) All BEopt default options for this parameter were deemed eligible and were chosen for optimization for select groups (pre-1942 only).
- Furnace – (Furnace-Central A/C optimization only) Only options that represented improvements to the existing system's efficiency were deemed eligible and selected for optimization. Options include gas furnaces with AFUE ratings of 78% and above (up to 98%) and an electric furnace with an AFUE of 100%.
- Boiler – (Pre-1942 groups only; Boiler-Room A/C optimization only) Similar to the A/C and furnace parameters, the options chosen for optimization included only those that represent an improvement to the existing system's efficiency. This includes both condensing and non-condensing gas boilers having AFUE of 80% and higher (up to 98%). Boilers were only optimized for pre-1942 vintage groups.
- Electric Baseboards – (MSHP optimization only) BEopt requires for electric baseboards to be selected when simulating MSHP, thus, the only default option (beside 'none') of 100% efficiency
- MSHP – (MSHP optimization only) All default options were selected for optimization for this parameter for all groups.
- GSHP – (GSHP optimization only) Chicagoland's close proximity to Lake Michigan has a large influence on the thermal conductivity of the area's soil and thus the potential to incorporate geothermal heating in the form of ground source heat pumps into homes. According to the United States Geology Survey, the water level has measured in the past between 15 and 2 feet below land surface in wells located throughout the Cook County (U.S. Geological Survey, 2013). The

soil of the entire Chicagoland area can be classified as illitic or silty/clayish (U.S. Department of Agriculture, 2012). The thermal conductivity of saturated silt/clay soil has a thermal conductivity within the range of 0.57-1 Btu/hr-ft-R (1-1.8 W/m-K) for saturated unfrozen soil and 1.15-1.44 (2-2.5 W/m-K) for saturated frozen soil (Farouki, 1981). From this information a thermal conductivity value of 1 Btu/hr-ft-R (1.8 W/m-K) will be used in the assumption of soil conductivity and is considered as being high conductivity soil by BEopt. Thus, only default options representing systems installed in soil with high conductivity (high-k) were chosen for the optimization of GSHP.

- Ducts – (Ducted HVAC systems, i.e. furnace-central a/c and GSHP only) The options deemed appropriate for optimization by BEopt depended on vintage and thusly, the presence of pre-existing ductwork. For groups without pre-existing ductwork (pre-1942) all default options were selected. For all remaining groups (1942-1978), only options that represented a decrease in leakage from the existing were selected, including both insulated and uninsulated ducts with leakage percentages of 15% or less, as well as an option to relocate ducts to finished space.

An air-source heat pump (ASHP) case was initially included among the HVAC systems simulated for optimization. However, conventional ASHP have been recommended for use mostly in moderate climates. As outdoor temperatures fall below ~17.6ºF (-8ºC) the productivity of the ASHP begins to degrade significantly (Sami & Tulej, 1995). Moreover, it has been reported that most ASHP systems shut off when ambient temperatures reach freezing, 32ºF (0ºC) and switch to backup heating consuming fuel (Bertsch & Groll, 2008). Since the average mean seasonal temperature for the Chicagoland winters in the past decade was found to be 26.1ºF (-3.2ºC) (National Weather Service, 2014), it was determined that the implementation of ASHP would indeed necessitate a backup heating system. Supplemental heat could not be accurately modeled in BEopt simultaneously with ASHP, as the methods of heating are considered to be mutually exclusive. While advancements have been made to increase feasibility of their implementation in cold climates (Sami & Tulej, 1995; Guoyuan, Qinhu, & Yi, 2003; Bertsch & Groll, 2008), the developers of BEopt have yet to make cold climate ASHP options available/appropriate for simulation (NREL, 2014). Therefore, the results of the simulations involving this particular system were ultimately considered invalid for the context of this thesis and will not be reported.

The following parameters and corresponding options were selected for all HVAC cases in all groups:

- Ceiling Fan – All default options for ceiling were deemed appropriate by BEopt, however, the options selected for optimization were limited to 'none', 'benchmark', 'standard efficiency', 'high efficiency', and 'premium efficiency'
- Water Heater – Options that represented an improvement in efficiency from the existing were deemed appropriate and only those that were operated using gas or electric, or heat pump water heater (HPWH) options were selected.
- Solar Water Heating (SWH), SWH Azimuth, and SWH Tilt – All default options for these parameters were considered appropriate and selected for optimization.
- Lighting – Lighting options were deemed appropriate by BEopt if they consumed less electricity than the existing case and were thus selected for optimization.

Included are options for 40 to 100% hardwired lighting to be converted to fluorescent, 40-100% hardwired and plug-in lighting to be converted to fluorescent, conversion of 50% hardwired and plug-in lighting to fluorescent and 10% to Light-Emitting Diode (LED), and fixed lighting electricity consumption of 1300 kWh/yr.

Optimization simulations did not include analysis of building user preference or behavior parameters such as natural ventilation, shading, and large appliances other than water heaters and HVAC equipment (e.g. refrigerators, washers, dryers, etc.) or building characteristics that are not practical to change such as building orientation and distance from neighbors. The options for these parameters were selected based either on PARR assumptions, options that best fit EUI, or BEopt defaults and left unchanged throughout the simulation processes.

Retrofit systems were expected be highly influenced by Chicagoland's cold-humid climate (Spanier, Scheu, Brand, & Yang, 2012; Bichiou & Krarti, 2011). With average annual HDD65 and CDD65 of about 6500 and 840 °F-days, respectively Chicagoland is thusly considered to be in the climate zone 5 (National Weather Service, 2014; ASHRAE, 2010). For all simulations, the Energy Plus Weather (EPW) Location was appropriately set at 'USA_IL_Chicago-OHare.Intl.AP.725300_TMY3.epw'. Moreover, as the scope of this work includes the entire Chicagoland area, which includes several near suburbs, therefore, the terrain was set to 'Suburban' for all simulations.

The most recent release of BEopt (version 2.2) was equipped with capabilities for user-specified utility rates. For the modeling purposes of this work, Real-Time-Pricing (RTP) electricity cost profile was created based on actual RTP costs from the local electric utility, ComEd, for the year of 2012 acquired from their website (Commonwealth Edison Company, 2013). Decisions were made to use RTP instead of average block pricing in part because utilities are slowly changing to this method. RTP is based on the hourly market price of fuel and can result in monetary savings if monthly electricity usage is consistently above 400 kWh (Citizens Utility Board, 2013). The lowest average kWh/month demonstrated by the groups of interest is ~738 kWh/month; therefore, the use of RTP is considered appropriate for the scope of this work. Further investigation of using RTP compared to average block pricing is also recommended in future work to further explore potential cost impacts to optimal retrofit packages. For natural gas usage pricing, an average of the monthly cost of gas found on the website of the local natural gas utility (Nicor Gas) was used (Nicor Gas, 2014). All other values for economics (e.g. inflation rate, discount rate, etc.) and payment (e.g. loan interest rate, loan period, marginal income tax rate, etc.) were left as the BEopt Default values.

Although the target for this work is to develop packages toward a 50% site energy savings, the simulations were set to terminate when a 50% source energy savings was met for the following reasons:

- The setting for simulations to terminate at a 50% source energy savings allowed for the exploration of potentially higher site energy savings percentages. With the source/site ratios kept at the BEopt defaults of 3.15 and 1.09 for electric and gas respectively, a source energy reduction of 50% would at least ensure a 50% site energy reduction.
- Analysis of the results from the first simulations uncovered that the iteration points that represented a 50% site savings had a higher annualized energy related

cost than iteration points with higher energy savings in certain HVAC cases for all groups. This was specifically seen in the HVAC cases that involved the MSHP and GSHP systems.

3.3 Use of Amazon Elastic Compute Cloud (EC2)

Initial BEopt simulation tests were performed in a Virtual workstation running Windows 7 Professional on a MacBook Air equipped with a 1.8 GHz Intel Core i7 processor and 4 GB 1333 MHZ DDR3. The first simulation was allowed to run for about 15 hours, during which only 8 iterations or 1249 simulations were completed, before the test was manually terminated. Because it was understood that several cases would need to be simulated for each group, the decision to outsource simulations to a remote server was made and thus for this purpose, several C3 High-CPU instances were test on Amazon Elastic Compute Cloud (EC2) (Amazon, 2014). A C3 High-CPU Eight Extra Large instance with utilizing 108 (32 core x 3.375 unit) compute units and 60 GB of memory was ultimately created and used for remote simulations. The chosen instance was setup to use the latest Microsoft Windows Server operating system and BEopt was installed just as it would be on a typical PC computer. Simulations were managed though the Microsoft Remote Desktop application installed on the previously mentioned MacBook. The simulation run time was reduced down to about 1.5 hours/case using Amazon EC2.

Ultimately, each group model involved the optimization of a minimum of 4 cases, and each case had a minimum of 9 iterations. Some cases required the simulation of an upwards of 25 iterations with an mean number of about 15 iterations per case. Using the mean 15 iterations per case, it was calculated that it would have required a minimum of about 1125 hours to complete simulations on the above-mentioned MacBook. Using Amazon EC2, the required minimum run time was reduced to 80 hours equating to about a 92.8% reduction in simulation run time to complete simulations.

CHAPTER 4

RESULTS AND DISCUSSION

Analyses of the optimization simulations performed for each of the appropriate groups are illustrated and discussed in the following subsections.

4.1 Optimization Results

Group 4: Brick, 1942-1978, 1 to 1.5 stories (no split level) Group 4 has measured mean floor area of 1217 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a floor area of 1178 ft^2. The floor layouts and exterior 3D image of the BEopt model for this group are shown in Figure 5. As per PARR findings and assumptions, this group was modeled as slab construction (no basement).

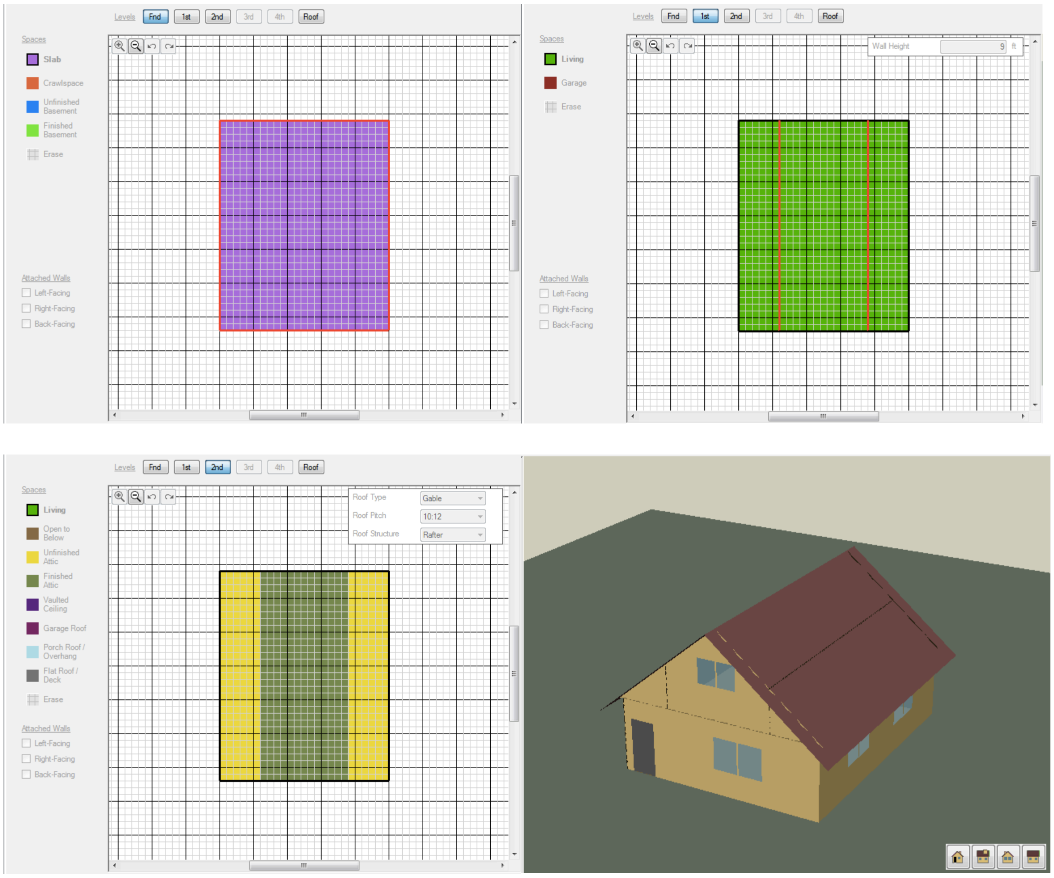


Figure 5. Group 4: BEopt model: foundation, first, and second (attic) floor layouts and 3d view

AERC are calculated by annualizing the energy related cash flows (e.g. mortgage/loan payments, replacement costs, utility bill payments, and residual values) over the analysis period (for the purposes of this work, the analysis period is 30 years for all groups). Then the resulting annualized costs are subtracted from the reference for every cash flow but utility bills (NREL BEopt Development Team, 2014). Ideally, desirable packages would be present on the lower right portion of the graph along the positive x-axis and would represent a higher energy savings at a lower AERC relative to the rest of the iterations points for the enclosure case. The annualized energy related cost versus site energy savings along with their least cost lines for the iteration points (Iter Pt) resulting from the building enclosure optimization shown by Figures 6. For reference, Figure 7 illustrates their corresponding positions in terms of annualized energy related cost versus source energy savings.

It can be observed that a site energy savings of about 32% (least cost option) simply by updating the enclosure and keep existing HVAC systems (See Fig. 6). This translates to about a 25% source energy savings (See Fig. 7). It can also be seen that the least cost option has an annualized energy related cost that is about $200/yr less than the existing case.

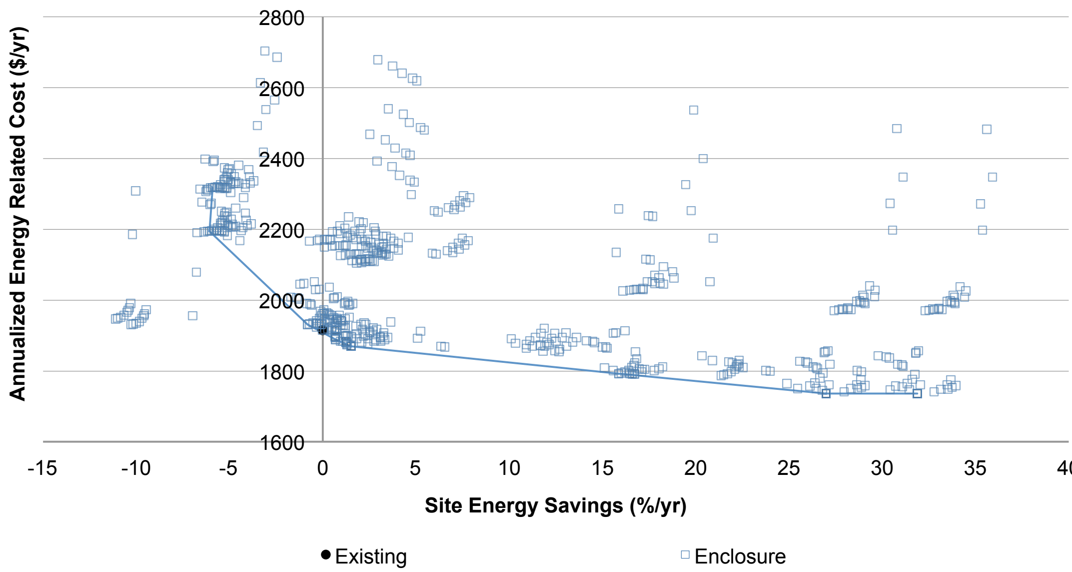


Figure 6. Group 4: Building Enclosure optimization results in terms of sites energy savings

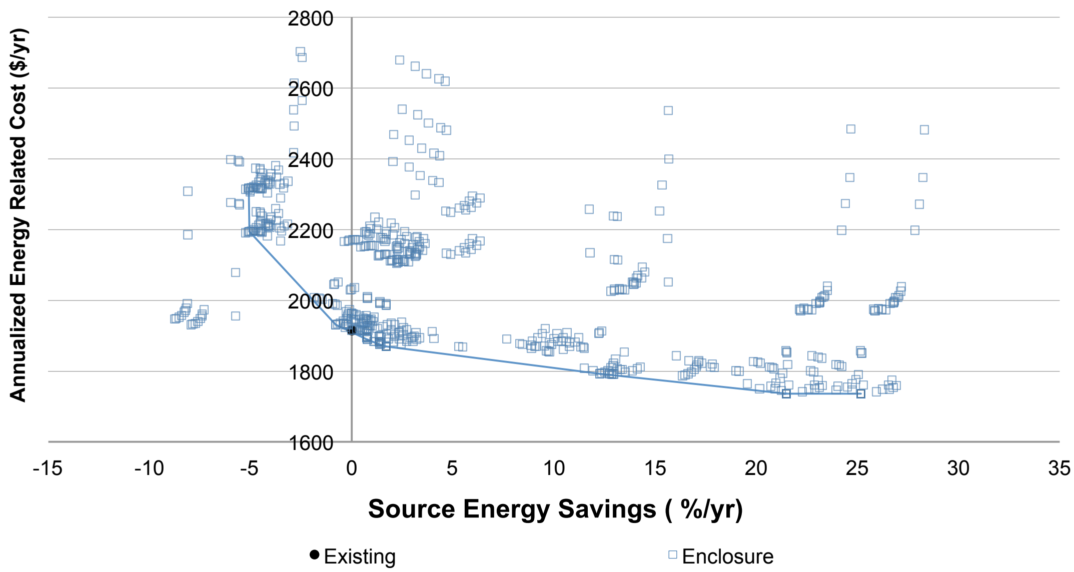


Figure 7. Group 4: Building Enclosure optimization results in terms of source energy savings.

Table 4 lists the original 'Today' scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves.

Table 4. Group 4 Optimal Building Enclosure: Optimized Parameters, 'Today' scenario assumptions, and BEopt upgrades.

Parameter name	'Today'	Enclosure: Iter 7, Pt 38
Exterior Wall (Masonry)	4-in Hollow Brick, R-3 Fiberglass Batt, 1-in furring, 24 in O.C.	4-in Hollow Brick, R-19 Fiberglass Batt, 2x6, 24 in o.c.
Exterior Finish	Brick, Medium/Dark	No Change
Interzonal Walls	R-7 Fiberglass Batt, Gr-3, 2x4, 16 in O.C.	No Change
Unfinished Attic	Ceiling R-19 Fiberglass (Blown-in), Vented	Roof R-19 Closed Cell Spray Foam
Finished Roof	R-19 Fiberglass (Blown-in), 2x6 Rafters	No Change
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Leaky	Typical
Mechanical Ventilation	Spot Ventilation Only	No Change

*Two-step upgrades were not considered realistic for this vintage (Spanier, Scheu, Brand, & Yang, 2012) and were not simulated.

For this building group, the optimal enclosure option involves upgrades to the exterior wall construction, unfinished attic insulation, and air leakage only. Despite having options deemed appropriate by BEopt to optimize, the slab parameter was not among those chosen for simulation since it was not considered practical to insulate the slab in a retrofit scenario.

BEopt recommends for a 2x6, 24 inches on center (o.c.) framed wall with R-19 fiberglass batt insulation between the stud cavities to be built along the interior side of the masonry wall. Similar upgrades have been implemented in Chicago houses of this typology and vintage as an energy efficiency measure in part of the Green Bungalow

Initiative developed by HCBA and sponsored by the City of Chicago (Knight, 2004). Thus, it is considered to be a valid suggestion. The upgrade in envelope tightness from leaky to typical reflects about a 22% increase in enclosure tightness. This is considered to be an appropriate upgrade as studies suggest that weatherization techniques can reduce air tightness via blower door tests by 13-40% (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). Insulation retrofit of the unfinished attic is considered to be an appropriate upgrade for the context of Group 4 and energy reduction target set for this work, as closed cell insulation is a common retrofit option in cases where open access to the underside of the roof is available. Closed cell insulation is also considered to have superiority over other insulations such as fiberglass batting or loose fill insulation because it provides increased thermal resistance as well as acts an air and moisture barrier (Lubeck & Conlin, 2010). The non-upgrades to other parameters are acceptable, as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

Using the optimized building enclosure parameters listed in Table 4, HVAC optimization simulations were performed in another group of cases. The results from each of those cases are superimposed onto graphs illustrating the AERC in terms of site energy savings (see Fig. 8) and source energy savings (see Fig. 9) and their respective least cost fit lines. For the HVAC simulations, desirable packages would represent a site energy savings of at least 50% at a lower AERC relative to the rest of the iteration points of that particular system's case. Comparison of the two graphs shows critical differences in values between site and source energy savings, especially in the cases involving the mini-split and ground-source heat pumps. This difference is present because these systems involve a transfer of the largest load (i.e. the heating load) from gas to electric consuming and although a large site energy savings is present, as mentioned previously the source/site ratio for electricity is almost 3 times that of gas.

From the results shown in Figure 8, we can see that the options chosen for optimization of all HVAC cases formulate packages that either reach and/or exceed the targeted 50% site energy savings at an increased annualized energy related cost over the existing case. Moreover, the cases involving the mini split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but also equate to about a 60% site energy savings in their least cost options.

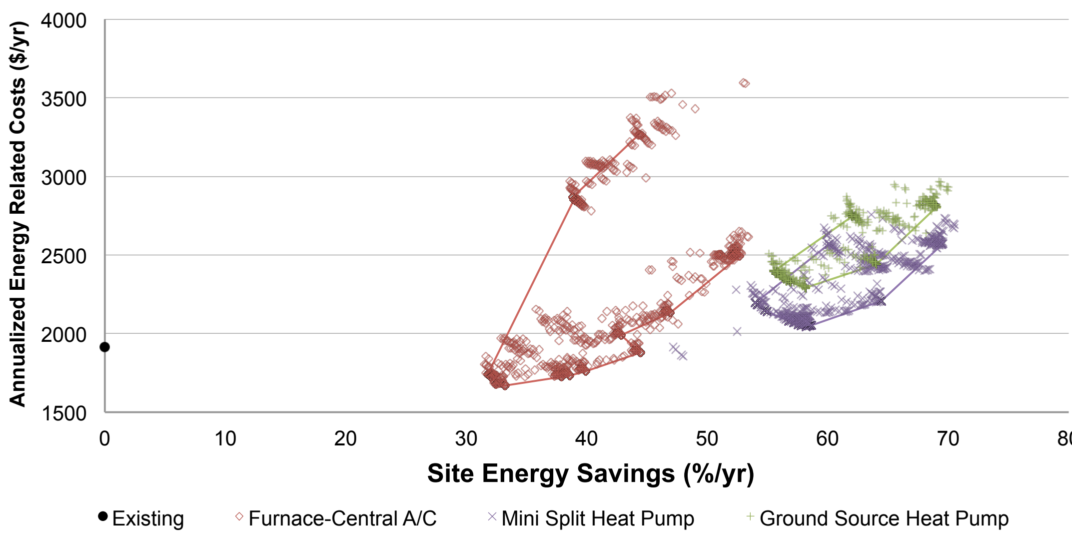


Figure 8. Group 4: HVAC optimization results in terms of site energy savings

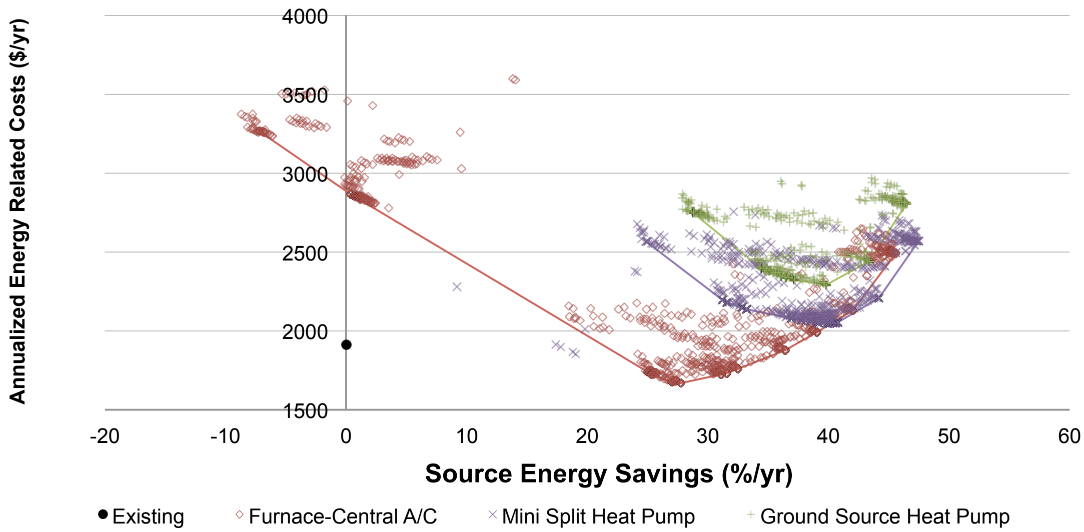


Figure 9. Group 4: HVAC optimization results in terms of source energy savings.

For each HVAC case one of two iteration points was chosen for further analysis: the iteration point representing at least a 50% site energy reduction; or the least cost iteration point for HVAC cases where the least cost iteration point has an energy reduction greater than 50% (i.e. MSHP and GSHP cases). The optimized parameter options, costs, and estimated energy savings associated with these iteration points alongside the 'Today' case are listed in Table 5. Note that any the initial and AERC reported for each case are those of the corresponding HVAC package combined with optimized Enclosure (previously discussed) for this group.

Table 5. (Page 1 of 2) Group 4: Brick, 1942-1978, 1 to 1.5 stories - Parameters options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 14, Pt 15**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 3**
Central A/C	SEER 10	SEER 24.5	None	None
Furnace	Gas, 78% AFUE	Gas, 98% AFUE	None	None
Electric Baseboard	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	Typical, Uninsulated (Unfinished Attic)	In Finished Space	None	In Finished Space
Ceiling Fan***	None	None	None	None
Water Heater	Gas 54% EF	HPWH, 80 gal, (electric)	No Change	No Change
Solar Water Heating	None	None	None	None
SWH Azimuth	N/A	N/A	N/A	N/A
SWH Tilt	N/A	N/A	N/A	N/A
Lighting	Benchmark	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in

Table 5. (Page 2 of 2) Group 4: Brick, 1942-1978, 1 to 1.5 stories - Parameters options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 14, Pt 15**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 3**
Initial Cost ($)	$0	$16,204	$11,242	$19,436
Annualized Energy Related Costs ($/yr)	$1,915	$2,320	$2,047	$2,292
% Site (Source) Savings	0	49.9 (39.6)	58.2 (39.9)	58.2 (39.8)

**Simulated using optimized building enclosure parameters.
***Reference ('Today') case was modeled with the assumption that no ceiling fans were installed.

It is observed that the addition of ceiling fans were not considered a cost effective upgrade for any of the cases. The addition of a solar water heating system was also not considered to be a cost effective upgrade for any of cases in this group.

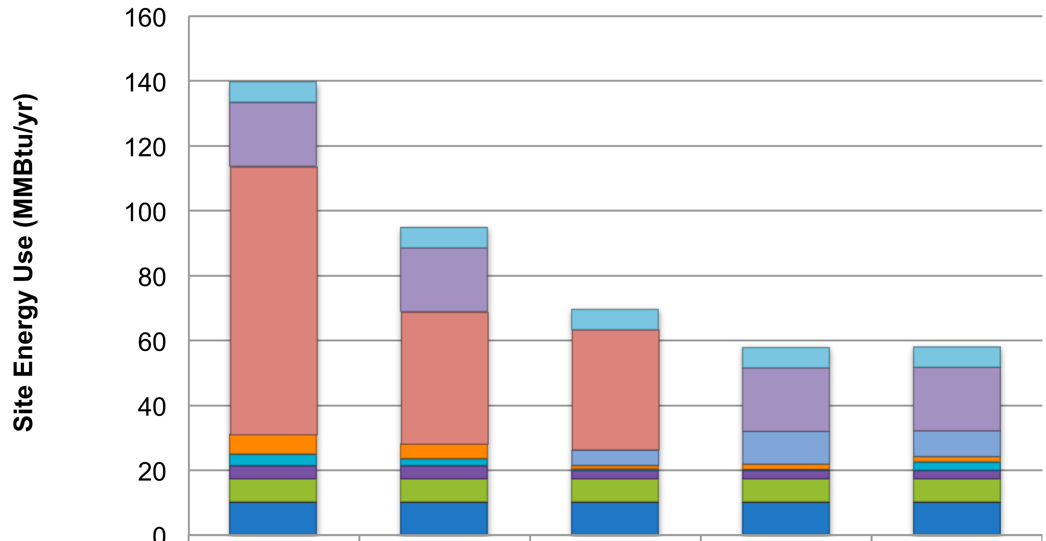
The Furnace–Central A/C case optimized an upgrade to the existing gas furnace to a gas, 98% AFUE furnace and an upgrade to the existing central A/C unit to one with a Seasonal Energy Efficiency Rating (SEER) 24.5. Both upgrades represent the most efficient and largest sized of the default options for their respective parameters. BEopt recommended the location of the ducts to be moved from unfinished attic space to finished living area as the default total leakage for this parameter option is given to be zero. This is considered to be valid as any actual leakage of conditioned air from the ductwork would be lost to finished space where it is ultimately intended. It is suggested that an electric powered heat pump water heater (HPWH) with an 80 gal storage tank replace the existing water heater. A HPWH extracts heat from surround air and uses it to heat water. Although, a study concluded that a HPWH is significantly more efficient than conventional gas water heaters when HVAC interaction is not included (i.e. water heater is installed in unfinished/unconditioned space) and during the cooling season when HVAC interaction is included, it was also shown to be less efficient than a conventional gas water heater in the heating season (Steven Winter Associates, INC., 2012). Since the Chicagoland area experiences more HDD than CDD and Group 4 was modeled with a slab construction assumption, it is also assumed that any hot water heater would be located within conditioned space, thus this upgrade was not expected for this particular group and application.

A MSHP system is a type of ASHP. It provides both space heating and cooling. Unlike the typical ASHP system, the MSHP is ductless, which makes it a good candidate for retrofit in homes without existing ductwork. This system is composed of an outdoor compressor and a small indoor air handing unit. Each indoor handling unit is designed to be able to condition small zones, not unlike a room A/C (window unit). Newer models are capable of working effectively in cold climates and BEopt default MSHP options are based on NREL research of mini-split heat pumps that are compatible with cold climates (NREL, 2014; Winker, 2011). The addition of electric baseboards is recommended to act as supplemental heat when necessary. For this case BEopt recommended the installation of a SEER 23, 11.1 HSPF, combined with 100% efficient electric baseboard heaters as supplemental heat. This is representative of the most efficient MSHP option. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings. This iteration point is observed to have the least initial and AERC and the highest site/source energy savings. However, it should be noted that for this vintage of homes, it can be assumed that the existing electric circuit panel for the home may not provide adequate electricity service for this type of retrofit and would need to be upgraded. BEopt may not have taken this additional retrofit into consideration for MSHP plus electric baseboard simulations; therefore, the initial costs, payback periods, and Modified Internal Rate of return (MIRR) for the MSHP case may not be as accurate as other cases. Further investigation of the costs associated with the conversion to electric heating is necessary for this group and all others herein.

A GSHP is a heat pump that exchanges heat energy with the ground to provide space heating and cooling through a ducted system. BEopt simulated that the optimal

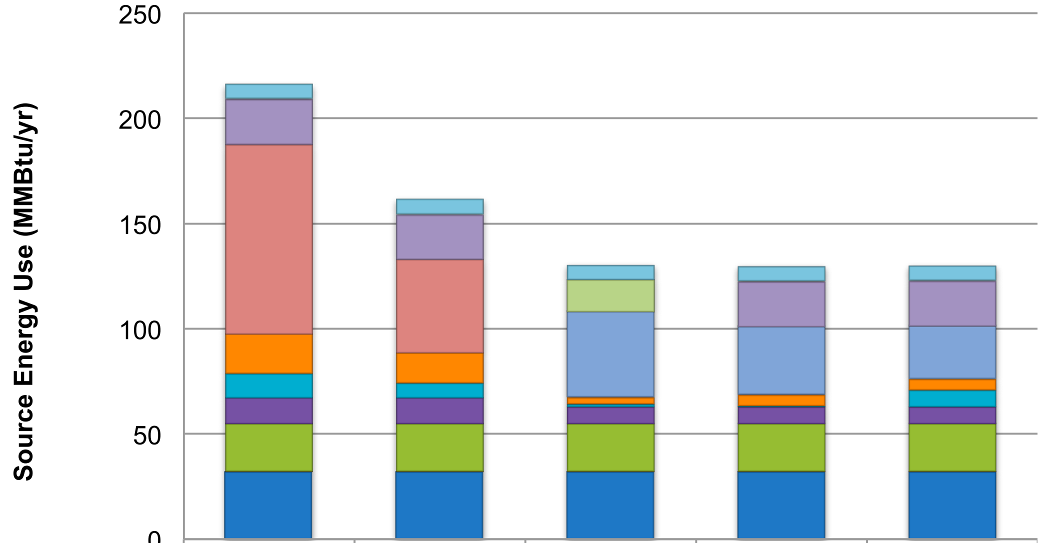
GSHP unit is one with an Energy Efficiency Rating (EER) of 20.2, a coefficient of productivity (COP) of 4.2 with pipes bored into soil with high ground conductivity (High-k), and utilizing thermally enhanced (Enh) grout between the pipes and the ground. As with the Furnace-Central A/C case, BEopt recommends for installation of the ducts to be within the finished space. An upgrade to the water heater was not recommended because the initial cost to upgrade is not offset by energy related cost savings for this case. As with all other cases, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 10 shows estimated site energy usage by end use of the packages listed in Tables 4 and 5, while Figure 11 shows estimated source energy usage. It can be observed that while both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 10), the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 11).



	Today	Enclosure: Iter 7, Pt 38	Furnace-Central A/C: Iter 14, Pt 15**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 3**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	19.77	19.75	0.00	19.76	19.69
Hot Water (E)	0.00	0.00	0.00	0.00	0.00
Heating (G)	82.55	40.83	37.20	0.00	0.00
Heating (E)	0.00	0.00	4.78	10.25	8.08
Cooling (E)	6.01	4.54	1.02	1.72	1.64
HVAC Fan/Pump (E)	3.59	2.26	0.55	0.22	2.57
Lights (E)	3.90	3.90	2.53	2.53	2.53
Lg. Appl. (E)	7.20	7.20	7.20	7.20	7.20
Vent Fan (E)	0.06	0.06	0.06	0.06	0.06
Misc. (E)	10.10	10.10	10.10	10.10	10.10

Figure 10. Group 4: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 7, Pt 38	Furnace-Central A/C: Iter 14, Pt 15**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 3**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	21.55	21.52	0	21.53	21.47
Hot Water (E)	0	0	15.04	0	0
Heating (G)	89.99	44.51	0	0	0
Heating (E)	0	0	40.54	32.33	25.47
Cooling (E)	18.95	14.32	3.22	5.42	5.19
HVAC Fan/Pump (E)	11.33	7.11	1.73	0.7	8.1
Lights (E)	12.29	12.29	7.97	7.97	7.97
Lg. Appl. (E)	22.71	22.71	22.72	22.72	22.72
Vent Fan (E)	0.19	0.19	0.18	0.18	0.18
Misc. (E)	31.83	31.83	31.83	31.83	31.83

Figure 11. Group 4: Source energy use of critical optimal iteration points

The simple payback period of a project represents the time required for a repayment of the original investment but does not incorporate future costs (e.g. replacement costs or technology upgrades at wear out), future changes to cost savings (e.g. utility cost changes due to fuel price escalation), or the time value of money or loan financing. Figure 12 illustrates the simple payback periods for each of the optimal packages.

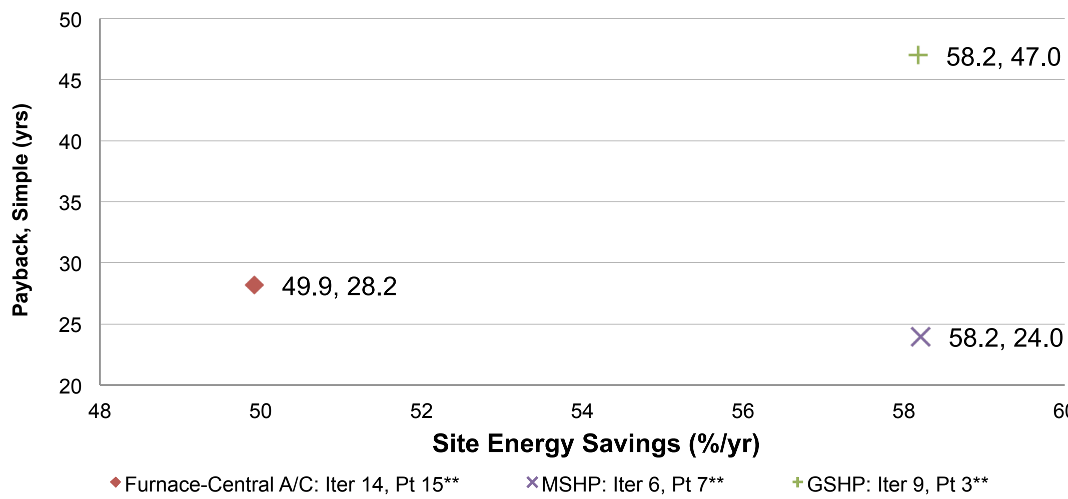


Figure 12. Group 4: Simple Payback of critical optimal iteration points

Desirable options lie within the lower and/or lower right portion of the graph, therefore It can be inferred that for group 4 the cases involving the furnace and MSHP have the expected payback period of less than 30 years and may be more desirable retrofit packages than the GSHP which has an expected payback period of more than 45 years.

The Modified Internal Rate of Return (MIRR) is a financial measure used to analyze the attractiveness of an investment (Lin, 1976) and is an effective indicator of relative profitability (Yoon & Choi, 2002). Figure 13 illustrates the MIRR of each of the optimal packages for group 4 in terms of site energy savings.

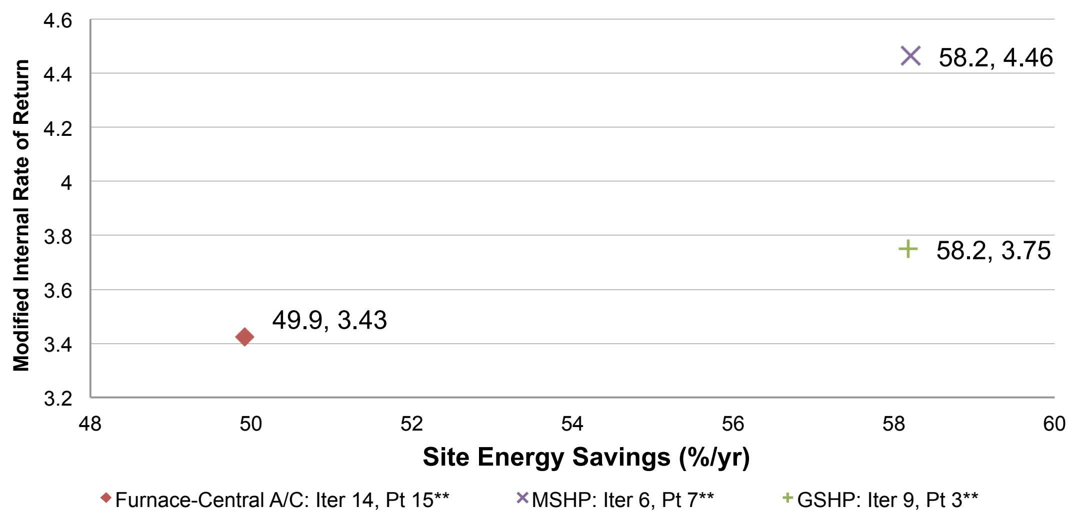


Figure 13. Group 4: Modified Internal Rate of Return of critical optimal iteration points

The most attractive investments present themselves at the upper portion and/or upper right portion of the graph. It can be deduced that the case that is expected to have the highest MIRR is the MSHP, followed by the GSHP case. The Furnace-Central A/C case was reported to have the lowest MIRR.

Through analyses of all the figures given for Group 4 it is concluded in combination with the optimized enclosure that a retrofit of a MSHP system is the most cost effective option, representing one of the most site energy saving options while also having the lowest payback period and highest MIRR.

Group 5: Brick, Pre-1978, Split level (1.5 stories) Group 5 has a measured mean floor area of 1299 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 1305 ft^2. This group was modeled with a full-unfinished basement and an attached garage on slab. The floor layouts and exterior 3D image of the BEopt model for this group are shown in Figure 14.

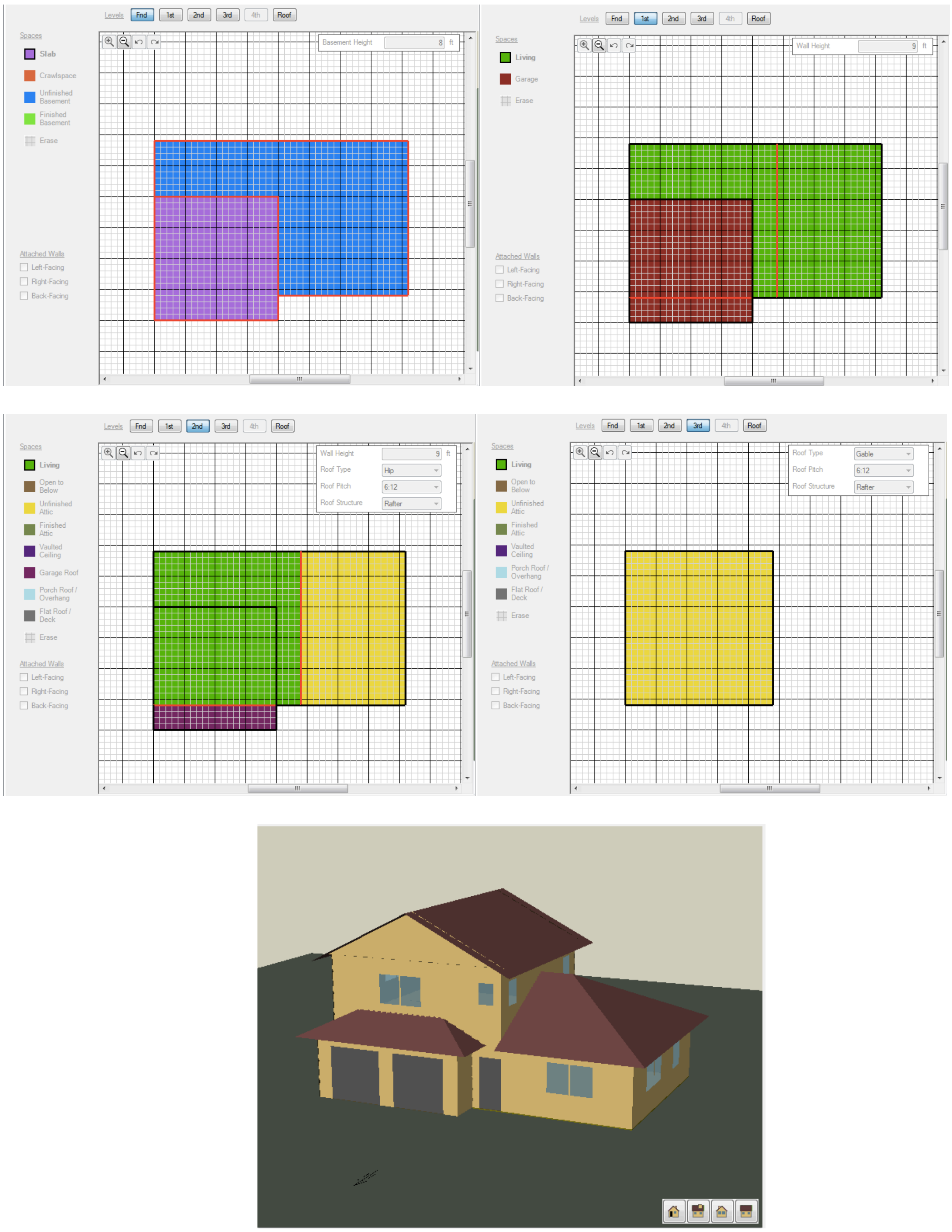


Figure 14. Group 5: BEopt model: foundation, first, second, and third (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 15 and 16 respectively. It can be observed that a site energy savings of about 27% (least cost option) can be achieved simply by updating the enclosure and keeping existing HVAC systems. This translates to about a 21% source energy savings. It can also be seen that the least cost option has an annualized energy related cost that is about $200/yr less than the existing case.

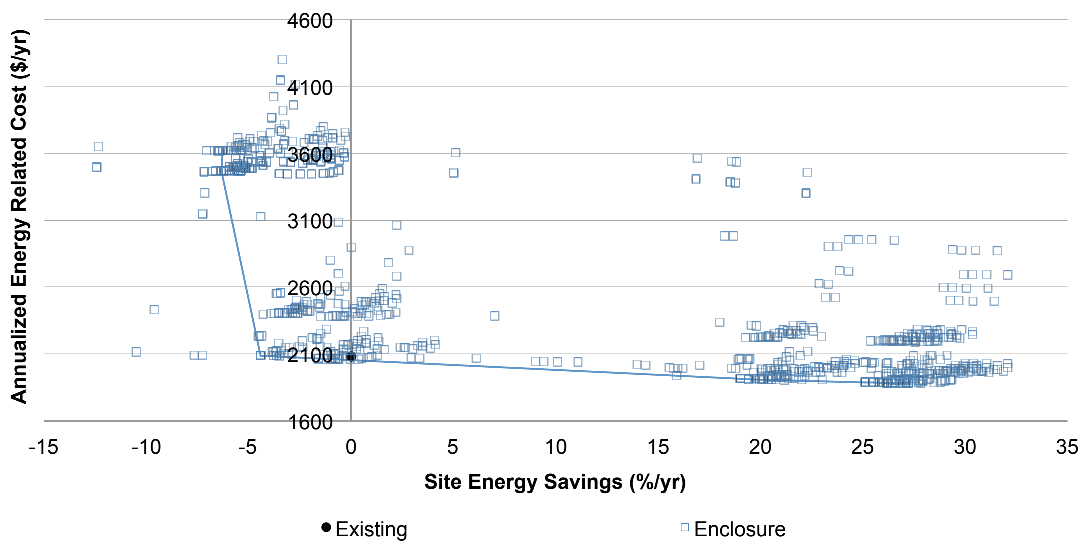


Figure 15. Group 5: Building Enclosure optimization results in terms of sites energy savings

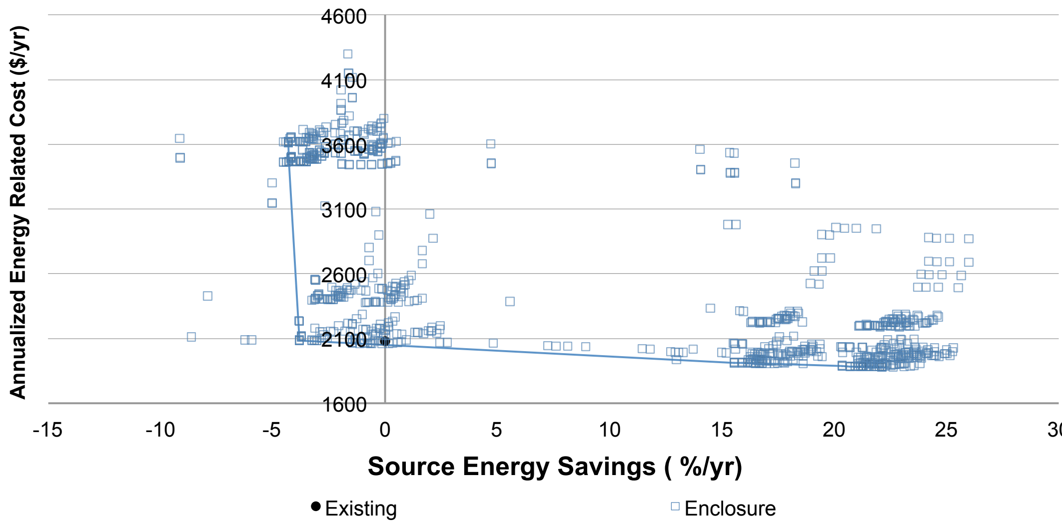


Figure 16. Group 5: Building Enclosure optimization results in terms of source energy savings.

Table 6 lists the original 'Today' scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves. For this residential building group, the optimal option involves upgrades to the exterior wall construction, interzonal walls (walls separating the unconditioned from conditioned space, in this case between the garage and living space), unfinished attic insulation, and air leakage only.

Table 6. Group 5 Optimal Building Enclosure: Optimized Parameters, 'Today' scenario assumptions, and BEopt upgrades.

Parameter name	Today	Enclosure: Iter 12, Pt 6
Exterior Wall (Masonry)	4-in Hollow Brick, R-3 Fiberglass Batt, 1-in furring, 24 in o.c.	4-in Hollow Brick, R-19 Fiberglass Batt, 2x6, 24 in o.c.
Exterior Finish	Brick, Medium/Dark	No Change
Interzonal Walls	R-7 Fiberglass Batt, GR-3, 2x4, 16 in o.c.	R-13 Fiberglass (Blown-in), Gr-1, 2x4, 16 in o.c.
Unfinished Attic	Ceiling R-11 Fiberglass (Blown-in), Vented	Ceiling R-25 Fiberglass (Blown-in), Vented
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Interzonal Floor	R-11 Fiberglass, (Blown-in)	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Leaky	Typical
Mechanical Ventilation	Spot Ventilation Only	No Change

As with group 4, the suggestion for interior built out and insulation of the exterior brick wall is appropriate and expected (Knight, 2004). The upgrade in enclosure tightness from leaky to typical is appropriate as it equates to about a 22% increase in enclosure tightness (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). Insulation retrofit of the interzonal walls, presumably the walls separating the garage from the rest of the home, is appropriate for the context of group 5, as is the suggestion for R-25 blown-in fiberglass insulation to be installed in the attic. The non-upgrades to other parameters are acceptable, as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

The AERC resulting from each of the HVAC optimizations after the implementation of the selected optimal closure for this group are illustrated in terms of site energy savings (see Fig. 17) and source energy savings (see Fig. 18) below.

From the results shown in Figure 17, we can see that the options chosen for optimization all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but each of their least cost options equate to about an estimated 61% site energy savings.

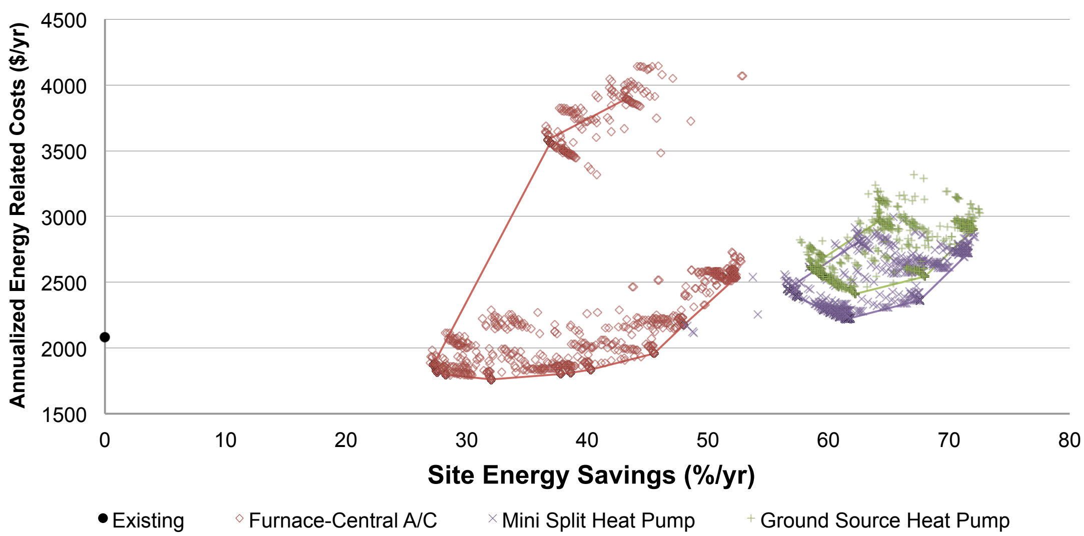


Figure 17. Group 5: HVAC optimization results in terms of site energy savings

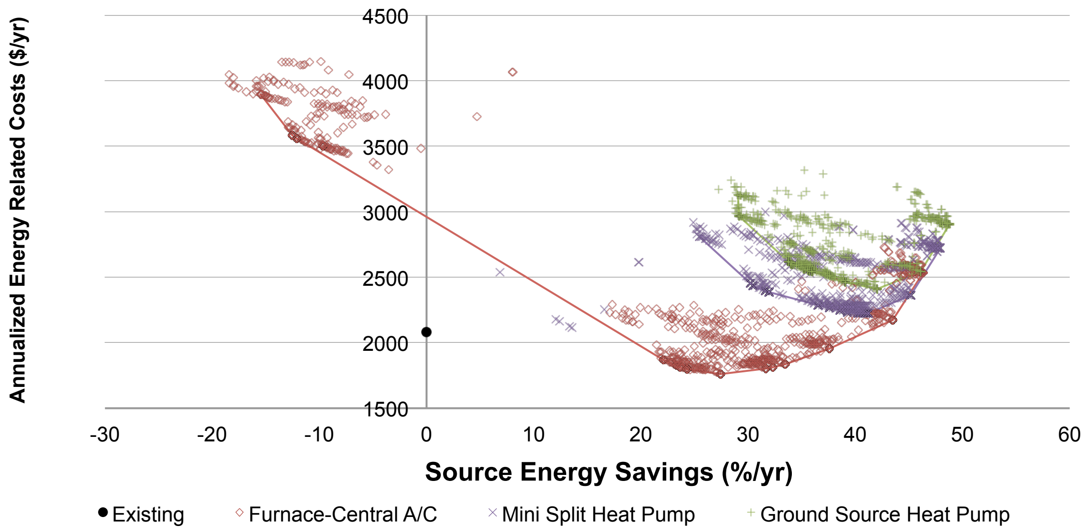


Figure 18. Group 5: HVAC optimization results in terms of source energy savings.

The optimized parameter options, costs, and energy savings for the iteration points chosen for further analysis are listed in Table 7 below. It can be seen that the MSHP iteration point has the least associated costs and the highest energy savings of the three HVAC systems.

Table 7. (Page 1 of 2) Group 5: Brick, Pre-1978, Split-level (1.5 stories) - Parameters options, costs and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 17, Pt 52**	MSHP: Iter 6, Pt 9**	GSHP: Iter 11, Pt 57**
Central A/C	SEER 10	SEER 24.5	None	None
Furnace	Gas 78% AFUE	Gas, 98% AFUE	None	None
Electric Baseboard	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	SEER 25, 11.3 HSPF	None
Ground Source Heat Pump	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	Typical, Uninsulated (Unfinished Basement)	In Finished Space	None	In Finished Space
Ceiling Fan***	None	None	None	None
Water Heater	Gas, 54% EF	Gas, Tankless, Condensing	No Change	No Change
Solar Water Heating	None	64 ft^2 Closed Loop	None	None
SWH Azimuth	N/A	Back Roof	N/A	N/A
SWH Tilt	N/A	Latitude	N/A	N/A
Lighting	Benchmark	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in

Table 7. (Page 2 of 2) Group 5: Brick, Pre-1978, Split-level (1.5 stories) - Parameters options, costs and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 17, Pt 52**	MSHP: Iter 6, Pt 9**	GSHP: Iter 11, Pt 57**
Initial Cost ($)	$0	$18,610	$11,190	$19,070
Annualized Energy Related Costs ($/yr)	$2,081	$2,325	$2,225	$2,416
% Site (Source) Savings	0	49.7(40.2)	61.6(40.8)	62.1(41.8)

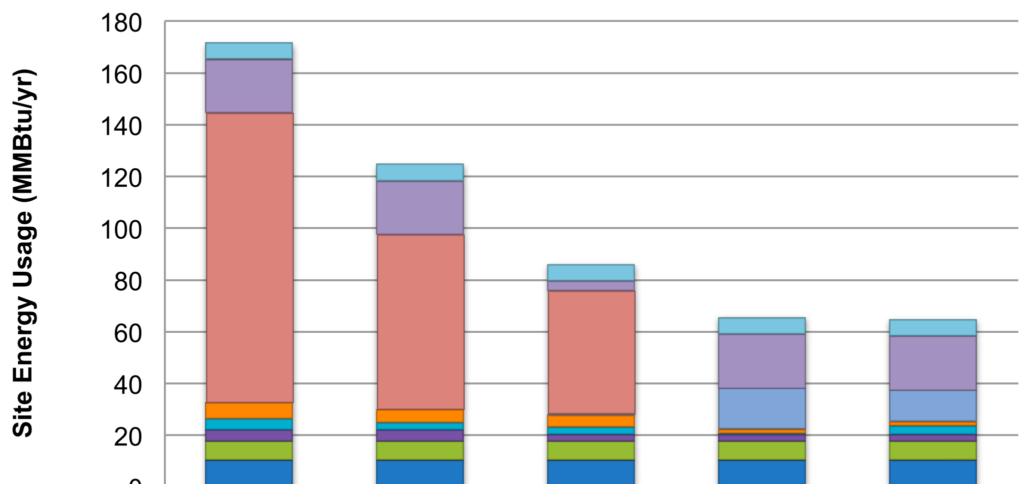
It is observed the addition of ceiling fans were not considered a cost effective upgrade for any of the cases.

The Furnace–Central A/C case, BEopt optimized the upgrade to a gas, 98% AFUE furnace from the existing and an upgrade to a 24.5 SEER central A/C are considered appropriate recommendations. The recommendation to install ducts in finished space is practical since installation within the walls is more difficult in homes without pre-conceived space dedicated for ductwork. It is suggested that a 64 ft^2 closed loop solar water heating system, oriented on the back roof of the house (south side), and tilted to a degree that equals the latitude of Chicago+15º be installed as a supplement preheat method to the water heater. A tankless condensing water heater is suggested as an upgrade from the existing water heater. Condensing water heaters utilize heat recovered from exit flue gases to preheat incoming cold water. Unlike common hot water heaters, tankless water heaters do not have storage tanks and heat water on demand. User behavior may have to accommodate this upgrade to ensure the fulfillment of hot water loads. There are no other issues expected from making this upgrade, as it is an energy retrofit that is increasing in popularity.

For the MSHP case, BEopt recommended the installation of a SEER 25, 11.3 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt did not suggest an upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

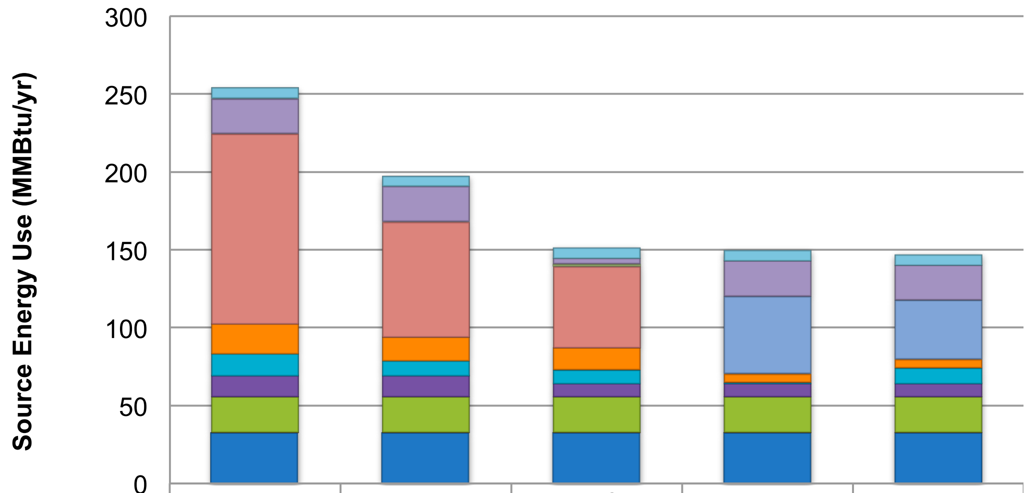
As with Group 4, BEopt simulated that the optimal GSHP unit as an EER of 20.2, COP 4.2 High-k soil, Enh grout the most efficient and largest sized unit for this parameter. BEopt recommends for installation of the ducts to be within the finished space. An upgrade to the water heater was not recommended because the initial cost to upgrade is not offset by energy related cost savings. Also like Group 4, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 19 shows estimated site energy usage of the packages listed in Tables 6 and 7, while Figure 20 shows estimated source energy usage. It can be observed that while both heat pumps (i.e. mini-split, and ground-source) are expected to consume less energy on site (see Fig. 19), it is verified that the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 20).



	Today	Enclosure: Iter 12, Pt 6	Furnace-Central A/C: Iter 17, Pt 52**	MSHP: Iter 6, Pt 9**	GSHP: Iter 11, Pt 57**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	20.53	20.72	3.71	21.12	21.10
Hot Water (E)	0.00	0.00	0.00	0.00	0.00
Heating (G)	111.84	67.50	47.73	0.00	0.00
Heating (E)	0.00	0.00	0.36	15.76	12.03
Cooling (E)	6.18	5.05	4.61	1.70	1.67
HVAC Fan/Pump (E)	4.43	3.02	2.79	0.33	3.25
Lights (E)	4.34	4.34	2.81	2.81	2.81
Lg. Appl. (E)	7.20	7.20	7.20	7.20	7.20
Vent Fan (E)	0.07	0.07	0.07	0.07	0.07
Misc. (E)	10.28	10.28	10.28	10.28	10.28

Figure 19. Group 5: Site energy use of critical optimal



	Today	Enclosure: Iter 12, Pt 6	Furnace-Central A/C: Iter 17, Pt 52**	MSHP: Iter 6, Pt 9**	GSHP: Iter 11, Pt 57**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	22.37	22.57	4.04	23.01	23
Hot Water (E)	0	0	1.15	0	
Heating (G)	121.91	73.58	52.03	0	0
Heating (E)	0	0	0	49.67	37.9
Cooling (E)	19.47	15.9	14.53	5.36	5.28
HVAC Fan/Pump (E)	13.95	9.52	8.8	1.04	10.23
Lights (E)	13.66	13.66	8.86	8.86	8.86
Lg. Appl. (E)	22.71	22.71	22.72	22.72	22.72
Vent Fan (E)	0.21	0.21	0.21	0.21	0.21
Misc. (E)	32.4	32.4	32.4	32.4	32.4

Figure 20. Group 5: Source energy use of critical optimal iteration points

Figure 21 illustrates the simple payback periods for each of the optimal packages for Group 5.

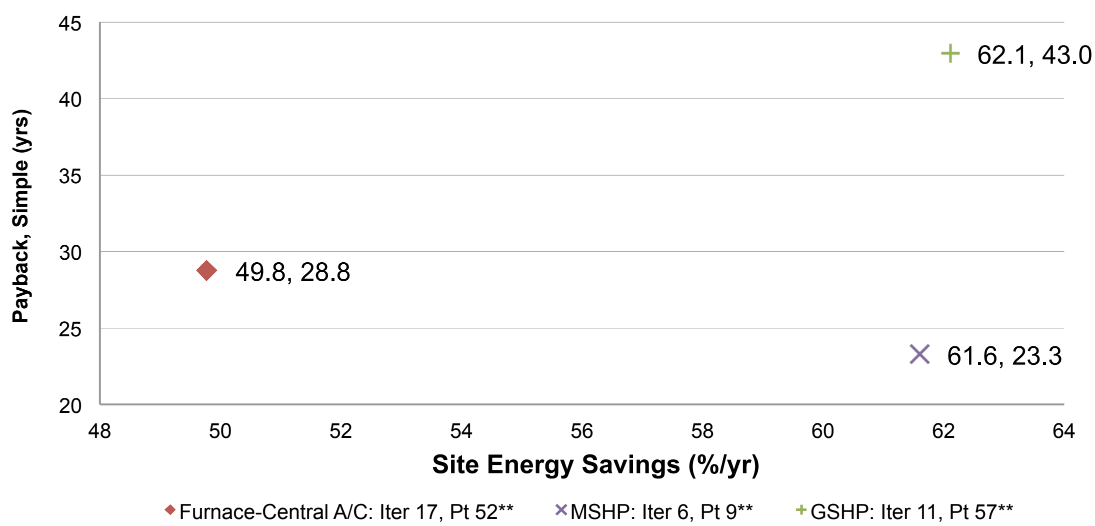


Figure 21. Group 5: Simple Payback of critical optimal iteration points

It can be inferred that the cases involving the furnace and MSHP have the expected payback period of less than 35 years and may be more desirable retrofit packages than the GSHP case, which has an expected payback period of more than 40 years.

Figure 22 illustrates the MIRR of each of the optimal packages for Group 5 in terms of site energy savings.

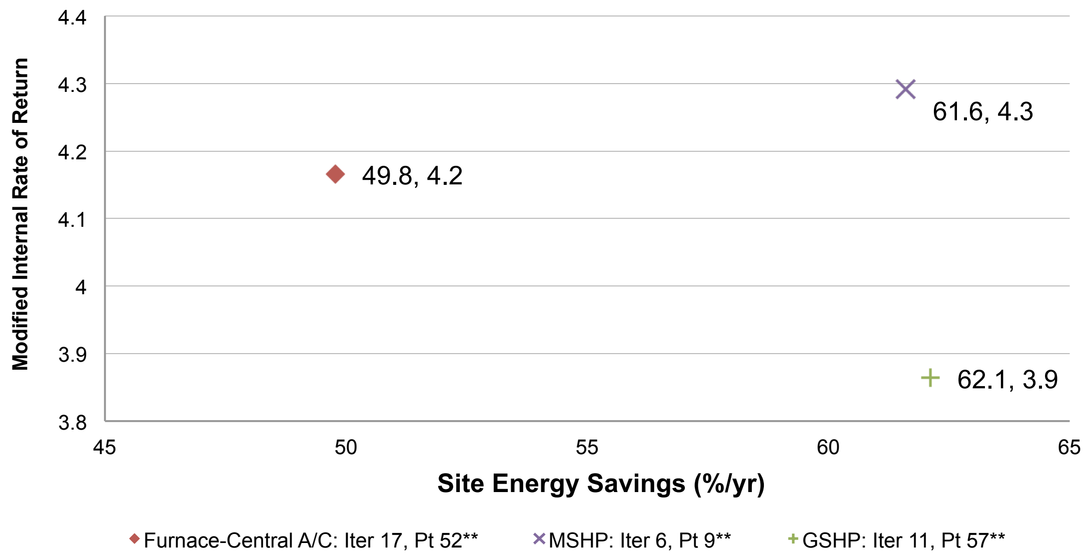


Figure 22. Group 5: Modified Internal Rate of Return of critical optimal iteration points

It can be deduced that the case that is expected to have the highest MIRR is the MSHP, followed by the Furnace-Central A/C and the GSHP cases.

Through analyses of all the figures given for Group 5 it is concluded that in combination with the optimized enclosure option the addition of a MSHP is the most cost effective option toward a 50% site energy reduction and representing one of the most site energy saving while also having the lowest payback period and highest MIRR.

Group 6: Brick, 1942-1978, 2 stories Group 6 has measured mean square footage of 2059 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 2064 ft^2. This group was modeled with a full-unfinished basement and an attached garage on slab. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 23.

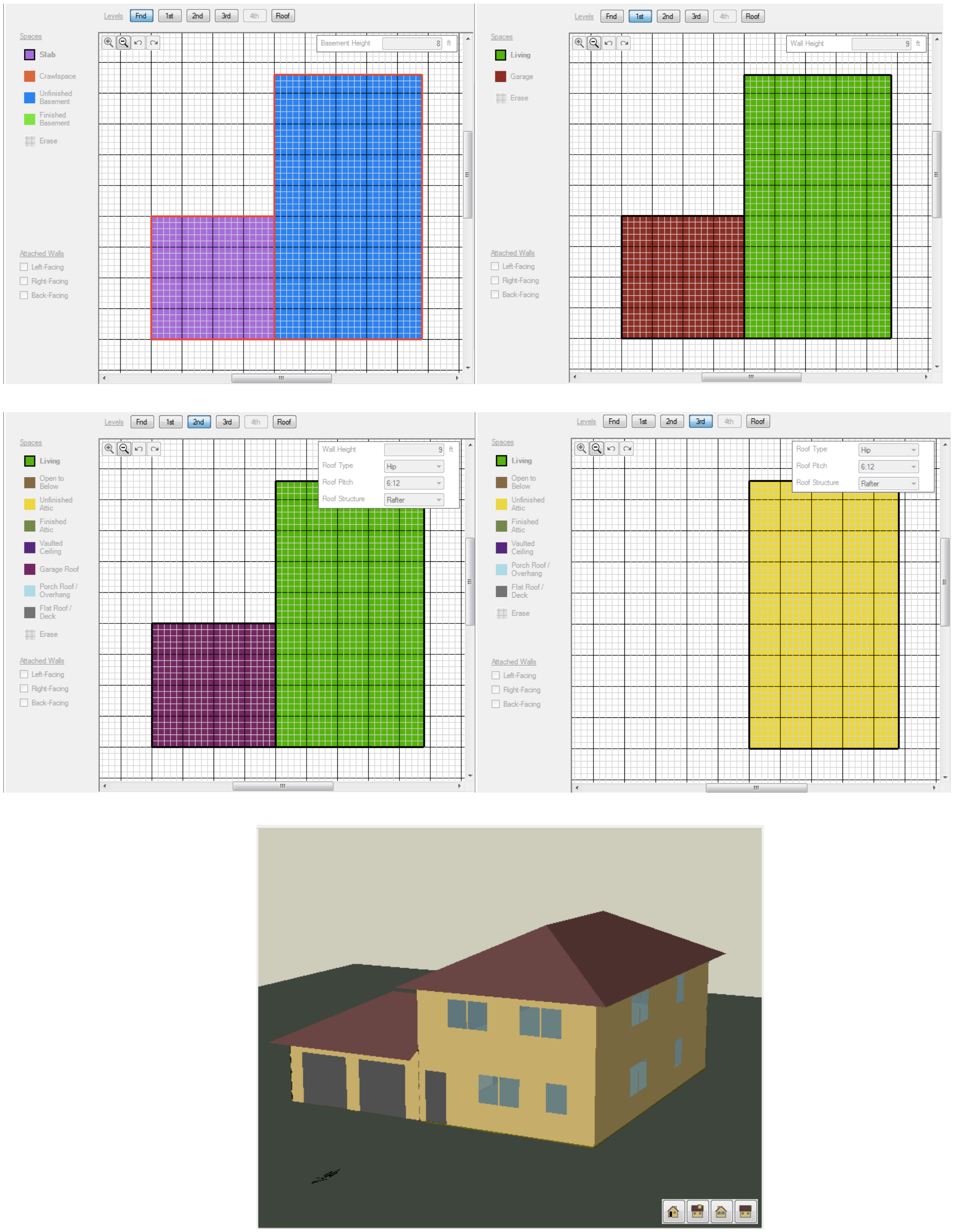


Figure 23. Group 6: BEopt model: foundation, first, second, and third (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 24 and 25 respectively. It can also be observed that a site energy savings of about 31% (least cost option) simply by updating the enclosure and keep existing HVAC systems (See Fig. 24). This translates to about a 26% source energy savings. The optimal (least cost) enclosure package has an annualized energy related cost that is about $300/yr less then the existing scenario.

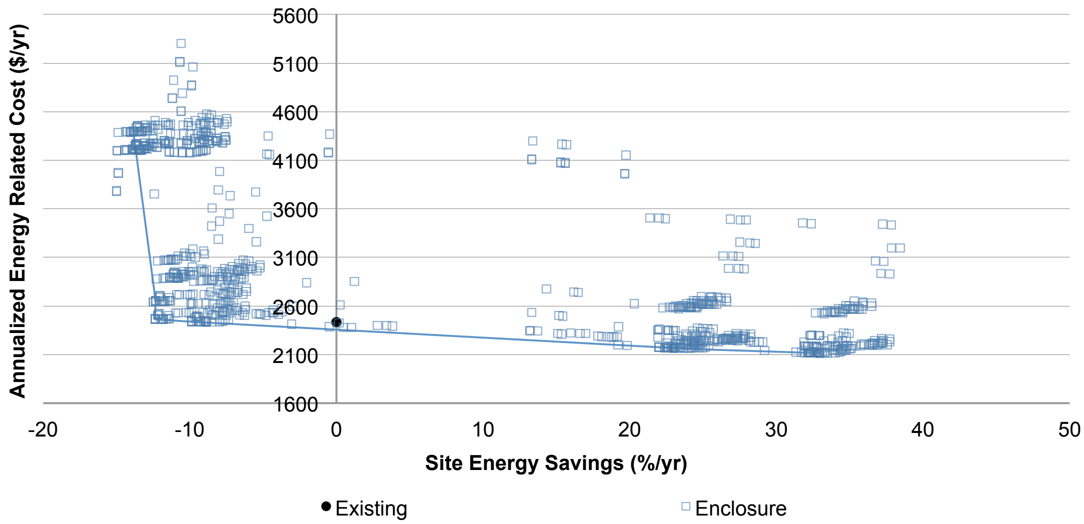


Figure 24. Group 6: Building Enclosure optimization results in terms of sites energy savings

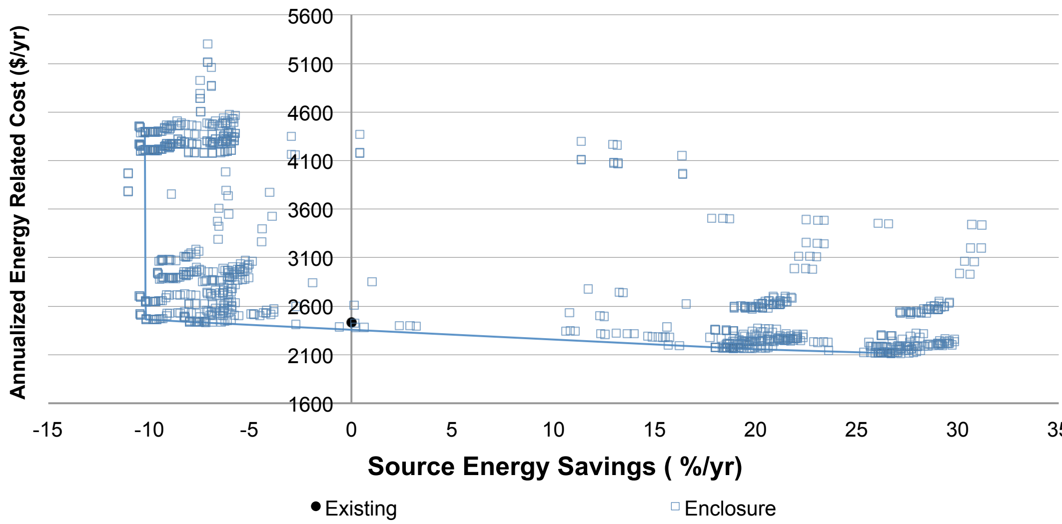


Figure 25. Group 6: Building Enclosure optimization results in terms of source energy savings.

Table 8 lists the original 'Today' scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost. For this residential building group, the optimal option involves upgrades to the exterior wall, unfinished attic insulation, and air leakage only.

Table 8. Group 6: Optimal Building Enclosure: Optimized Parameters, 'Today' scenario assumptions, and BEopt upgrades.

Parameter name	'Today'	Enclosure: Iter 12, Pt 71
Exterior Wall (Masonry)	4-in Hollow Brick, R-3 Fiberglass Batt, 1-in furring, 24 in o.c.	4-in Hollow Brick, R-19 Fiberglass Batt, 2x6, 24 in o.c.
Exterior Finish	Brick, Medium/Dark	No Change
Interzonal Walls	R-7 Fiberglass Batt, GR-3, 2x4, 16 in o.c.	No Change
Unfinished Attic	Ceiling R-11 Fiberglass (Blown-in), Vented	Ceiling R-25 Fiberglass (Blown-in), Vented
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Typical	Tight
Mechanical Ventilation	Spot Ventilation Only	No Change

As with Groups 4 and 5, the suggestion for interior built out and insulation of the exterior brick wall is appropriate and expected (Knight, 2004). The upgrade in envelope tightness from typical to tight reflects about a 22% increase in enclosure tightness and is considered to be an appropriate upgrade (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). Insulation retrofit of the unfinished attic is also considered appropriate for the context of Group 6. The non-upgrades to other parameters are appropriate, as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

The results form each of the HVAC case optimizations can be seen in the following graphs illustrating the AERC in terms of site energy savings (see Fig. 26) and source energy savings (see Fig. 27) and their respective least cost fit lines.

From the results shown in Figure 26, it can be seen that the options chosen for optimization, most HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case. The iteration representing a 50% site energy savings for the furnace-central A/C case is estimated to have a slightly lower annualized energy related cost than the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated site energy savings of about 63%.

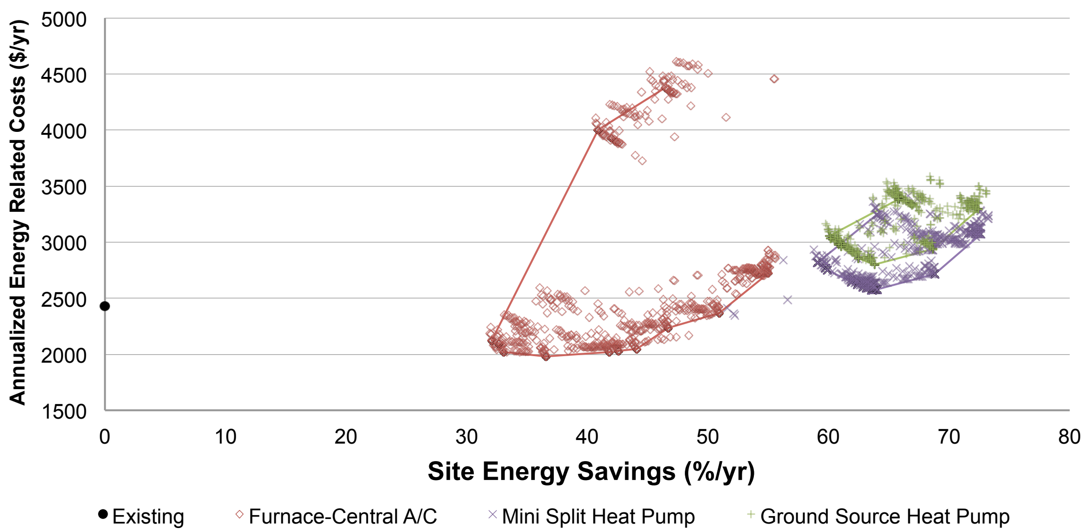


Figure 26. Group 6: HVAC optimization results in terms of site energy savings

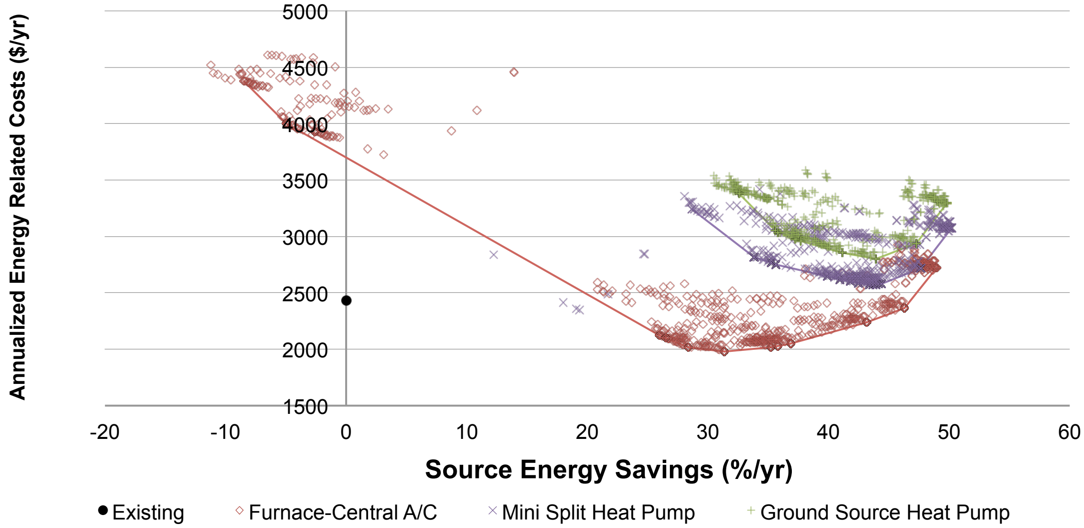


Figure 27. Group 6: HVAC optimization results in terms of source energy savings.

The optimized parameter options, costs, and energy savings for the iterations chosen for further analysis along side the 'Today' case are listed in Table 9. Although it is not represented as having the least initial cost, the optimal iteration point associated with the Furnace-Room A/C has the lowest annualized energy related cost equating to about a $100/yr savings from the existing condition.

Table 9. Group 6: Brick, 1942-1978, 2 stories - Parameters options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 11, Pt 12**	MSHP: Iter 4, Pt 7**	GSHP: Iter 17, Pt 3**
Central A/C	SEER 10	SEER 24.5	None	None
Furnace	Gas, 78% AFUE	Gas, 98% AFUE	None	None
Electric Baseboard	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	Typical, Uninsulated (Unfinished Basement)	In Finished Space	None	In Finished Space
Ceiling Fan***	None	None	None	None
Water Heater	Gas, 54% EF	Gas Tankless	No Change	No Change
Solar Water Heating	None	None	None	None
SWH Azimuth	N/A	N/A	N/A	N/A
SWH Tilt	N/A	N/A	N/A	N/A
Lighting	Benchmark	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in
Initial Cost ($)	$0	$17,506	$14,278	$23, 699
Annualized Energy Related Costs ($/yr)	$2,430	$2,346	$2,576	$2,801
% Site (Source) Savings	0	49.9(45.5)	63.6(43.4)	63.8(43.9)

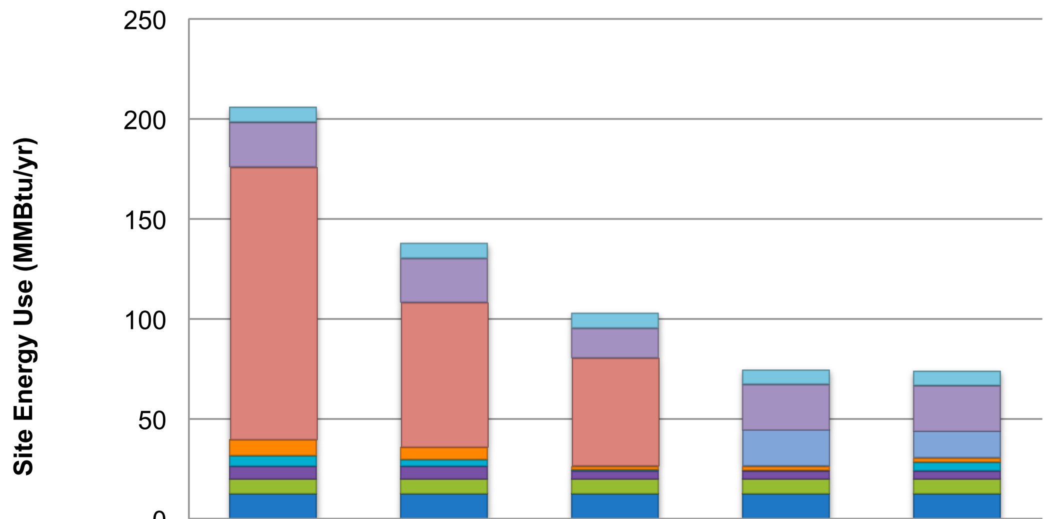
It is observed the addition of ceiling fans were not considered a cost effective upgrade for any of the cases. The addition of a solar water heating system was also not considered to be a cost effective upgrade for any of cases in this group.

The Furnace–Central A/C case, BEopt optimized the upgrade to a gas, 98% AFUE furnace from the existing and an upgrade to a 24.5 SEER central A/C are considered appropriate recommendations. The recommendation to install ducts in finished space is practical since installation within the walls is more difficult in homes without pre-conceived space dedicated for ductwork. Similar to upgrade suggestions for Group 5, a tankless condensing water heater is suggested as an upgrade from the existing water heater. Due to the size of the homes in this group, the upgrade to a tankless condensing water heater may not be able to handle high hot water loads (e.g. multiple showers taken in tandem or simultaneously with or without appliances using hot water running at the same time). However, user behavior can be changed to accommodate this retrofit in order to ensure the availability of hot water at all times necessary.

For the case involving the optimization of a MSHP system, BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

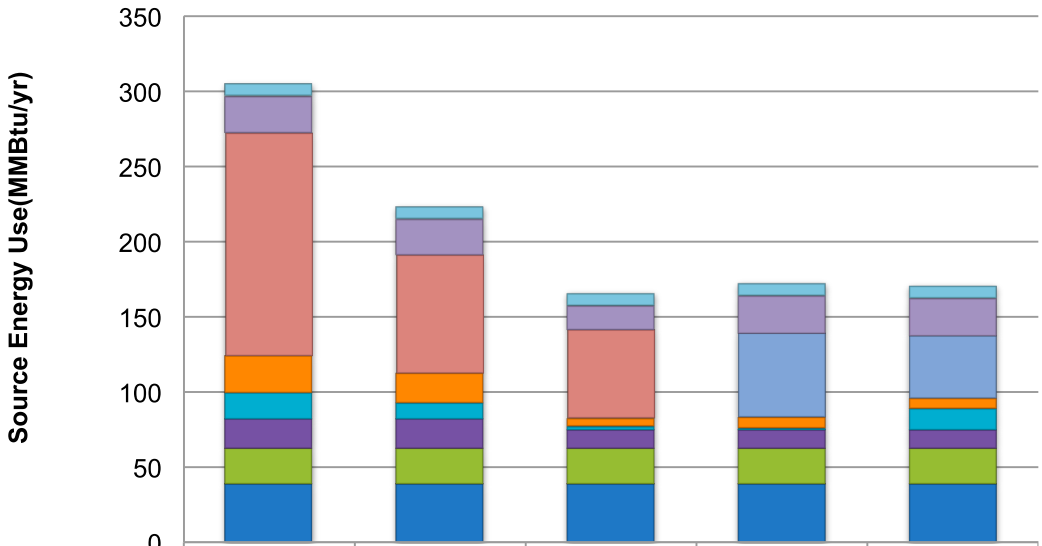
BEopt simulated that the optimal GSHP unit to be EER 20.2, COP 4.2, High-k soil, Enh grout between the pipes and the ground. BEopt recommends for installation to be within the finished space. An upgrade to the water heater was not recommended. As with all other cases, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 28 shows estimated site energy usage by end use of the packages listed in Tables 8 and 9, while Figure 29 shows estimated source energy usage. It can be observed that while both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 28), it is verified that the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see fig. 29).



	Today	Enclosure: Iter 12, Pt 71	Furnace-Central A/C: Iter 11, Pt 12**	MSHP: Iter 4, Pt 7**	GSHP: Iter 17, Pt 3**
Lg. Appl. (G)	7.61	7.61	7.61	7.61	7.61
Hot Water (G)	22.41	22.05	14.92	23.04	23.02
Hot Water (E)	0.00	0.00	0.00	0.00	0.00
Heating (G)	136.09	72.49	54.17	0.00	0.00
Heating (E)	0.00	0.00	0.00	17.71	13.23
Cooling (E)	7.91	6.23	1.66	2.36	2.25
HVAC Fan/Pump (E)	5.51	3.47	0.80	0.37	4.41
Lights (E)	6.12	6.12	3.97	3.97	3.97
Lg. Appl. (E)	7.42	7.42	7.42	7.42	7.42
Vent Fan (E)	0.08	0.08	0.08	0.08	0.08
Misc. (E)	12.28	12.28	12.28	12.28	12.28

Figure 28. Group 6: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 12, Pt 71	Furnace-Central A/C: Iter 11, Pt 12**	MSHP: Iter 4, Pt 7**	GSHP: Iter 17, Pt 3**
Lg. Appl. (G)	8.30	8.30	8.30	8.30	8.30
Hot Water (G)	24.42	24.03	16.26	25.10	25.10
Hot Water (E)	0.00	0.00	0.00	0.00	0.00
Heating (G)	148.34	79.02	59.05	0.00	0.00
Heating (E)	0.00	0.00	0.00	55.81	41.71
Cooling (E)	24.96	19.62	5.23	7.43	7.08
HVAC Fan/Pump (E)	17.38	10.92	2.52	1.17	13.91
Lights (E)	19.27	19.27	12.49	12.49	12.49
Lg. Appl. (E)	23.40	23.40	23.40	23.40	23.40
Vent Fan (E)	0.26	0.26	0.26	0.26	0.26
Misc. (E)	38.71	38.71	38.71	38.71	38.71

Figure 29. Group 6: Source energy use of critical optimal iteration points

Figure 30 illustrates the simple payback periods for each of the cases. It can be inferred that the cases involving the boiler, furnace, and MSHP have the expected payback period of less than 25 years and may be more desirable retrofit packages than the GSHP case which has an expected payback period of more than 35 years.

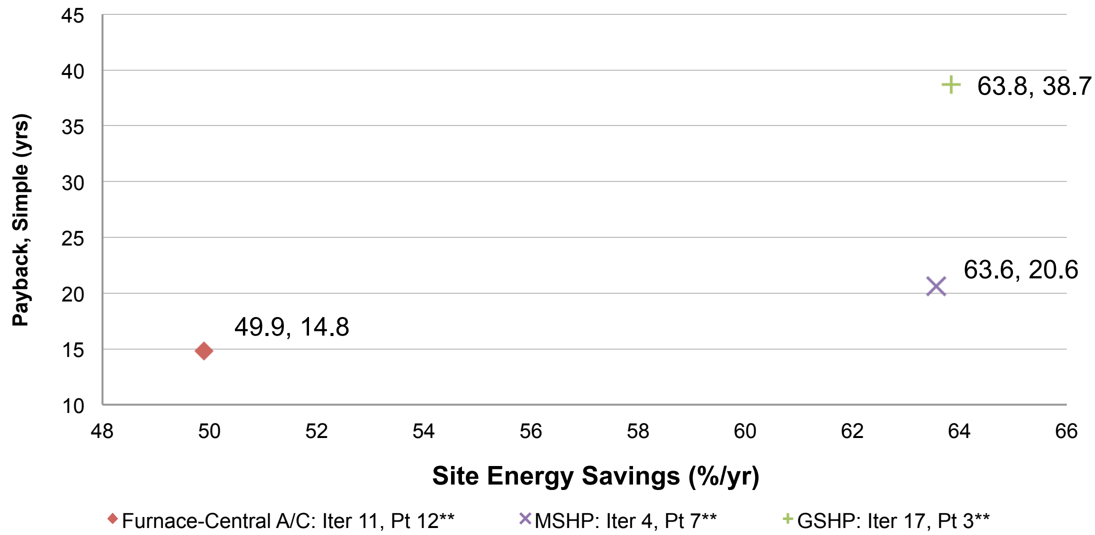


Figure 30. Group 6: Simple Payback of critical optimal iteration points

Figure 31 illustrates the MIRR of each of the optimal packages for Group 6 in terms of site energy savings

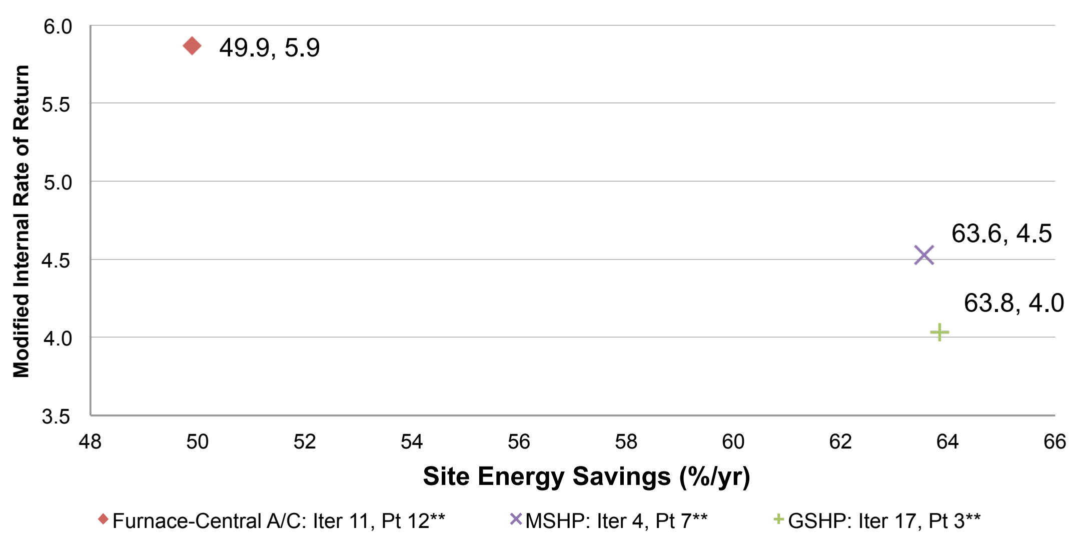


Figure 31. Group 6: Modified Internal Rate of Return of critical optimal iteration points

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It can be deduced that the case that is expected to have the highest MIRR is the Furnace-Central A/C case, followed by the MSHP and the GSHP cases.

Through analyses of all the figures given for Group 6 it is concluded that in combination with the optimized enclosure option the update to the existing as detailed in the Furnace-Central A/C case is the most cost effective option toward a 50% site energy reduction as it represents the lowest payback period and highest MIRR.

Group 7: Brick, Pre-1942, 1 to 1.5 stories (no split level) Group 7 has measured mean square footage of 1141 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 1140 ft^2. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 32.

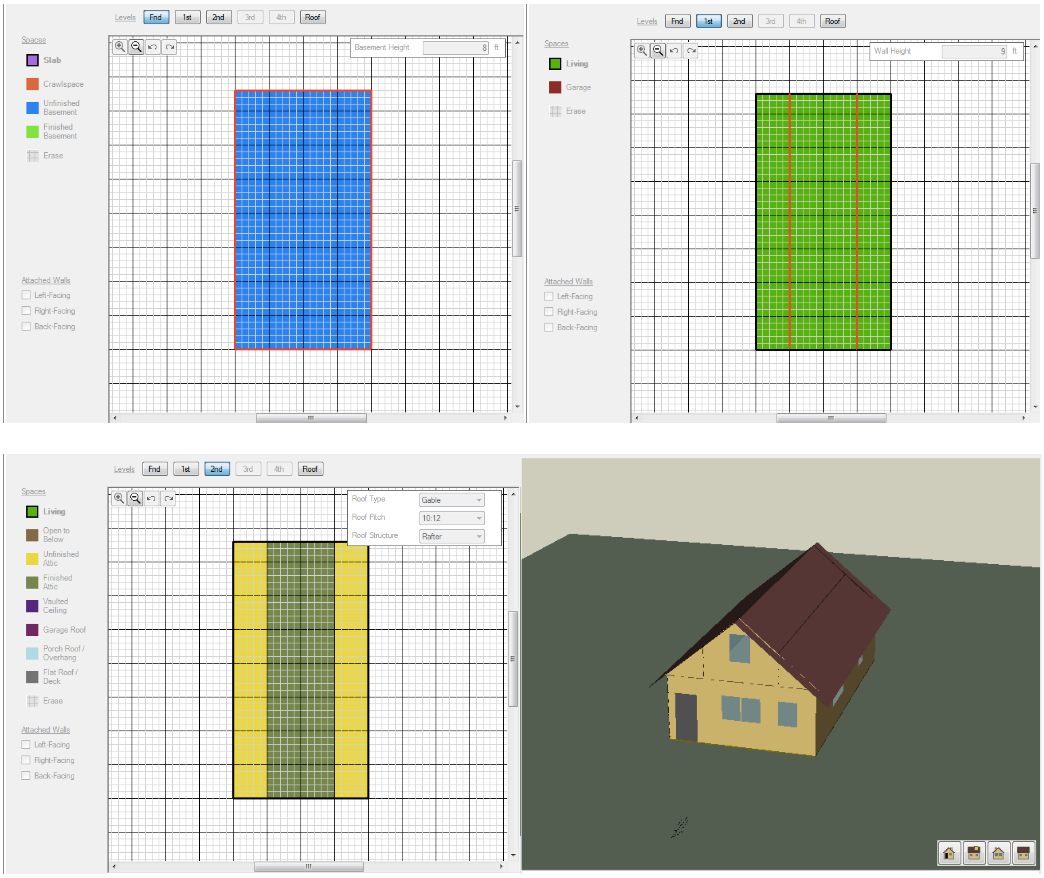


Figure 32. Group 7: BEopt model: foundation, first, and second (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 33 and 34 respectively. It can be observed that a site energy savings of about 30% (least cost option) simply by updating the enclosure and keep existing HVAC systems. This translates to about a 25% source energy savings.

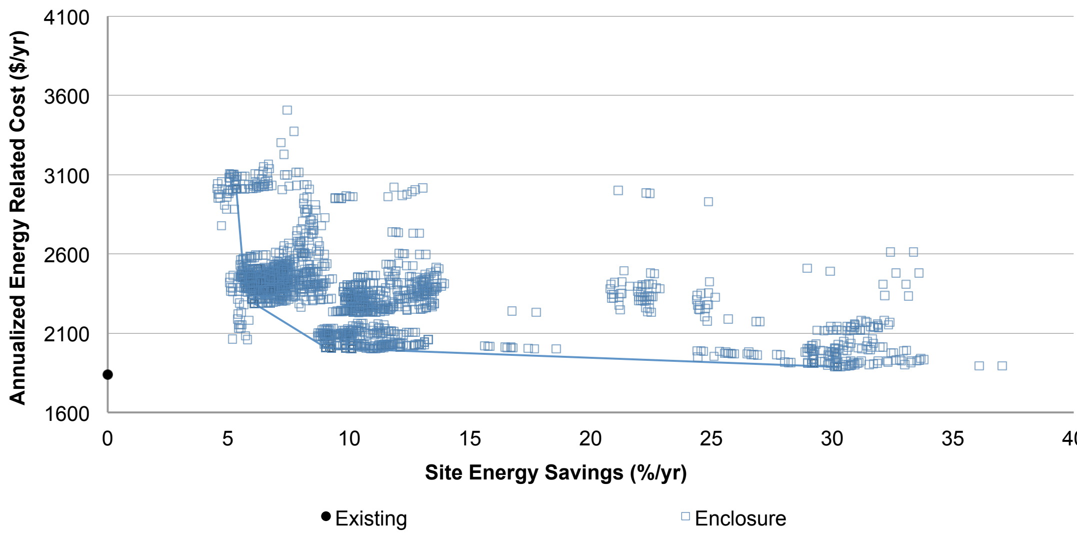


Figure 33. Group 7: Building Enclosure optimization results in terms of site energy savings

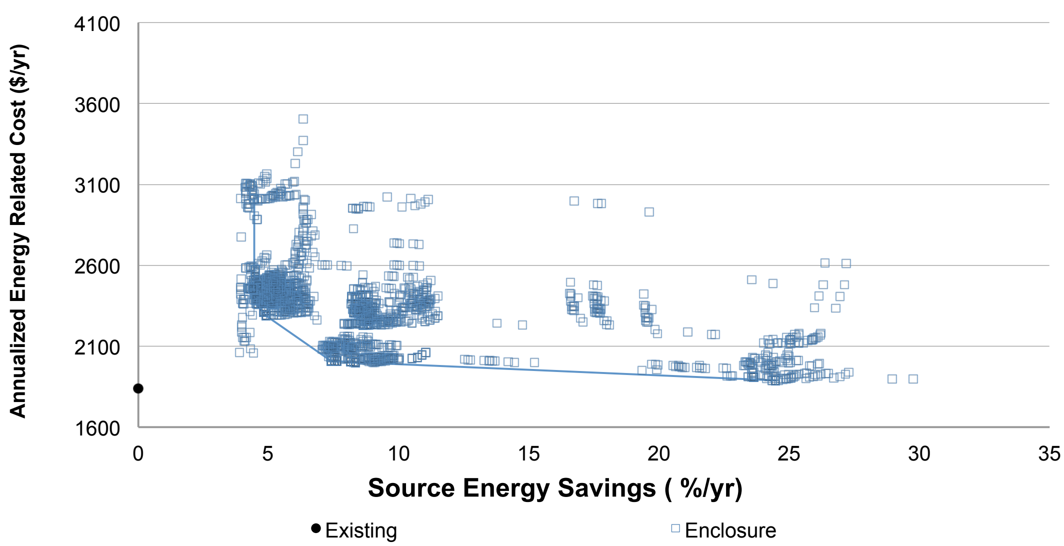


Figure 34. Group 7: Building Enclosure optimization results in terms of source energy savings.

Table 10 lists the original ‘Today’ scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves. For this residential building group, the optimal option involves upgrades to the exterior wall construction, interzonal walls, unfinished attic insulation, and air leakage only.

Table 10. Group 7: Optimal Building Enclosure: Optimized Parameters, ‘Today’ scenario assumptions, and BEopt upgrades.

Parameter name	‘Today’	Enclosure: Iter 25 Pt 1
Exterior Wall (Masonry)	4-in Hollow Brick, Uninsulated, 1-in furring, 24 in o.c.	4-in Hollow Brick, R-19 Fiberglass Batt, 2x6, 24 in o.c.
Exterior Finish	Brick, Medium/Dark	No Change
Interzonal Walls	Uninsulated, 2x4, 16 in o.c.	R-13 Fiberglass (Blown-in), Gr-1, 2x4, 16 in o.c.
Unfinished Attic	Ceiling R-7 Fiberglass (Blown-in), Vented	Ceiling R-19 Fiberglass (Blown-in), Vented
Finished Roof	R-19 Fiberglass (Blown-in)	No Change
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Interzonal Floor	Uninsulated	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Very Leaky	Leaky
Mechanical Ventilation	None	No Change

As with all previous groups, the suggestion for interior built out and insulation of the exterior brick wall is appropriate and expected (Knight, 2004). The upgrade in envelope tightness from very leaky to leaky reflects about a 22% increase in enclosure tightness and is considered to be an appropriate upgrade (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). Insulation retrofit of the unfinished attic is also considered appropriate for the context of Group 7. The non-upgrades to other parameters are appropriate, as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

Using the optimized building enclosure parameters listed in Table 10, HVAC optimization simulations were performed in separate cases. Figures 35 and 36 illustrate the results of HVAC optimization representing the AERC in terms of site energy savings and source energy savings respectively along side their corresponding least cost fit lines. Comparison of the two graphs shows critical differences in values between site and source energy savings especially in the cases involving the mini-split and ground-source heat pumps, as expected.

From the results shown in Figure 35, we can see that the options chosen for optimization all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated 60% site energy savings.

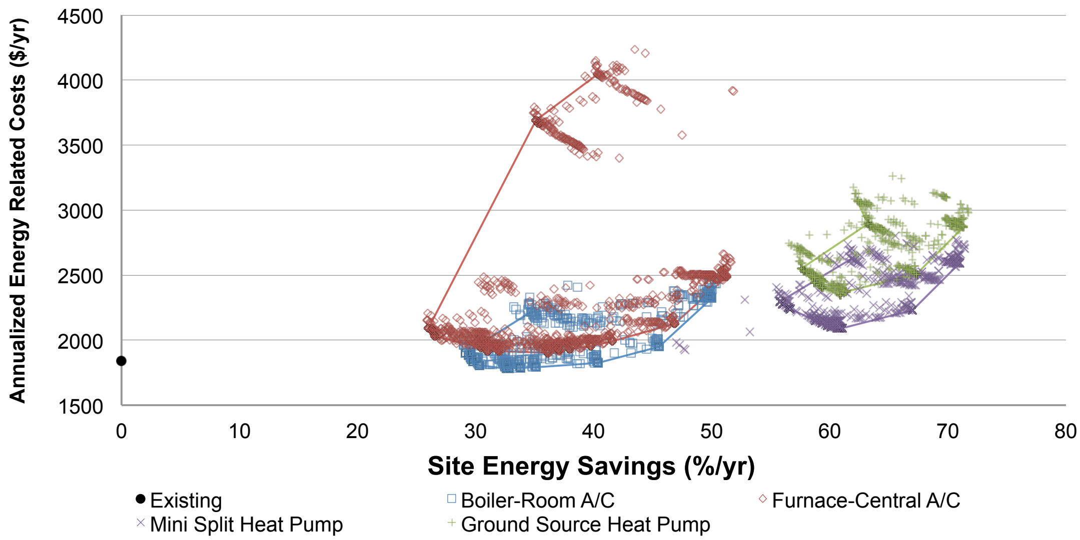


Figure 35. Group 7: HVAC optimization results in terms of site energy savings

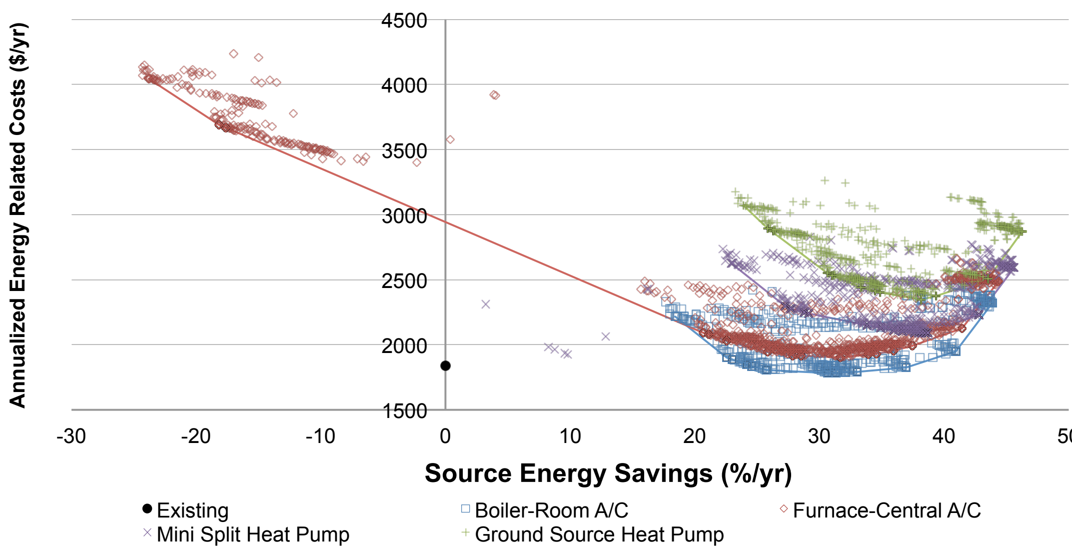


Figure 36. Group 7: HVAC optimization results in terms of source energy savings.

The optimized parameter options, annualized energy costs, and energy saving for each of the iteration points chosen for further investigation along side the ‘Today’ case are listed in Table 11. It is observed that the MSHP retrofit package has the lowest annualized energy and initial costs compared to the other optimized HVAC cases.

Table 11. (Page 1 of 2) Group 7: Brick, Pre-1942, 1 to 1.5 stories - Parameters options for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 14, Pt 24**	Furnace-Central A/C: Iter 16, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 8, Pt 3**
Central A/C	None	None	SEER 24.5	None	None
Room A/C	EER 10	EER 10.7, 20% Conditioned	None	None	None
Furnace	None	None	Gas, 98% AFUE	None	None
Boiler	Gas, Hot Water, Forced, 80% AFUE	Gas, Hot Water, Condensing, 98% AFUE	None	None	None
Electric Baseboard	None	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	None	None	In Finished Space	None	15% Leakage, R-6, 50% Surface Area, 1 Return (Unfinished Basement)

Table 11. (Page 2 of 2) Group 7: Brick, Pre-1942, 1 to 1.5 stories - Parameters options for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 14, Pt 24**	Furnace-Central A/C: Iter 16, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 8, Pt 3**
Ceiling Fan***	None	None	None	None	None
Water Heater	Gas, 54% EF	Gas Tankless, Condensing	Gas Tankless, Condensing	No Change	No Change
Solar Water Heating	None	None	64 ft^2 Closed Loop	None	None
SWH Azimuth	N/A	N/A	Back Roof	N/A	N/A
SWH Tilt	N/A	N/A	Latitude	N/A	N/A
Lighting	Benchmark	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in
Initial Cost ($)	$0	$20,609	$26,072	$10,565	$19,708
Annualized Energy Related Costs ($/yr)	$1,840	$2,322	$2,290	$2,090	$2,347
% Site (Source) Savings	0	50.0(43.9)	51.3(43.7)	60.6(37.6)	60.9(38.2)

It is observed the addition of ceiling fans were not considered a cost effective upgrade for any of the cases. The addition of a solar water heating system was also not considered to be a cost effective upgrade for any of cases in this group.

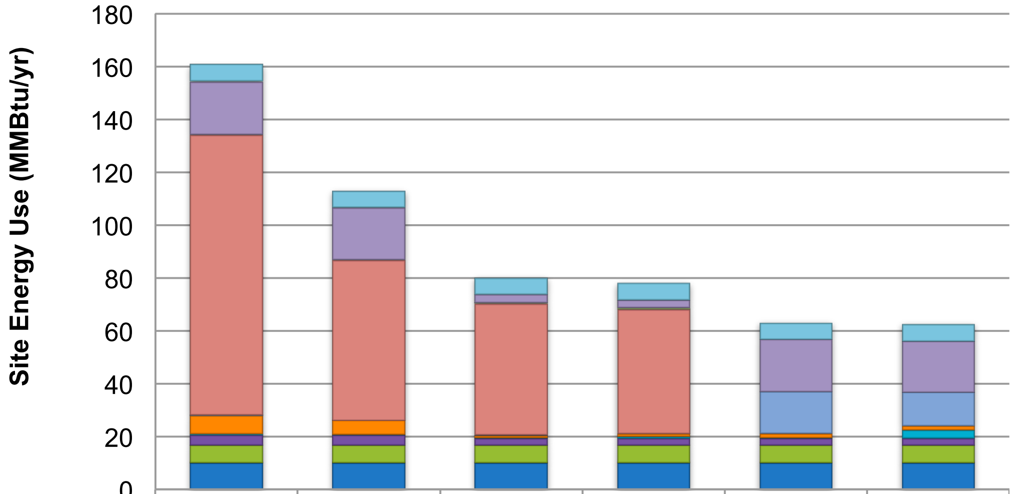
For the Boiler-Room A/C optimization case, the room air conditioner was upgraded from an EER 10, conditioning 100% of the home, to a EER 10.7 with only 20% of the home's square footage of living space is conditioned at a time. This can be interpreted as air conditioners are installed and are continuously running in 20% of the living space or units are installed where needed but only 20% of the home is being cooled simultaneously and applies for each group this option was recommended. The boiler was upgraded to a 98% AFUE condensing boiler. Condensing boilers have been highly recommended for homes in cold climates by the American Council for an Energy-Efficient Economy (ACEE), the DOE, and many other organizations (ACEEE, 2012; U.S. Department of Energy, 2012). They have been shown to have an increased efficiency of up to 10% compared to non-condensing counterparts (Che, Liu, & Gao, 2004) because they are able to recover residual heat from exiting flue gasses that would otherwise be lost by a conventional boiler and use it to preheat the cold water entering the boiler. An organization in the United Kingdom implies that a condensing boiler can be an appropriate retrofit into existing boiler systems (Energy Efficiency Best Practice in Housing, 2003). Moreover, researchers in China have concluded and verified with a retrofit case that it is possible to convert an existing non-condensing boiler system by adding a condensing heat exchanger (Che, Liu, & Gao, 2004). The temperature of exiting flue gases from a conventional boiler can be an upwards of 302ºF (150ºC) some even as high as 392ºF (200ºC) and any water vapor present does not condense at such temperatures (Che, Liu, & Gao, 2004). In order for a condensing boiler system to operate at its maximum efficiency, the exit gases must be cooler. Che et al. found that the condensing boiler they were studying reached its highest efficiency when its exit gases were as low as 68ºF (20ºC) (Che, Liu, & Gao, 2004). It is important to note condensing boilers output water for heating at lower temperatures than non-condensing boilers thus existing radiators may not be compatible. While BEopt models using specifications for baseboard radiators, a number of homes in the Chicagoland area built pre-1978 are fitted with oversized cast iron radiators, therefore, the estimated cost to retrofit this particular optimization package may not accurately reflect the cost for installation in those homes. BEopt optimized a tankless condensing water heater as an upgrade from the existing water heater. Tankless condensing water heaters work very similarly to condensing boilers in that they utilize exit flue gases to preheat incoming cold water on. Unlike common hot water heaters, tankless water heaters do not have storage tanks and heat water on demand. User behavior may have to accommodate this upgrade to ensure the fulfillment of hot water loads. There are no other issues expected from making this upgrade, as it is a very common retrofit. It is also recommended for this case that 100% of hardwired and plug-in lighting be converted to fluorescent, this is also a very common energy reduction strategy.

For the Furnace–Central A/C case, BEopt optimized the upgrade to a gas, 98% AFUE furnace from the existing and an upgrade to a 24.5 SEER central A/C are considered appropriate recommendations. The recommendation to install ducts in finished space is practical in homes without pre-conceived space dedicated for ductwork. As with the previous case, a tankless condensing water heater is suggested as an upgrade from the existing water heater. It is suggested that a 64 ft^2 closed loop solar water heating system, oriented on the back roof of the house (south side), and tilted to a degree that equals the latitude of Chicago+15º be installed as a supplement preheat method to the water heater.

For the case involving the optimization of a MSHP system, BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

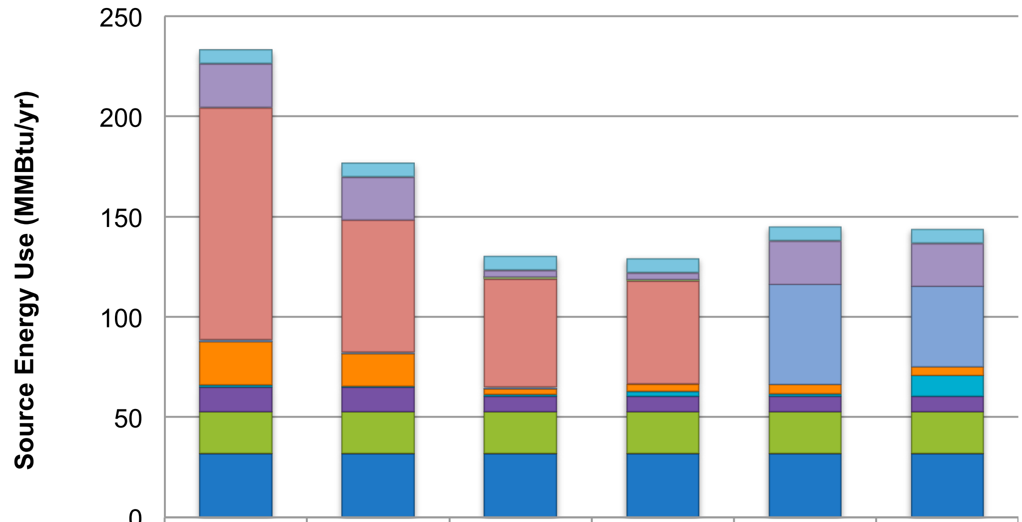
BEopt simulated that the optimal GSHP unit to be EER 20.2, COP 4.2, High-k soil, Enh grout between the pipes and the ground. BEopt recommends for installation to stay in its existing location and be insulated 15% Leakage (typical), R-6, 50% Surface Area, 1 Return (Unfinished Basement). This is considered a practical as duct sealing and insulating was found to be an effective retrofit measure toward space heating and cooling energy savings by numerous studies (Rhodes, Stephens, & Webber, 2011; Jump, Walker, & Modera, 1996; Parker, Fairey, & Gu, 1993). An upgrade to the water heater was not recommended. As with all other cases, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 37 shows estimated site energy usage by end use of the packages listed in Tables 10 and 11 while Figure 38 shows estimated source energy usage. It can be observed that both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 37) it is verified that the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 38).



	Today	Enclosure: Iter 25, Pt 1**	Boiler-Room A/C: Iter 14, Pt 24**	Furnace-Central A/C: Iter 16, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 8, Pt 3**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	19.87	19.80	3.12	3.12	19.80	19.50
Hot Water (E)	0.00	0.00	0.36	0.36	0.00	0.00
Heating (G)	106.05	60.55	49.69	47.08	0.00	0.00
Heating (E)	0.32	0.16	0.20	0.00	15.84	12.81
Cooling (E)	6.84	5.19	0.95	1.23	1.63	1.49
HVAC Fan/Pump (E)	0.41	0.24	0.25	0.71	0.32	3.22
Lights (E)	3.81	3.81	2.47	2.47	2.47	2.47
Lg. Appl. (E)	6.62	6.62	6.62	6.62	6.62	6.62
Vent Fan (E)	0.06	0.06	0.06	0.06	0.06	0.06
Misc. (E)	10.04	10.04	10.04	10.04	10.04	10.04

Figure 37. Group 7: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 25, Pt 1**	Boiler-Room A/C: Iter 14, Pt 24**	Furnace-Central A/C: Iter 16, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 8, Pt 3**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	21.66	21.58	3.40	3.40	21.59	21.26
Hot Water (E)	0.00	0.00	1.13	1.13	0.00	0.00
Heating (G)	115.60	66.01	54.16	51.32	0.00	0.00
Heating (E)	1.01	0.49	0.62	0.00	49.94	40.37
Cooling (E)	21.56	16.36	3.00	3.88	5.14	4.70
HVAC Fan/Pump (E)	1.29	0.76	0.78	2.23	0.99	10.13
Lights (E)	12.01	12.01	7.79	7.79	7.79	7.79
Lg. Appl. (E)	20.84	20.84	20.84	20.84	20.84	20.84
Vent Fan (E)	0.18	0.18	0.18	0.18	0.18	0.18
Misc. (E)	31.66	31.66	31.66	31.66	31.66	31.66

Figure 38. Group 7: Source energy use of critical optimal iteration points

Figure 39 illustrates the simple payback periods for each of the cases. It can be inferred that the cases involving the boiler, furnace, and MSHP have the expected payback period of less than 40 years and may be more desirable retrofit packages than the GSHP case which has an expected payback period of more than 60 years.

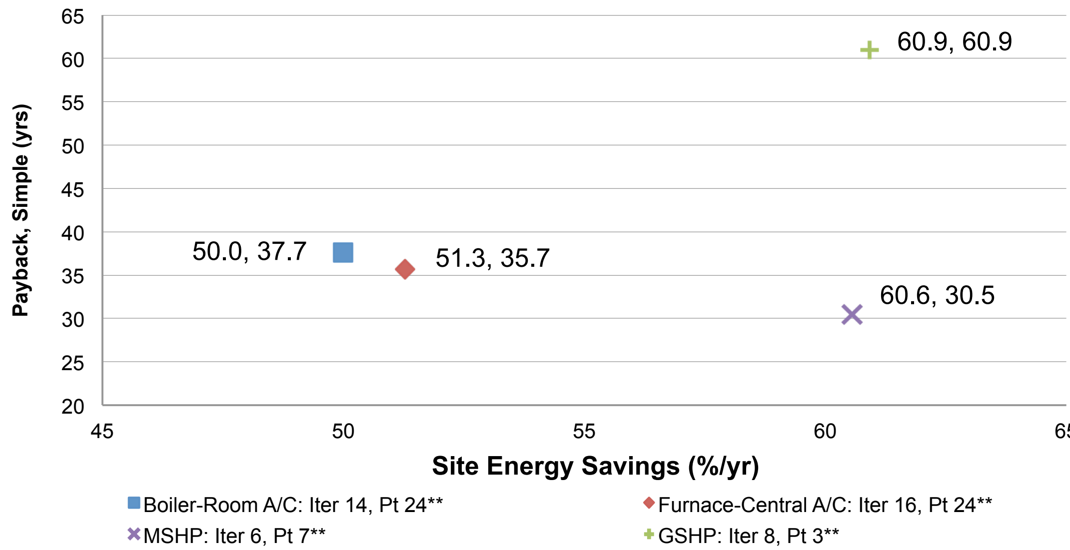


Figure 39. Group 7: Simple Payback of critical optimal iteration points

Figure 40 illustrates the Modified Internal Rate of Return (MIRR) for each optimal package. It can be deduced that the case that is expected to have the highest MIRR is the MSHP case, followed by the Boiler-Room A/C and Furnace-Central A/C cases.

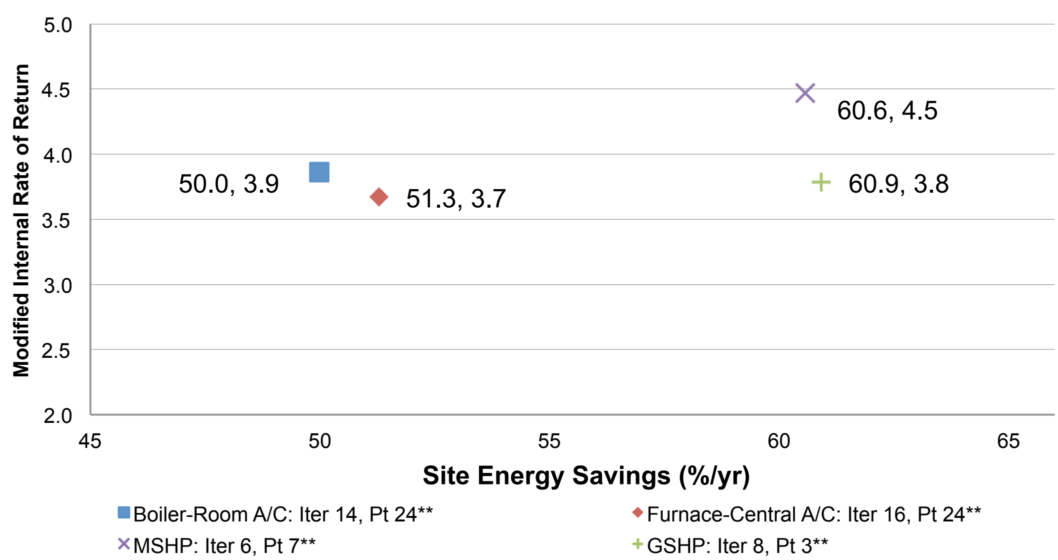


Figure 40. Group 7: Modified Internal Rate of Return of critical optimal iteration points

Through analyses of all the figures given for Group 7 it is concluded that an upgrade to the MSHP is the most cost effective option toward a 50% site energy reduction and representing one of the most site energy saving while also having the lowest payback period and highest MIRR.

Group 8: Brick, Pre-1942, 2 stories Group 8 has measured mean square footage of 1884 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 1872 ft^2. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 41.

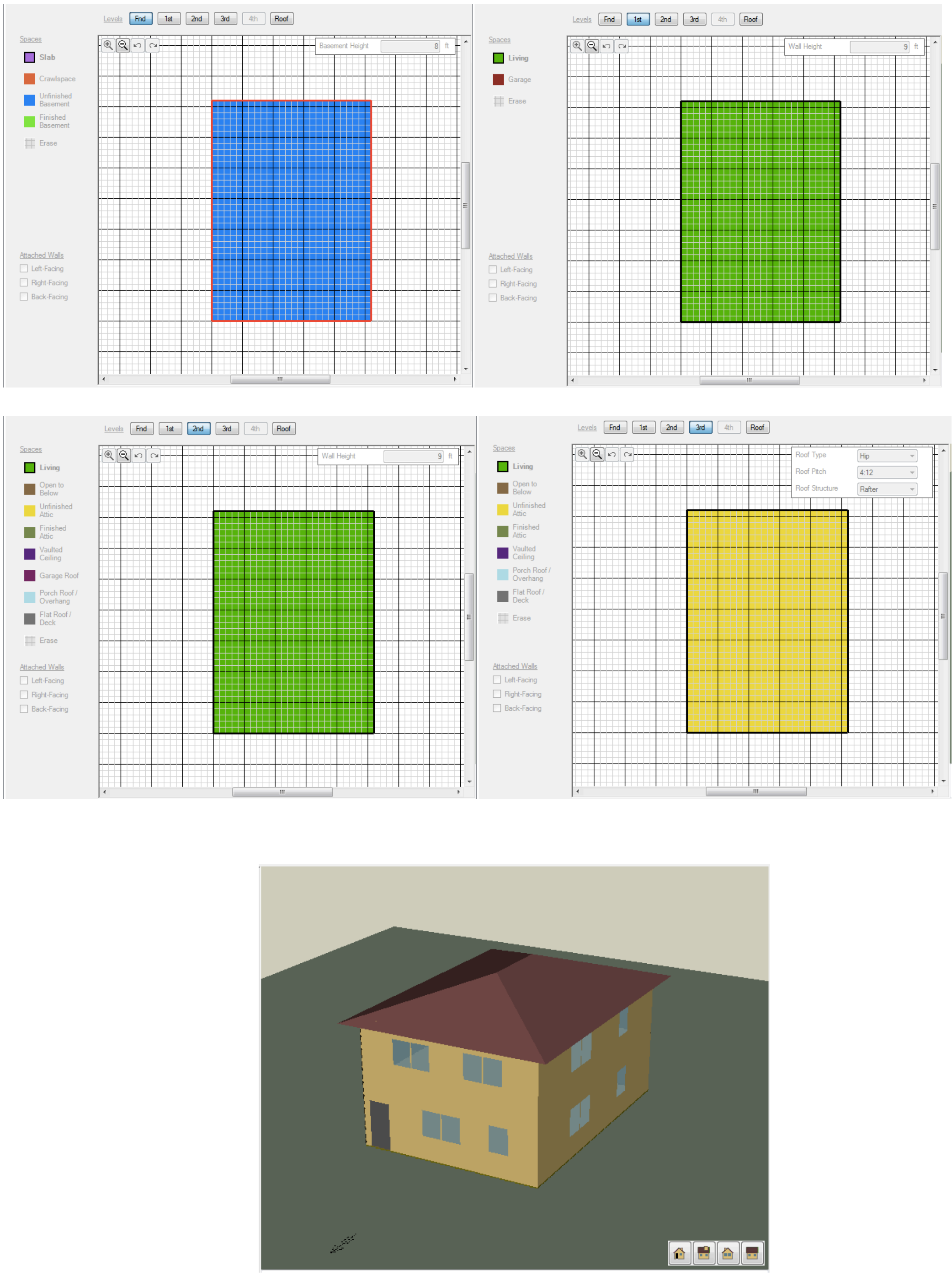


Figure 41. Group 8: BEopt model: foundation, first, and second (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 42 and 43 respectively. As expected, it is observed that several of the iterations do not have an equal value of percentage energy reduction in terms of source energy as it is reported in terms of site energy due to corresponding source/site ratios being greater than one. It can also be observed that a site energy savings of about 39% (least cost option) simply by updating the enclosure and keep existing HVAC systems. This translates to about a 32% source energy savings. The least cost iteration point also has an annualized energy cost that is about $300/yr less than the existing case.

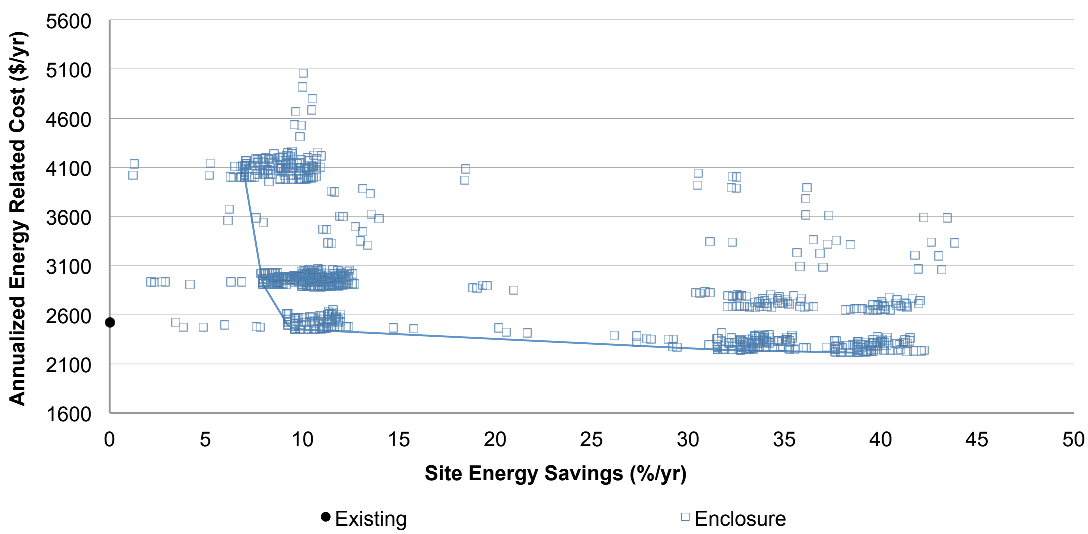


Figure 42. Group 8: Building Enclosure optimization results in terms of sites energy savings

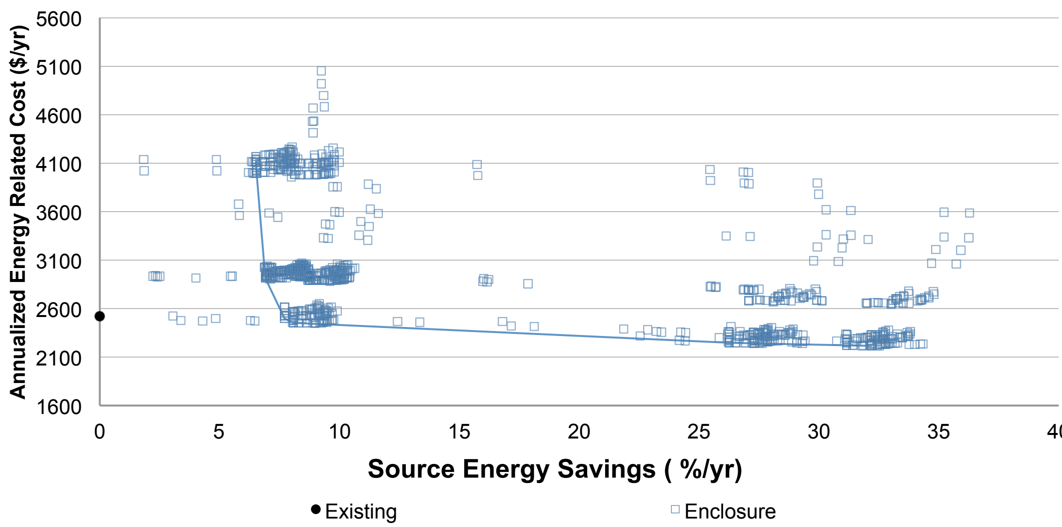


Figure 43. Group 8: Building Enclosure optimization results in terms of source energy savings.

Table 12 lists the original 'Today' scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves. For this residential building group, the optimal option involves upgrades to the exterior wall construction, unfinished attic insulation, and air leakage only.

Table 12. Group 8: Optimal Building Enclosure: Optimized Parameters, 'Today' scenario assumptions, and BEopt upgrades.

Parameter name	'Today'	Enclosure: Iter 11, Pt 56
Exterior Wall (Masonry)	4-in Hollow Brick, Uninsulated, 1-in furring, 24 in O.C.	4-in Hollow Brick, R-19 Fiberglass Batt, 2x6, 24 in o.c.
Exterior Finish	Brick, Medium/Dark	No Change
Unfinished Attic	Ceiling R-7 Fiberglass (Blown-in), Vented	Ceiling R-30 Fiberglass Batt, Vented
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Leaky	Typical
Mechanical Ventilation	None	No Change

As with all previous groups, the suggestion for interior built out and insulation of the exterior brick wall is appropriate and expected (Knight, 2004). The upgrade in envelope tightness from leaky to typical reflects about a 22% increase in enclosure tightness and is considered to be an appropriate upgrade (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). Insulation retrofit of the unfinished attic is also considered appropriate for the context of Group 8. The non-upgrades to other parameters are appropriate, as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

With the optimized enclosure package implemented, the results from the HVAC optimization for this group are illustrated as AERC in terms of site energy savings (see Fig. 44) and source energy savings (see Fig. 45) and their respective least cost fit lines. Comparison of the two graphs shows critical differences in values between site and source energy savings especially in the cases involving the mini-split and ground-source heat pumps as expected.

From the results shown in Figure 44 we can see that the options chosen for optimization for all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case with exception of the Boiler-Room A/C and Furnace-Central A/C cases. These cases have AERC that are less than the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated 67% site energy savings.

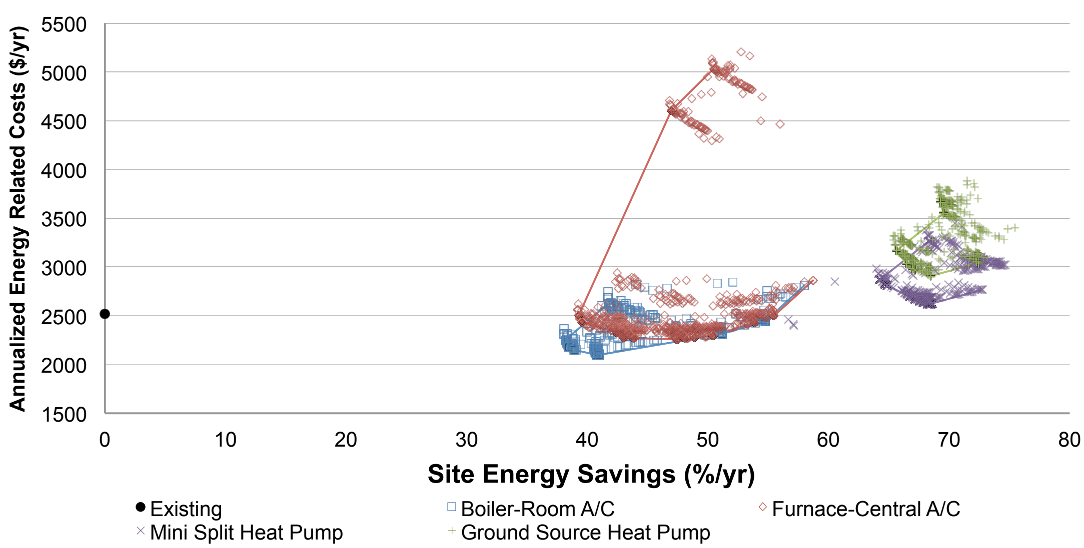


Figure 44. Group 8: HVAC optimization results in terms of site energy savings

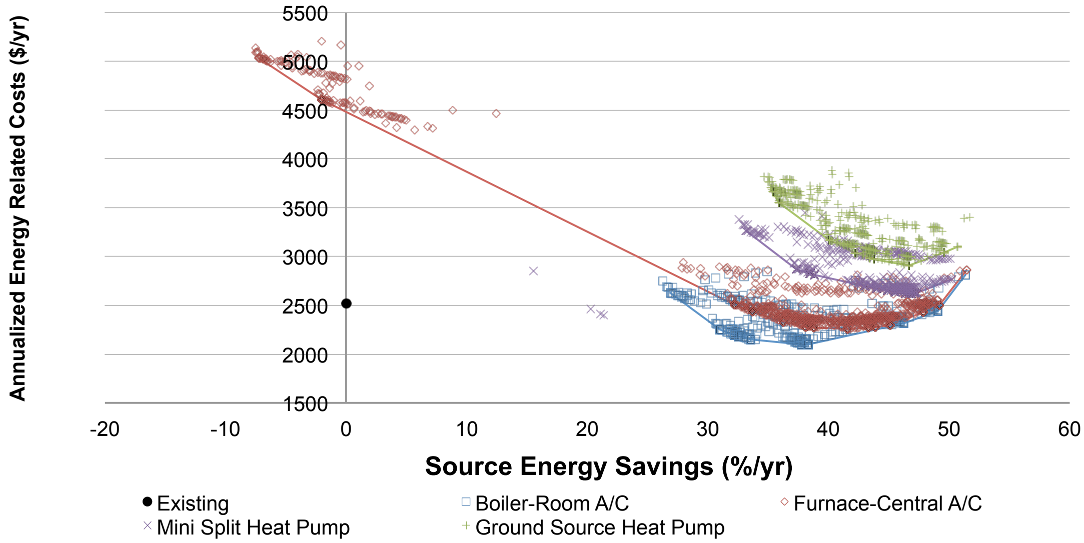


Figure 45. Group 8: HVAC optimization results in terms of source energy savings.

With the optimal enclosure package mentioned above implemented, the optimized HVAC packages chosen for continued analysis and their parameter options, costs, and energy savings are listed in Table 13. Note that the Boiler-Room A/C case represents the option with the lowest initial cost, and one of the lowest AERC that is estimated to be about $220/yr less than the existing case.

Table 13. (Page 1 of 2) Group 8: Brick, Pre-1942, 2 stories - Parameters options, costs, and energy savings for critical iteration points for all cases

Parameter Name	‘Today’	Boiler-Room A/C: Iter 7, Pt 3**	Furnace-Central A/C: Iter 11, Pt 83**	MSHP: Iter 4, Pt 7**	GSHP: Iter 8, Pt 3**
Central A/C	None	None	SEER 18	None	None
Room A/C	EER 10	EER 10.7, 20% Conditioned	None	None	None
Furnace	None	None	Gas, 98% AFUE	None	None
Boiler	Gas, Hot Water, Forced, 80% AFUE	Gas, Hot Water, Condensing, 98% AFUE OAT Reset	None	None	None
Electric Baseboard	None	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	None	None	15% Leakage, R-6, 50% Surface Area, 1 Return (Unfinished. Basement)	None	15% Leakage, R-6, 50% Surface Area, 1 Return (Unfinished Basement)

Table 13. (Page 2 of 2) Group 8: Brick, Pre-1942, 2 stories – Parameter options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 7, Pt 3**	Furnace-Central A/C: Iter 11, Pt 83**	MSHP: Iter 4, Pt 7**	GSHP: Iter 8, Pt 3**
Ceiling Fan***	None	None	None	None	None
Water Heater	Gas, 54% EF	No Change	No Change	No Change	No Change
Solar Water Heating	None	None	None	None	None
SWH Azimuth	N/A	N/A	N/A	N/A	N/A
SWH Tilt	N/A	N/A	N/A	N/A	N/A
Lighting	Benchmark	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in
Initial Cost ($)	$0	$16,387	$18,362	$16,492	$27,558
Annualized Energy Related Costs ($/yr)	$2,522	$2,302	$2,290	$2,623	$2,905
% Site (Source) Savings	0	49.9(45.3)	49.9(43.7)	68.2(46.4)	68.4(46.7)

It is observed the addition of ceiling fans were not considered a cost effective upgrade for any of the cases. No improvements to the existing hot water heater was suggested, nor was addition of a solar water heating system considered to be a cost effective upgrade for any of cases in this group.

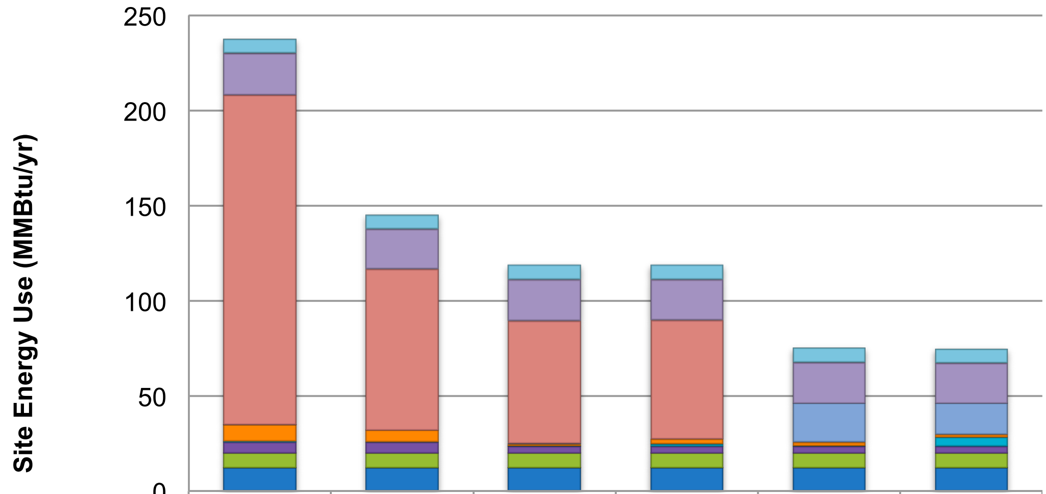
For the Boiler-Room A/C optimization case, the room air conditioner was upgraded from a EER 10, conditioning 100% of the home, to a EER 10.7 with only 20% of the home conditioned. Similar to Group 7, the boiler was upgraded to a 98% AFUE condensing boiler but this time with an outdoor air reset (OAT). A previously mentioned, it is important to note condensing boilers output water for heating at lower temperatures than non-condensing boilers thus existing radiators may not be compatible. Therefore, the estimated cost to retrofit this particular optimization package may not accurately reflect the cost for installation in those homes.

For the Furnace–Central A/C case, BEopt optimized the upgrade to a gas, 98% AFUE furnace from the existing and an upgrade to an 18 SEER central A/C are considered appropriate recommendations. BEopt recommends for installation to stay in its existing location and be insulated 15% Leakage (typical), R-6, 50% Surface Area, 1 Return (Unfinished Basement).

For the case involving the optimization of a MSHP system, BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

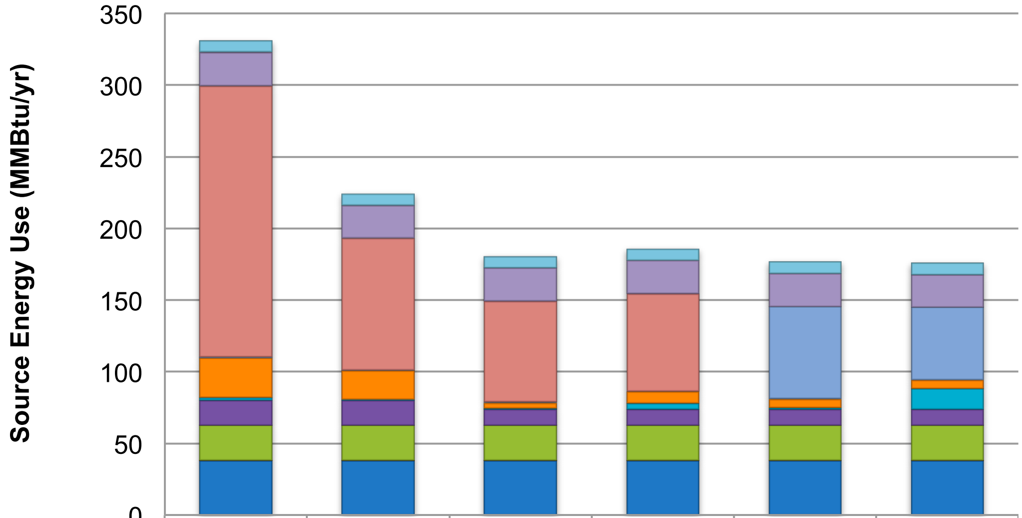
BEopt simulated that the optimal GSHP unit to be EER 20.2, COP 4.2, High-k soil, Enh grout between the pipes and the ground. BEopt recommends for installation to stay in its existing location and be insulated 15% Leakage (typical), R-6, 50% Surface Area, 1 Return (Unfinished Basement). An upgrade to the water heater was not recommended. As with all other cases for this group, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 46 shows estimated site energy usage of the packages listed in Tables 12 and 13 while Figure 47 shows estimated source energy usage. It can be observed that both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 46), the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 47).



	Today	Enclosure: Iter 11, Pt 56**	Boiler-Room A/C: Iter 7, Pt 3**	Furnace-Central A/C: Iter 11, Pt 83**	MSHP: Iter 4, Pt 7**	GSHP: Iter 8, Pt 3**
Lg. Appl. (G)	7.61	7.61	7.61	7.61	7.61	7.61
Hot Water (G)	21.71	21.00	21.63	21.37	21.63	21.30
Hot Water (E)	0.00	0.00	0.00	0.00	0.00	0.00
Heating (G)	172.97	84.50	64.57	62.41	0.00	0.00
Heating (E)	0.28	0.13	0.13	0.00	20.39	16.13
Cooling (E)	8.66	6.25	1.14	2.61	1.92	1.85
HVAC Fan/Pump (E)	0.66	0.30	0.31	1.41	0.40	4.55
Lights (E)	5.53	5.53	3.59	3.59	3.59	3.59
Lg. Appl. (E)	7.70	7.70	7.70	7.70	7.70	7.70
Vent Fan (E)	0.08	0.08	0.08	0.08	0.08	0.08
Misc. (E)	12.01	12.01	12.01	12.01	12.01	12.01

Figure 46. Group 8: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 11, Pt 56**	Boiler-Room A/C: Iter 7, Pt 3**	Furnace-Central A/C: Iter 11, Pt 83**	MSHP: Iter 4, Pt 7**	GSHP: Iter 8, Pt 3**
Lg. Appl. (G)	8.3	8.3	8.3	8.3	8.3	8.3
Hot Water (G)	23.66	22.89	23.58	23.29	23.58	23.23
Hot Water (E)		0	0	0	0	0
Heating (G)	188.54	92.1	70.37	68.02	0	0
Heating (E)	0.89	0.41	0.42	0	64.29	50.86
Cooling (E)	27.3	19.69	3.6	8.23	6.05	5.84
HVAC Fan/Pump (E)	2.08	0.96	0.97	4.45	1.27	14.37
Lights (E)	17.41	17.42	11.29	11.29	11.29	11.29
Lg. Appl. (E)	24.29	24.28	24.28	24.28	24.28	24.28
Vent Fan (E)	0.25	0.26	0.26	0.26	0.26	0.26
Misc. (E)	37.85	37.85	37.85	37.85	37.85	37.85

Figure 47. Group 8: Source energy use of critical optimal iteration points

Figure 48 illustrates the simple payback periods for each of the cases. It can be inferred that the cases involving the boiler, furnace, and MSHP have the expected payback period of less than 25 years and may be more desirable retrofit packages than the GSHP case which has an expected payback period of more than 40 years.

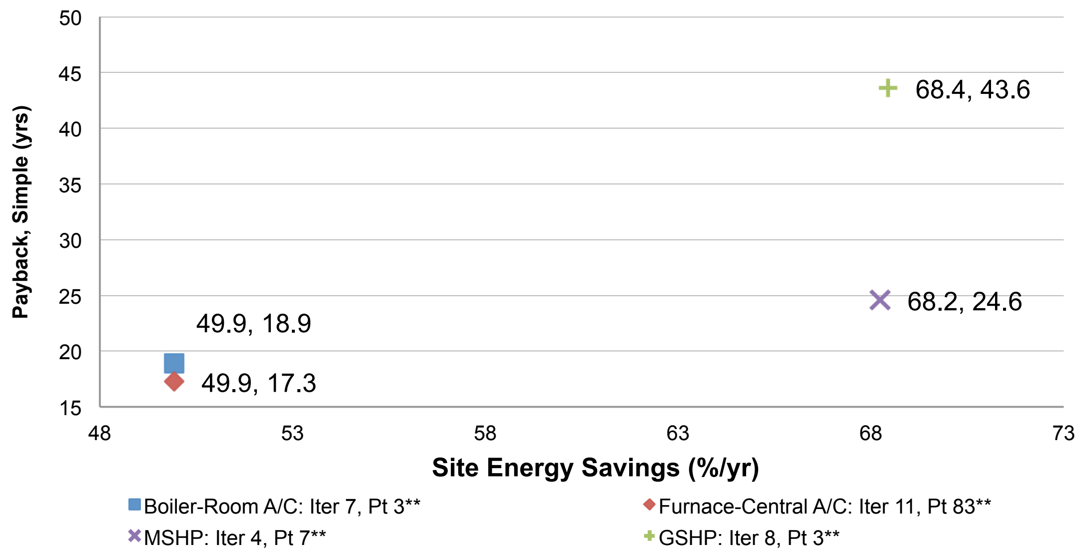


Figure 48. Group 8: Simple Payback of critical optimal iteration points

Figure 49 illustrates the Modified Internal Rate of Return (MIRR) for each of the cases. It can be deduced that the case that is expected to have the highest MIRR is the Boiler-Room A/C case, followed by the Furnace-Central A/C and the MSHP cases.

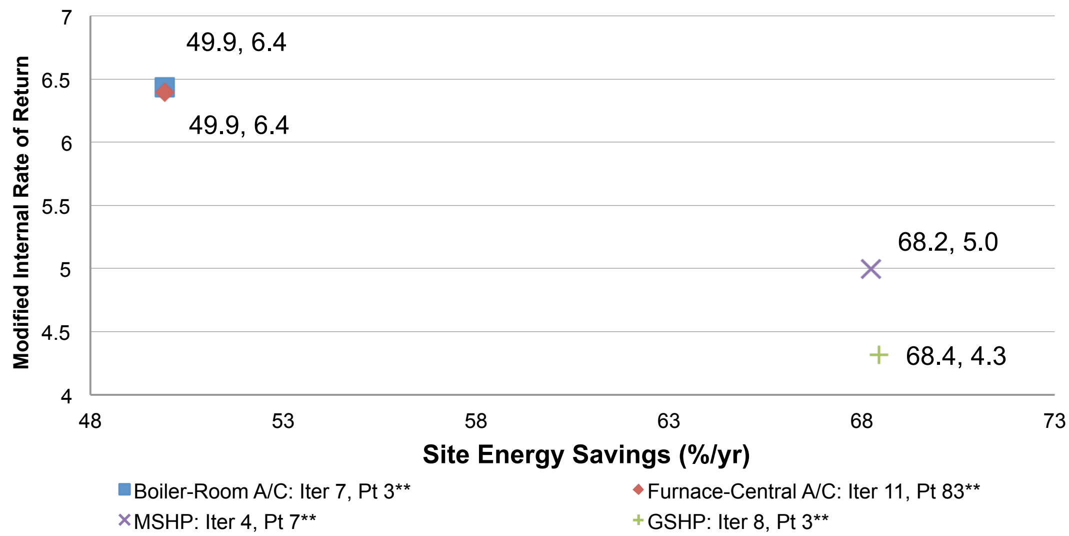


Figure 49. Group 8: Modified Internal Rate of Return of critical optimal iteration points

Through analyses of all the figures given for Group 8 it is concluded that an upgrade to the boiler system is the most cost effective option toward a 50% site energy reduction and representing the option having a low payback period and highest MIRR.

Group 10: Frame, All years, Split level (1.5 stories) Group 10 has measured mean square footage of 1349 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 1340 ft^2. BEopt is not capable of drawing split-level houses at this time, therefore, this group was modeled with building component assumptions similar to a pre-1942 frame bungalow style home with only the back half modeled as a 1.5 story as an attempt to match the split level description. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 50.

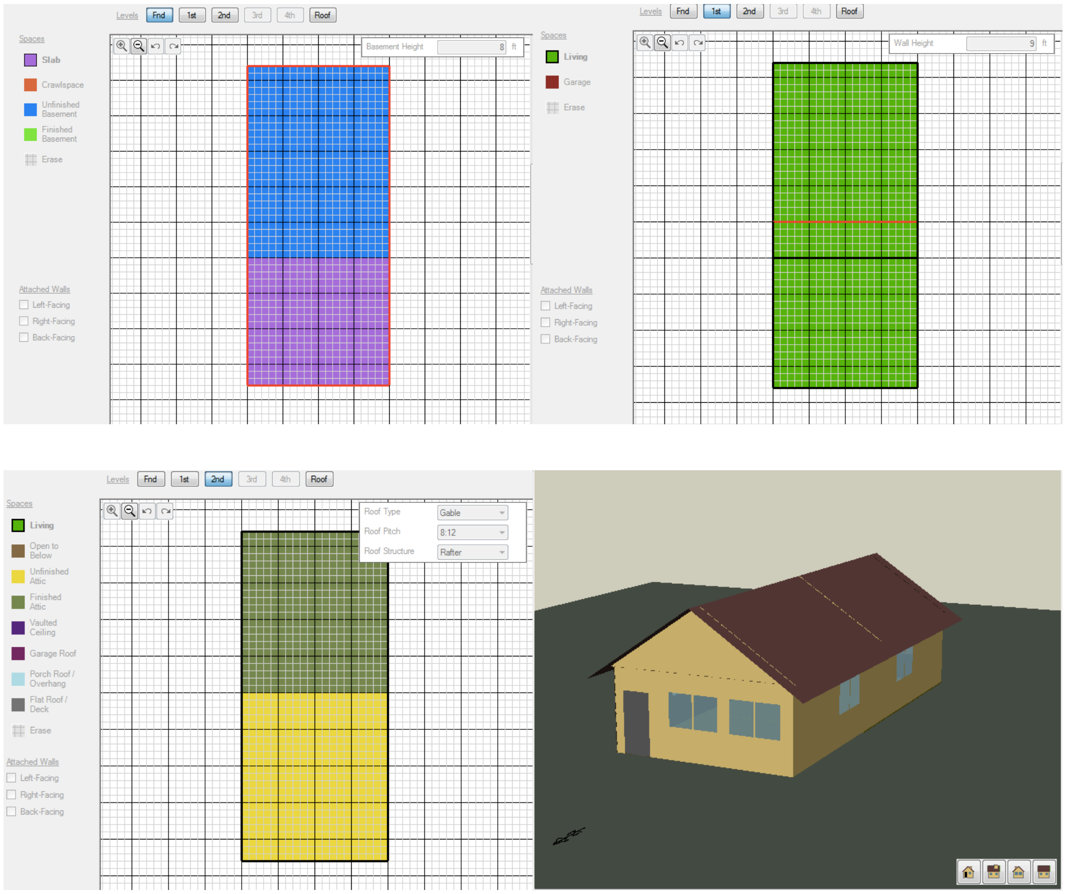


Figure 50. Group 10: BEopt model: foundation, first, and second (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 51 and 52 respectively. It can be observed that a site energy savings of about 32% (least cost option) simply by updating the enclosure and keep existing HVAC systems. This translates to about a 25% source energy savings. Moreover, the AERC for the least cost option is a little over $100/yr less than the existing case.

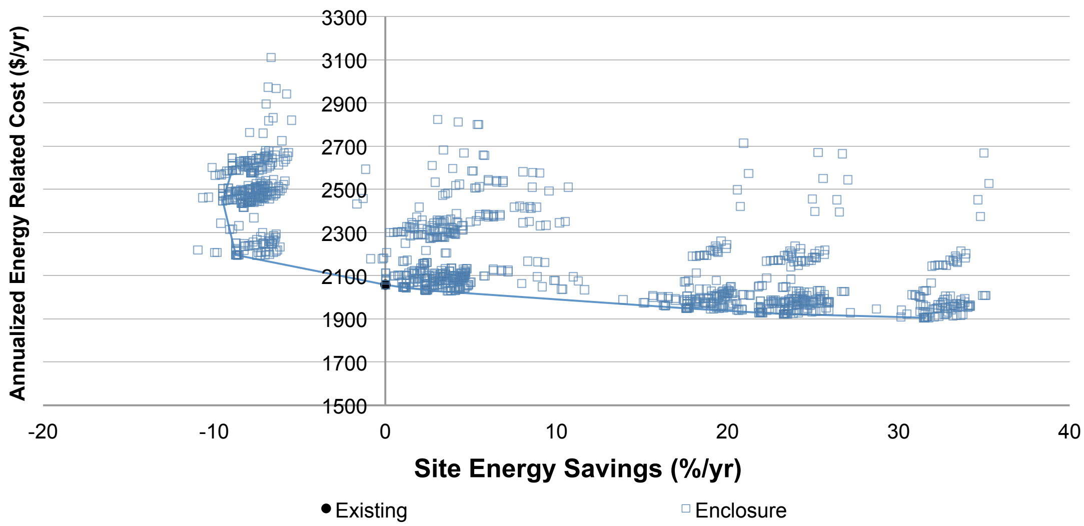


Figure 51. Group 10: Building Enclosure optimization results in terms of sites energy savings

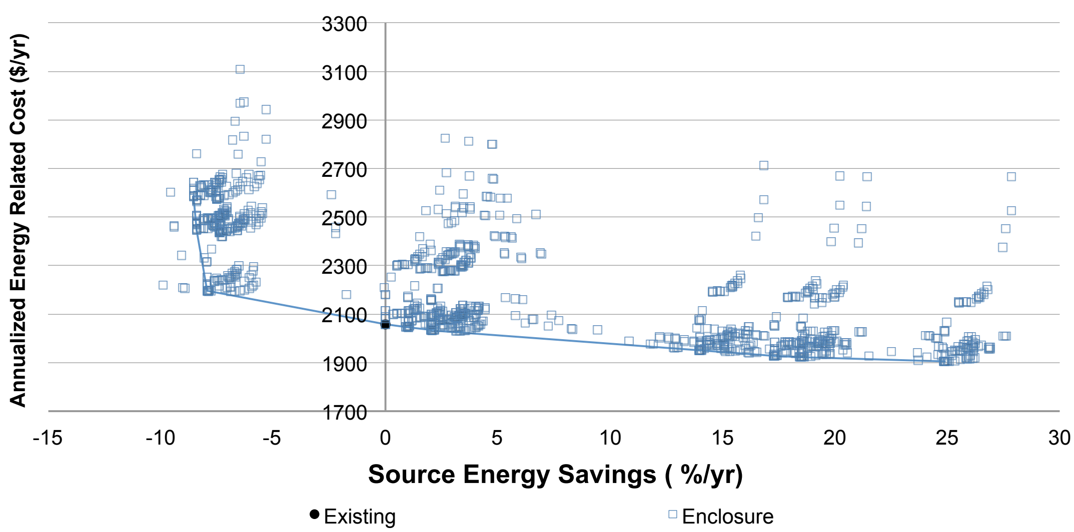


Figure 52. Group 10: Building Enclosure optimization results in terms of source energy savings.

Table 14 lists the original ‘Today’ scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves.

Table 14. Group 10: Optimal Building Enclosure: Optimized Parameters, ‘Today’ scenario assumptions, and BEopt upgrades.

Parameter name	‘Today’	Enclosure: Iter 14, Pt 61
Exterior Wall (Wood Stud)	Uninsulated, 2x4, 16 in O.C.	No Change
Wall Sheathing	None****	R12- Polyiso
Exterior Finish	Wood Siding, Light	No Change
Interzonal Walls	Uninsulated, 2x4, 16 in O.C.	R-13 Fiberglass (Blown-in), Gr-1, 2x4, 16 in O.C.
Unfinished Attic	Ceiling R-7 Fiberglass (Blown-in), Vented	Ceiling R-19 Fiberglass (Blown-in), Vented
Finished Roof	R-19 Fiberglass (Blown-in), 2x6 Rafters	No Change
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Very Leaky	Leaky
Mechanical Ventilation	None	No Change

****Exterior Oriented Strand Board (OSB) sheathing is included in the R-Value for the exterior wall parameter in BEopt and was not re-selected for the wall sheathing parameter.

For this residential building group, the optimal option involves upgrades to the wall sheathing, interzonal walls, unfinished attic insulation, and air leakage only. The parameters chosen to analyze any addition of insulation to the interior side of the wall were shown to be a more costly upgrade than the addition of insulation on the exterior side, therefore, the recommendation for R-12 Polyiso insulation underneath the sheathing is considered appropriate. By adding insulation to the interzonal walls that separate the conditioned from the unconditioned areas of the attic, heat loss through these walls is mitigated, thus, this recommendation is appropriate. Insulation retrofit unfinished attic to a R-19 blown-in insulation is considered appropriate as it is much more thermal resistant then the existing insulation (R-3) and the cost for the upgrade is offset by the energy savings it provides. The upgrade in envelope tightness from very leaky to leaky reflects about a 22% increase in enclosure tightness and is considered appropriate (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). The non-upgrades to other parameters are as expected as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

No previous case studies or reference of an exterior installation of polyisocyanurate rigid insulation as being the only insulation in the enclosure of a building in cold climate were found. Thus, an analysis was conducted using the free WUFI Light version 5.2 moisture design tool software to explore the moisture response of this upgrade. The wall was modeled using default specifications for the materials chosen based on their similarities to the specifications of the corresponding materials in BEopt; the wall modeled with the following material layers and thicknesses from exterior inward:

- One layer of southern yellow pine acting as exterior light colored wood siding with a thickness of ~3/4-inch (2 cm),
- One layer of polyisocyanurate insulation with a thickness of ~2-inch (5.08 cm),
- One layer of OSB with a thickness of ~1/2-inch (1.25 cm),
- One layer of airspace or softwood acting as 2x4 studs with a thickness of ~3.5-inch (9 cm), and
- One layer of gypsum plaster with a thickness of ~7/8-inch (2.02cm).

The climate for this simulation was set to Chicago, cold year with an interior relative humidity (RH) condition to be of normal moisture load. The moisture performance of the wall was simulated for the year of 2012 (January 1, 12:00:00 am-December 31, 11:59:59 pm). The software's default settings were unchanged for any other parameters. The results of the transverse section of the exterior wall through the uninsulated cavity between studs as well as a section through the studded portion of the wall for all elevations (i.e. north, east, south, and west) can be seen in Figures 53 and 54 respectively. The results are unanimous in that there seems to be no expected risk of moisture accumulation within the wall (i.e. RH does not reach 100%). Therefore, it can be concluded that this wall construction is likely acceptable in terms of moisture performance, although it should noted that this method does not capture the effects of air leakage and thus should be interpreted with caution. The original WUFI files and inputs for this simulation can be found at the following web address:

http://built-envi.com/portfolio/chicagoland-housing-retrofits/

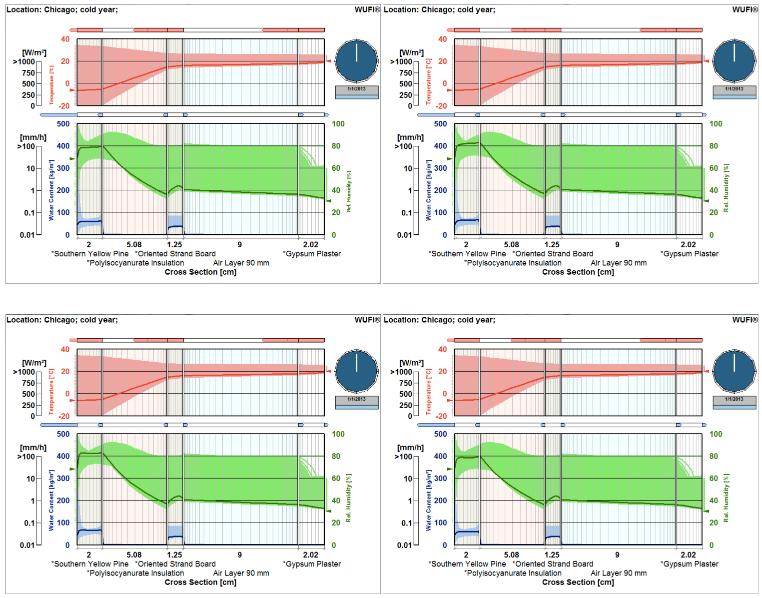


Figure 53. WUFI analysis of exterior polyiso R-12 insulated frame wall section taken through the cavity space between studs for all elevations (Top Left: North wall; Top Right: East Wall; Bottom Left: South Wall; Bottom Right: West Wall).

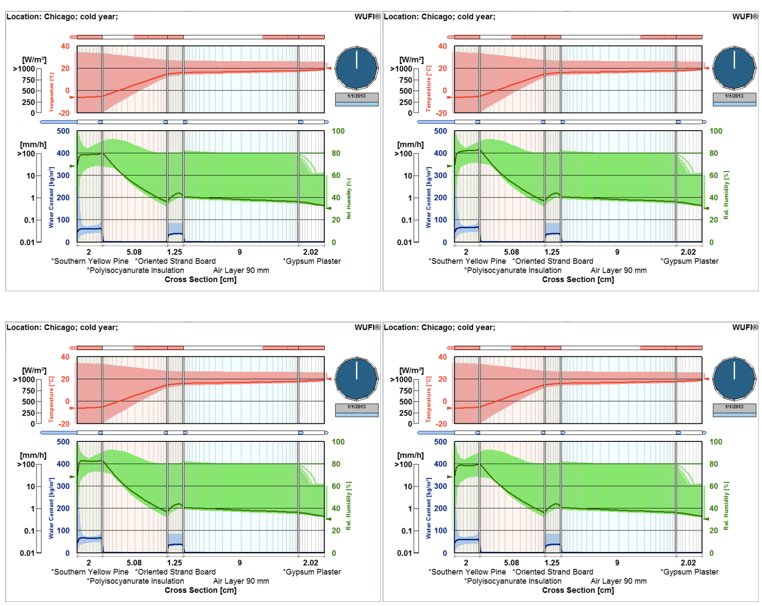


Figure 54. WUFI analysis of exterior polyiso R-12 insulated frame wall section taken through the stud for all elevations (Top Left: North wall; Top Right: East Wall; Bottom Left: South Wall; Bottom Right: West Wall).

Using the optimized building enclosure parameters listed in Table 14 HVAC optimization simulations were performed in separate cases. The results form each of those cases are superimposed onto graphs illustrating the AERC in terms of site energy savings (see Fig. 55) and source energy savings (see Fig. 56) and their respective least cost fit lines. Comparison of the two graphs shows critical differences in values between site and source energy savings especially in the cases involving the mini-split and ground-source heat pumps, as expected

From the results shown in Figure 55, it can be seen that the options chosen for optimization all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated 60% site energy savings.

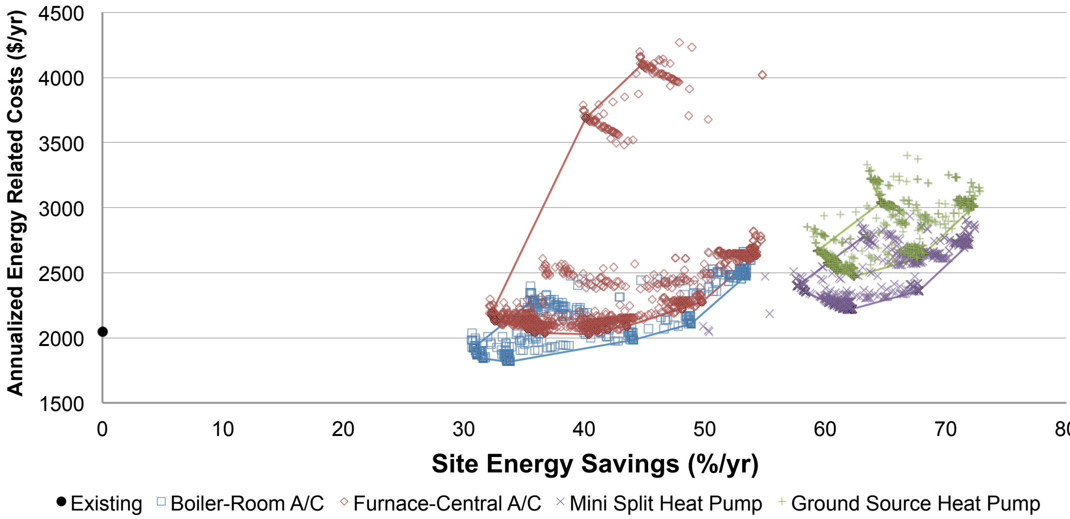


Figure 55. Group 10: HVAC optimization results in terms of site energy savings

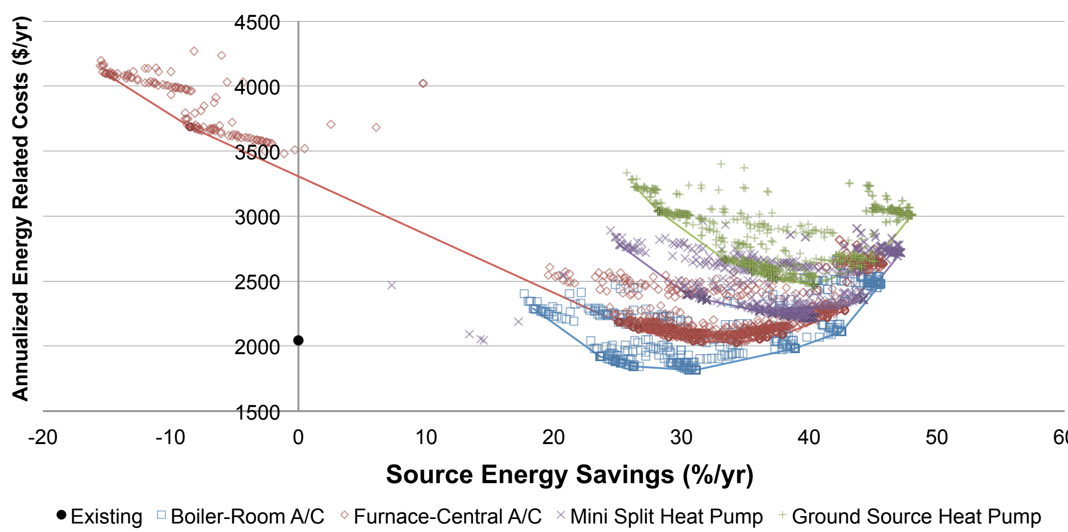


Figure 56. Group 10: HVAC optimization results in terms of source energy savings.

The iteration points chosen for further investigation for all HVAC cases, along side the ‘Today’ case are listed in Table 15. Note that the costs reported in this table represent those associated with the corresponding HVAC packages and the optimal enclosure package in combination. Although it does not represent the iteration with the least cost, the optimal Boiler-Room A/C iteration point has the least AERC of the four systems.

Table 15. (Page 1 of 2) Group 10: Frame, All years, Split level (1.5 stories) - Parameters options for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 8, Pt 13**	Furnace-Central A/C: Iter 13, Pt 66**	MSHP: Iter 4, Pt 7**	GSHP: Iter 7, Pt 38**
Central A/C	None	None	SEER 24.5	None	None
Room A/C	EER 10	EER 10.7, 20% Conditioned	None	None	None
Furnace	None	None	Gas, 98% AFUE	None	None
Boiler	Gas, Hot Water, Forced, 80% AFUE	Gas, Hot Water, Condensing, 98% AFUE	None	None	None
Electric Baseboard	None	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	None	None	In Finished Space	None	15% Leakage, R-6, 50% Surface Area, 1 Return (Unfinished Basement)

Table 15. (Page 2 of 2) Group 10: Frame, All years, Split level (1.5 stories) - Parameters options for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 8, Pt 13**	Furnace-Central A/C: Iter 13, Pt 66**	MSHP: Iter 4, Pt 7**	GSHP: Iter 7, Pt 38**
Ceiling Fan***	None	None	None	None	None
Water Heater	Gas, 54% EF	Gas Tankless, Condensing	Gas Tankless, Condensing	No Change	No Change
Solar Water Heating	None	None	None	None	None
SWH Azimuth	N/A	N/A	N/A	N/A	N/A
SWH Tilt	N/A	N/A	N/A	N/A	N/A
Lighting	Benchmark	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in
Initial Cost ($)	$0	$15,363	$20,923	$12,383	$21,720
Annualized Energy Related Costs ($/yr)	$2,046	$2,109	$2,272	$2,216	$2,477
% Site (Source) Savings	0	48.9(42.5)	49.8(42.8)	61.8(39.5)	62.2(40.1)

For the Boiler-Room A/C optimization case, the room air conditioner was upgraded from a EER 10, conditioning 100% of the home, to a EER 10.7 with only 20% of the home conditioned. The boiler was upgraded to a 98% AFUE condensing boiler. BEopt optimized a tankless condensing water heater as an upgrade from the existing water heater. Because tankless water heaters do not have storage tanks and heat water on demand, user behavior may have change to accommodate this upgrade to ensure the fulfillment of hot water loads. There are no issues expected from making this upgrade, as it is a very common retrofit. It is also recommended for this case that 100% of hardwired and plug-in lighting be converted to fluorescent, this is also a very common energy reduction strategy.

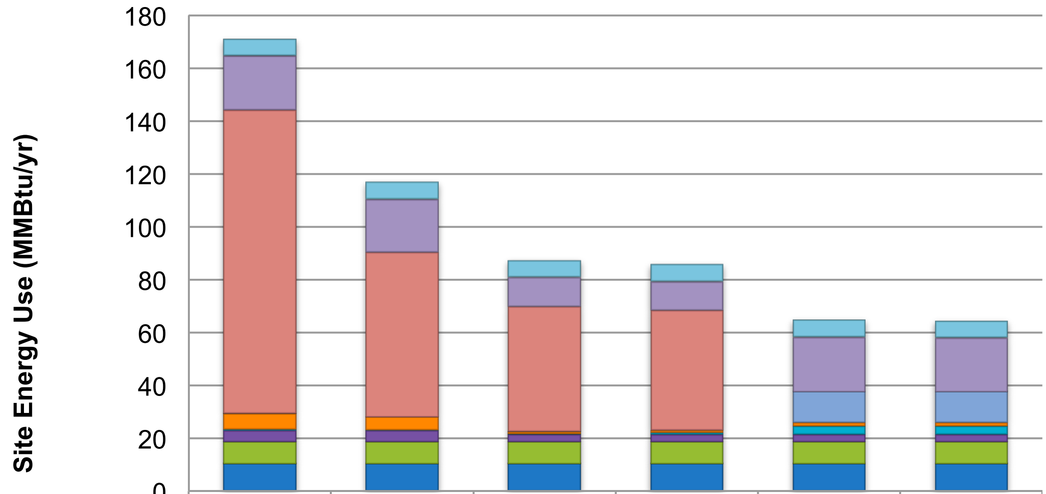
The Furnace–Central A/C case optimized with the same upgrade to the hot water heating system and lighting parameters as the Boiler-Room A/C case. The installation of a gas, 98% AFUE furnace is an appropriate recommendation. The recommendation to install ducts in finished space is practical since installation within the walls is more difficult in homes without pre-conceived space dedicated for ductwork.

For the case involving the optimization of a MSHP system, BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

BEopt simulated that the optimal GSHP unit to be EER 20.2, COP 4.2, High-k soil, Enh grout between the pipes and the ground. BEopt recommends for installation to stay in its existing location and be insulated 15% Leakage (typical), R-6, 50% Surface

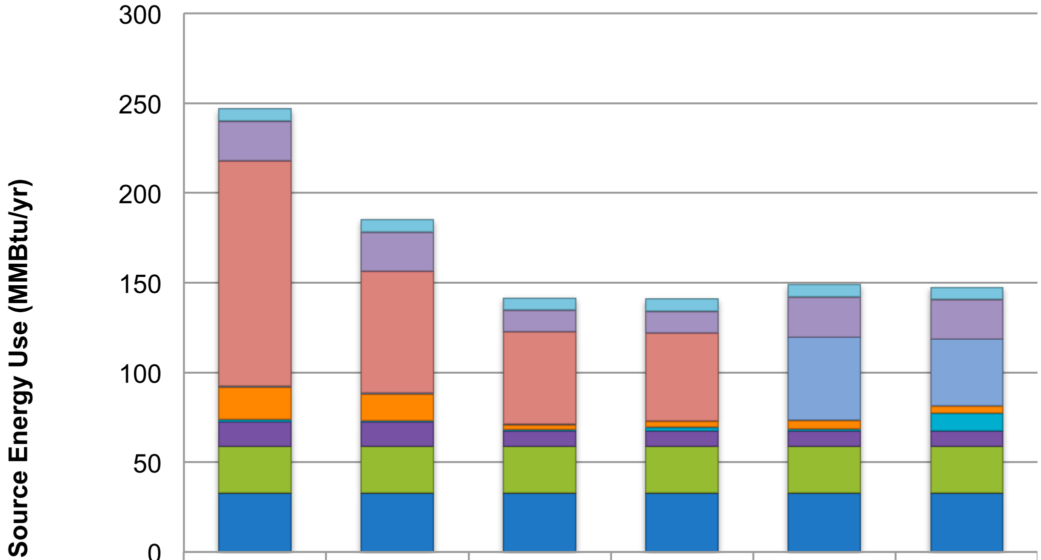
Area, 1 Return (Unfinished Basement). An upgrade to the water heater was not recommended. As with all other cases for this group, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 57 shows estimated site energy usage of the packages listed in Tables 14 and 15, while Figure 58 shows estimated source energy usage. It can be observed that both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 57) it that the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 58).



	Today	Enclosure: Iter 14, Pt 61	Boiler-Room A/C: Iter 8, Pt 13 **	Furnace-Central A/C: Iter 13, Pt 66**	MSHP: Iter 4, Pt 7**	GSHP: Iter 7, Pt 38**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	20.27	20.18	10.93	10.93	20.77	20.41
Hot Water (E)	0.00	0.00	0.00	0.00	0.00	0.00
Heating (G)	114.69	62.19	47.32	45.28	0.00	0.00
Heating (E)	0.28	0.14	0.15	0.00	11.76	11.76
Cooling (E)	5.74	4.79	0.82	1.07	1.40	1.40
HVAC Fan/Pump (E)	0.44	0.22	0.24	0.66	3.03	3.03
Lights (E)	4.28	4.28	2.78	2.78	2.78	2.78
Lg. Appl. (E)	8.18	8.18	8.18	8.18	8.18	8.18
Vent Fan (E)	0.07	0.07	0.07	0.07	0.07	0.07
Misc. (E)	10.33	10.33	10.33	10.33	10.33	10.33

Figure 57. Group 10: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 14, Pt 61	Boiler-Room A/C: Iter 8, Pt 13 **	Furnace-Central A/C: Iter 13, Pt 66**	MSHP: Iter 4, Pt 7**	GSHP: Iter 7, Pt 38**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	22.09	22	11.91	11.91	22.64	22.24
Hot Water (E)	0	0	0	0	0	0
Heating (G)	125.02	67.78	51.58	49.36	0	0
Heating (E)	0.87	0.44	0.47	0	46.39	37.06
Cooling (E)	18.07	15.09	2.57	3.36	4.79	4.4
HVAC Fan/Pump (E)	1.37	0.71	0.75	2.07	0.92	9.55
Lights (E)	13.49	13.49	8.75	8.75	8.75	8.75
Lg. Appl. (E)	25.8	25.8	25.8	25.8	25.8	25.8
Vent Fan (E)	0.24	0.24	0.24	0.24	0.24	0.24
Misc. (E)	32.56	32.56	32.56	32.56	32.56	32.56

Figure 58. Group 10: Source energy use of critical optimal iteration points

Figure 59 illustrates the simple payback periods for each of the cases. It can be inferred that the cases involving the boiler, furnace, and MSHP have the expected payback period of less than 35 years and may be more desirable retrofit packages than the GSHP case which has an expected payback period of more than 55 years.

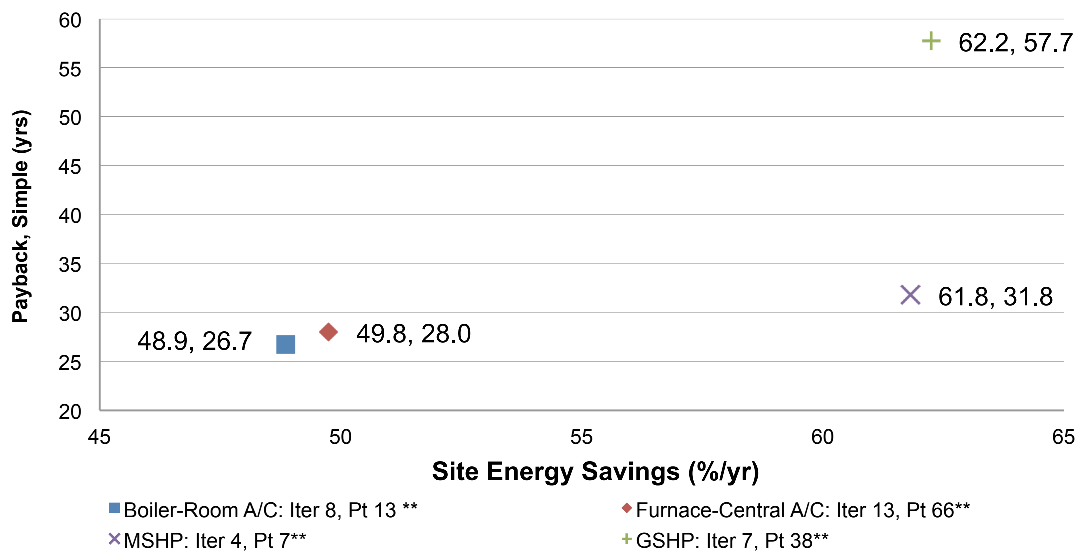


Figure 59. Group 10: Simple Payback of critical optimal iteration points

Figure 60 illustrates the Modified Internal Rate of Return (MIRR) for each case. It can be deduced that the case that is expected to have the highest MIRR is the Boiler-Room A/C case, followed by the Furnace-Central A/C and the MSHP cases.

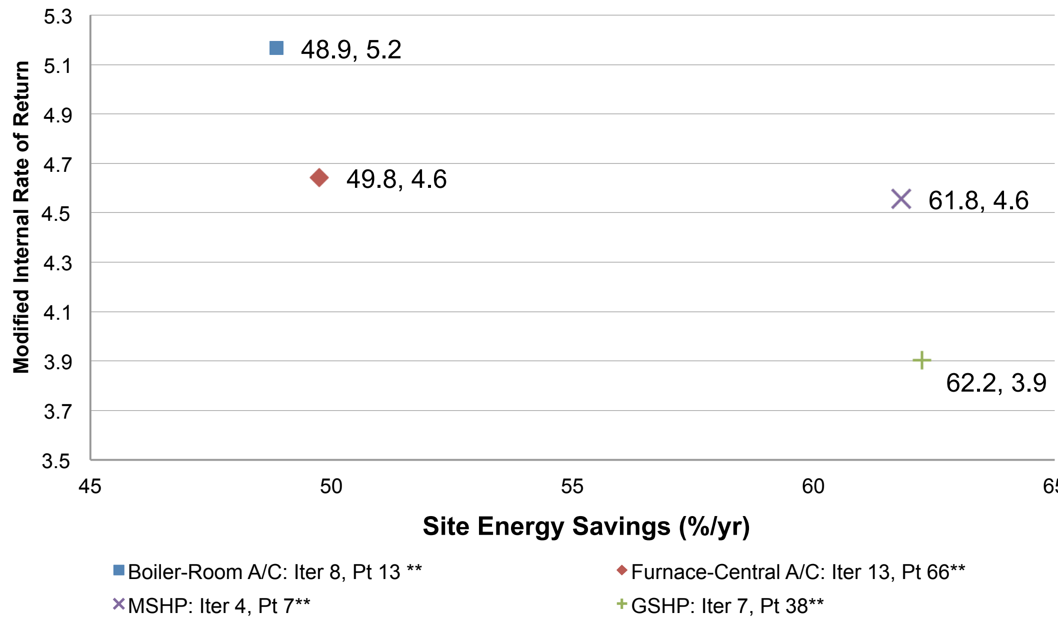


Figure 60. Group 10: Modified Internal Rate of Return of critical optimal iteration points

Through analyses of all the figures given for Group 10 it is concluded that an upgrade to the boiler system is the most cost effective option toward a 50% site energy reduction having the lowest payback period and highest MIRR.

Group 12: Frame, 1942-1978, 1 to 1.5 stories (no split level) Group 12 has measured mean square footage of 1185 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 1180 ft^2. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 61.

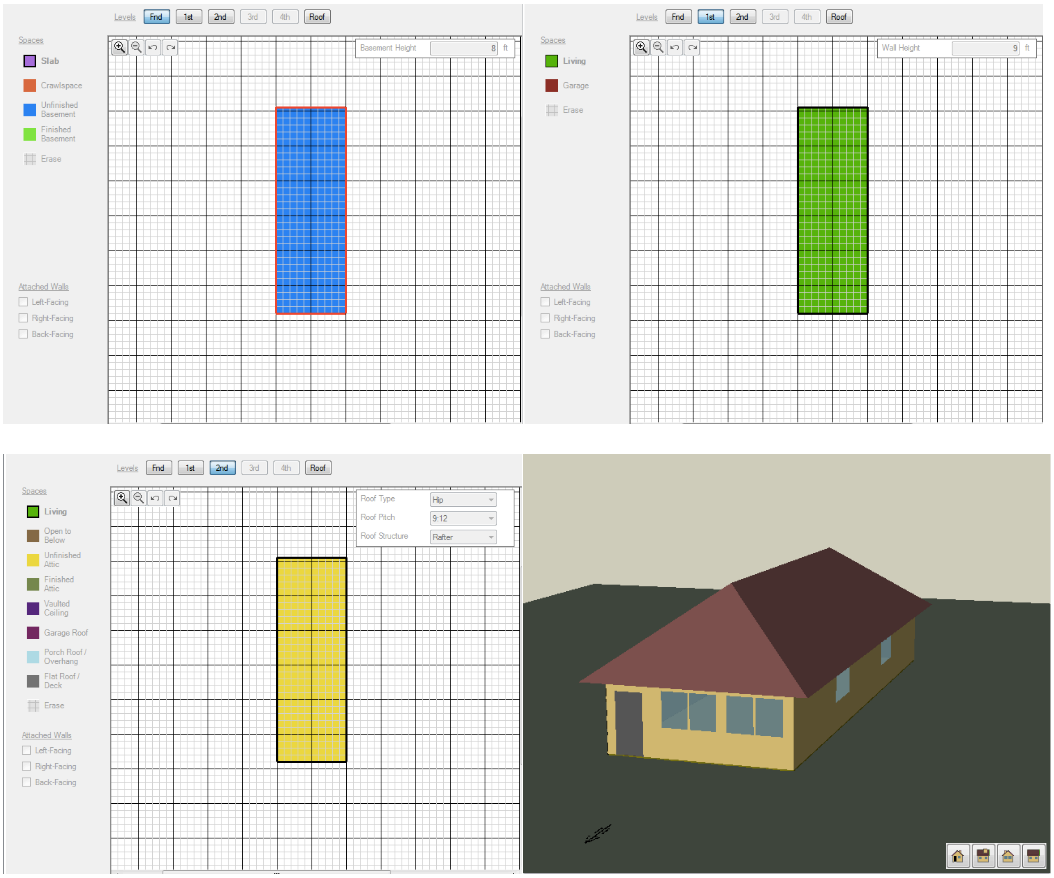


Figure 61. Group 12: BEopt model: foundation, first, and second (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 62 and 63 respectively. It can be observed that a site energy savings of about 20% (least cost option) simply by updating the enclosure and keep existing HVAC systems. This translates to about a 12% source energy savings. Also, the least cost enclosure package has an AERC that is slightly higher (+$25/yr) than the existing case.

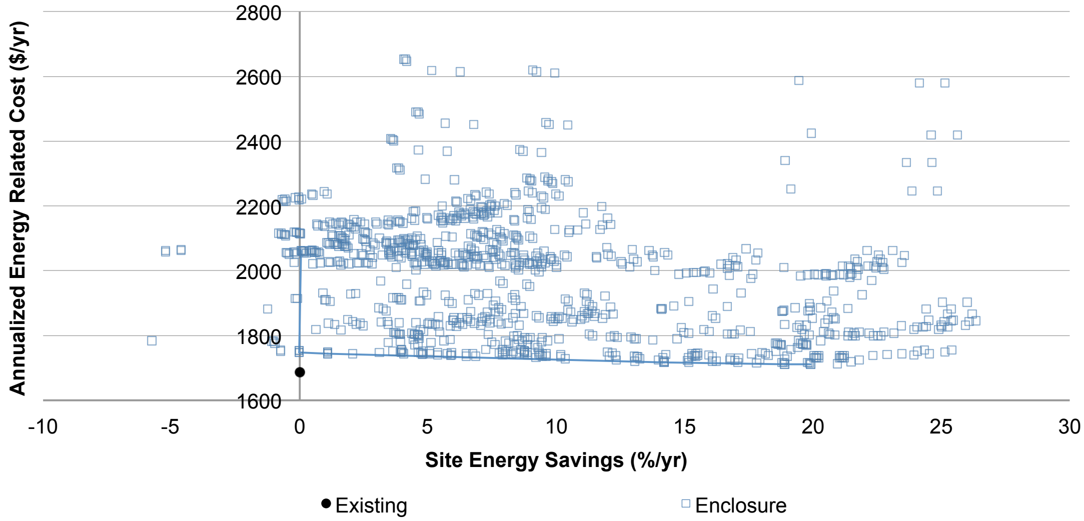


Figure 62. Group 12: Building Enclosure optimization results in terms of sites energy savings

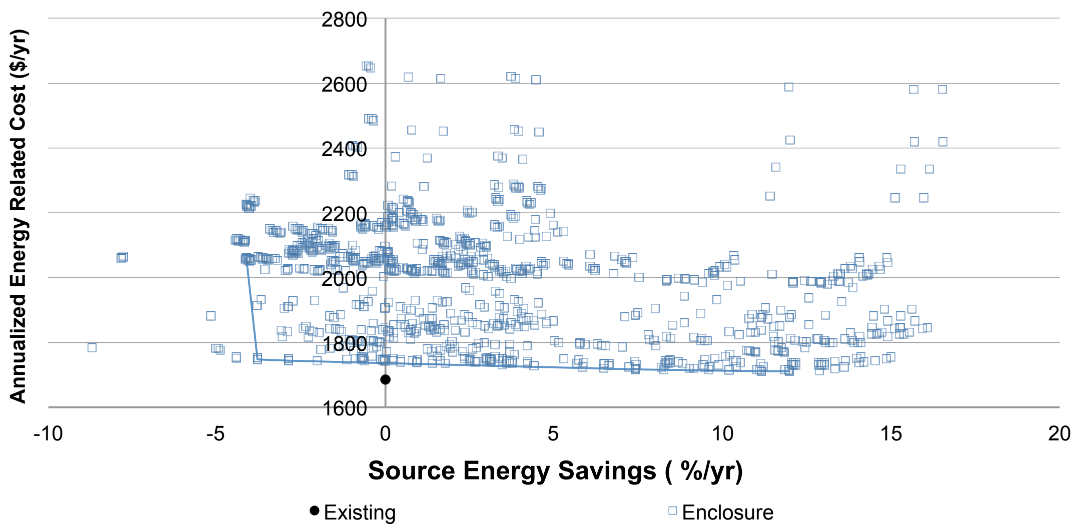


Figure 63. Group 12: Building Enclosure optimization results in terms of source energy savings.

Table 16 lists the original ‘Today’ scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves. For this residential building group, the optimal option involves upgrades to the wall sheathing, unfinished attic insulation, and air leakage only.

Table 16. Group 12: Optimal Building Enclosure: Optimized Parameters, ‘Today’ scenario assumptions, and BEopt upgrades.

Parameter name	‘Today’	Enclosure: Iter 14, Pt 65
Exterior Wall (Wood Stud)	R-7 Fiberglass Batt, Gr-3, 2x4, 16 in O.C.	No Change
Wall Sheathing	None****	R12- Polyiso
Exterior Finish	Wood Siding, Light	No Change
Unfinished Attic	Ceiling R-19 Fiberglass (Blown-in), Vented	Ceiling R-30 Fiberglass (Blown-in), Vented
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Interzonal Floor	R-11 Fiberglass	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Leaky	Typical
Mechanical Ventilation	Spot Ventilation Only	No Change

The parameters chosen to analyze any retrofit of insulation with a higher thermal resistance to the interior side of the wall were shown to be a more costly upgrade than the addition of insulation on the exterior side, therefore, the recommendation for R-12 Polyiso insulation underneath the sheathing is considered appropriate. By adding insulation to the interzonal walls that separate the conditioned from the unconditioned areas of the attic, heat loss through these walls is mitigated, thus, this recommendation is appropriate. Insulation retrofit unfinished attic to a R-19 blown-in insulation is considered appropriate as it is much more thermal resistant then the existing insulation (R-3) and the cost for the upgrade is offset by the energy savings it provides. The upgrade in envelope tightness from very leaky to leaky reflects about a 22% increase in enclosure tightness and is considered appropriate (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). The non-upgrades to other parameters are as expected as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

Retrofitting polyisocyanurate to the exterior side of the enclosure has the potential to negatively affect the moisture performance of that wall, therefore, an analysis was conducted using the free WUFI Light version 5.2 moisture design tool software to validate this upgrade. The wall was modeled using default specifications for the materials chosen based on their similarities to the specifications of the corresponding materials in BEopt; the wall modeled with the following material layers and thicknesses from exterior inward:

- One layer of southern yellow pine acting as exterior light colored wood siding with a thickness of ~3/4-inch (2 cm),
- One layer of polyisocyanurate insulation with a thickness of ~2-inch (5.08 cm),
- One layer of OSB with a thickness of ~1/2-inch (1.25 cm),

- One layer of R-7 Fiberglass batt (cellulose insulation was the only option similar to fiberglass batt in the free version of WUFI) or softwood acting as 2x4 studs with a thickness of ~3.5-inch (9 cm), and
- One layer of gypsum plaster with a thickness of ~7/8-inch (2.02cm).

The moisture analysis for this above wall was conducted using the same methodology and assumptions as the moisture investigation in Group 10. The results indicate that there seems to be no expected risk of moisture penetration within the wall (i.e. RH does not reach 100%) Therefore, it can be concluded that this wall construction is likely acceptable in terms of moisture performance, although it should noted that this method does not capture the effects of air leakage and thus should be interpreted with caution. The original WUFI files and inputs for this simulation can also be found at the following web address:

http://built-envi.com/portfolio/chicagoland-housing-retrofits/

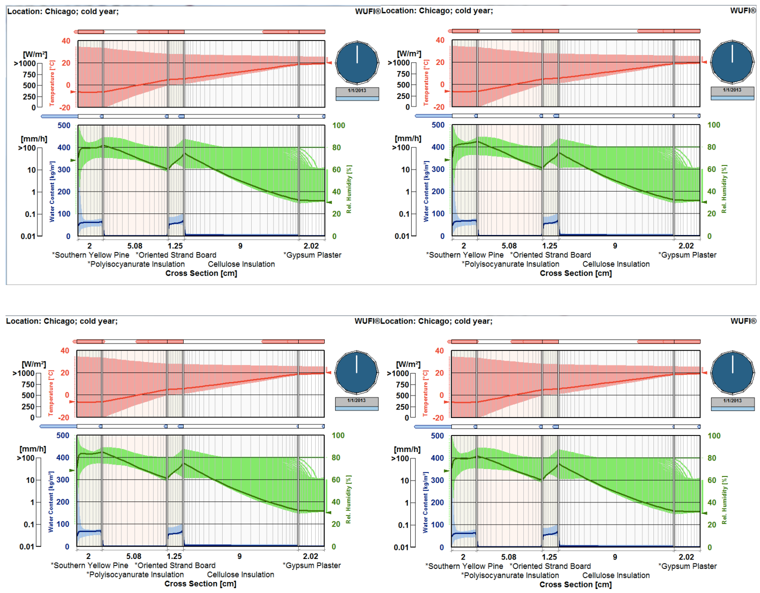


Figure 64. WUFI analysis of exterior polyiso R-12 insulated frame wall section taken through the insulated cavity between studs for all elevations (Top Left: North wall; Top Right: East Wall; Bottom Left: South Wall; Bottom Right: West Wall).

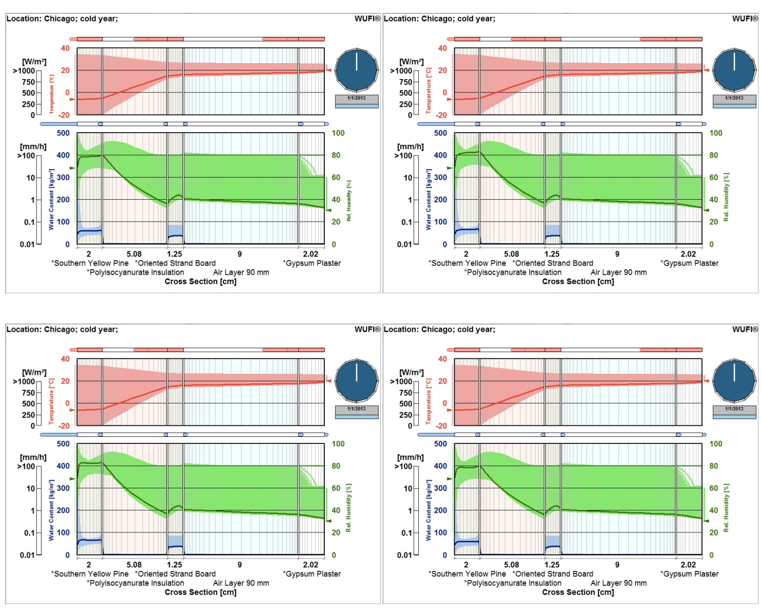


Figure 65. WUFI analysis of exterior polyiso R-12 insulated frame wall section taken through the stud for all elevations (Top Left: North wall; Top Right: East Wall; Bottom Left: South Wall; Bottom Right: West Wall).

Graphs expressing the AERC in terms of site energy savings and source energy savings and their respective least cost fit lines for the HVAC optimization for this group are illustrated by Figures 66 and 67 respectively.

From the results shown in Figure 66, it is observed that the options chosen for optimization all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case which an exception of the Furnace-Central A/C case (maximum of about a 45% site savings). Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated 53% site energy savings. All iteration points are represented as having an AERC higher than the existing case.

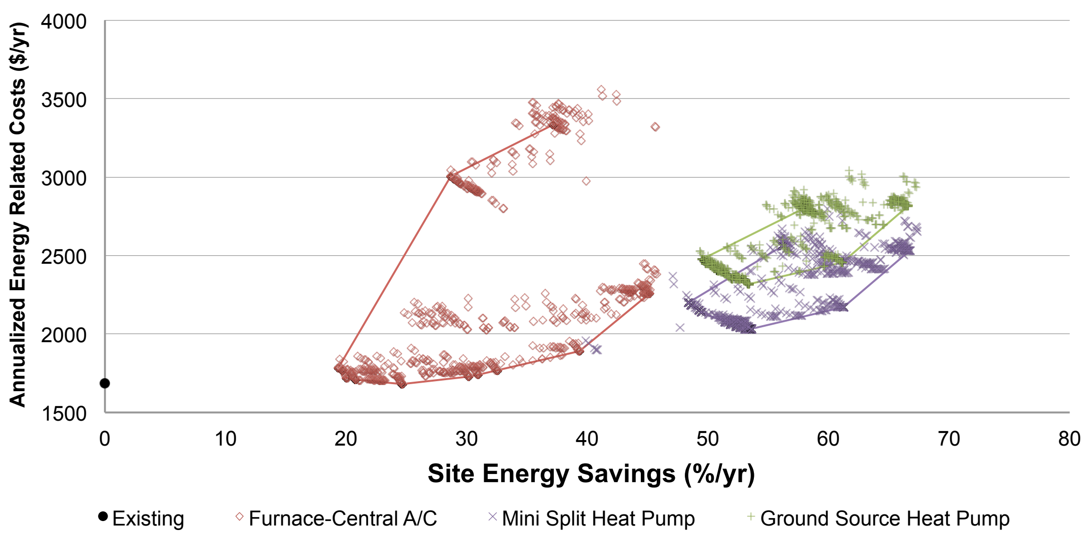


Figure 66. Group 12: HVAC optimization results in terms of site energy savings

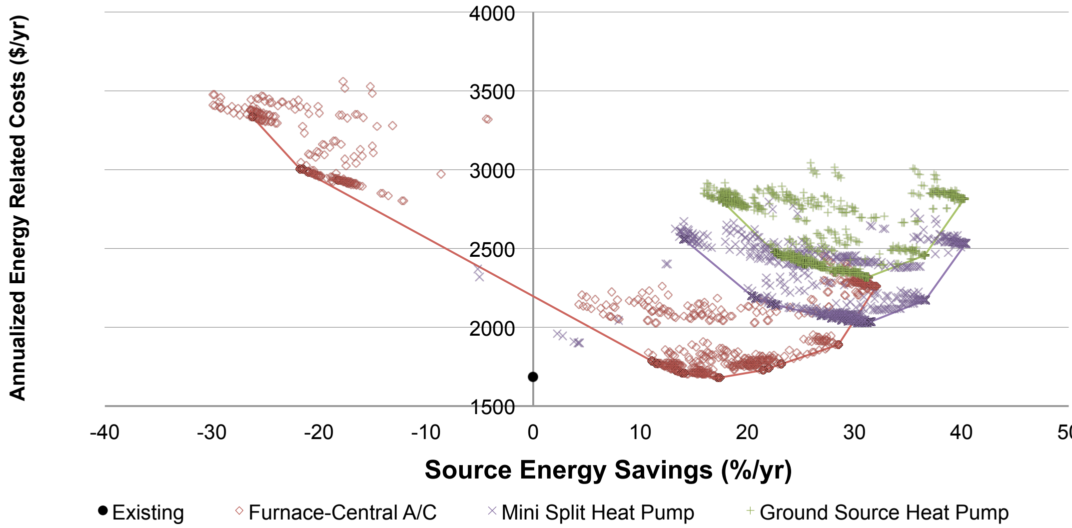


Figure 67. Group 12: HVAC optimization results in terms of source energy savings.

The parameters, costs, and energy savings for the iteration points chosen for further analysis as well as the 'Today' case are listed in Table 17. It should be noted that Furnace-Central A/C case fall a few percentage short of the 50% target site energy savings. Also, note that the MSHP package (in combination with the optimal enclosure for this group) is represented as having the lowest AERC and initial cost of the three systems.

Table 17. (Page 1 of 2) Group 12: Frame, 1942-1978, 1 to 1.5 stories - Parameter options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 14, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 21, Pt 58**
Central A/C	SEER 10	No Change	None	None
Furnace	Gas, 78% AFUE	Gas, 98% AFUE	None	None
Electric Baseboard	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	EER 20.2, COP 4.2, High-k Soil, Enh grout
Ducts	Typical, Uninsulated (Unfinished Basement)	In Finished Space	None	In Finished Space
Ceiling Fan***	None	None	None	None
Water Heater	Gas, 54% EF	Gas Tankless, Condensing	No Change	No Change
Solar Water Heating	None	64 ft^2 Closed Loop	None	None
SWH Azimuth	N/A	Back Roof	N/A	N/A
SWH Tilt	N/A	Latitude	N/A	N/A
Lighting	Benchmark	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in

Table 17. (Page 2 of 2) Group 12: Frame, 1942-1978, 1 to 1.5 stories - Parameter options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 14, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 21, Pt 58**
Initial Cost ($)	$0	$17,385	$8,977	$17,941
Annualized Energy Related Costs ($/yr)	$1,685	$2,090	$2,043	$2,263
% Site (Source) Savings	0	45.5(34.9)	53.3(30.7)	53.5(31.3)

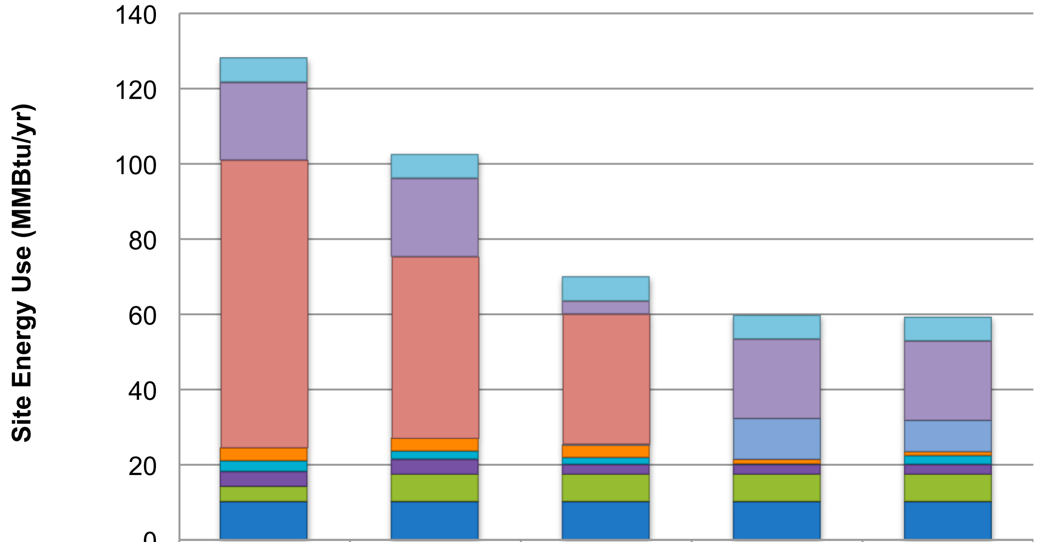
It is observed the addition of ceiling fans were not considered a cost effective upgrade for any of the cases.

The Furnace–Central A/C case optimized the installation of a gas, 98% AFUE furnace. The recommendation to install ducts in finished space is practical since installation within the walls is more difficult in homes without pre-conceived space dedicated for ductwork. BEopt optimized a tankless condensing water heater as an upgrade from the existing water heater. Condensing water heaters work very similarly to condensing boilers in that they utilize exit flue gases to preheat incoming cold water. Unlike common hot water heaters, tankless water heaters do not have storage tanks and heat water on demand. User behavior may have change to accommodate this upgrade to ensure the fulfillment of hot water loads. There are no other issues expected from making this upgrade, as it is a very common retrofit. It is suggested that a 64 ft^2 closed loop solar water heating system, oriented on the back roof of the house (south side), and tilted to a degree that equals the latitude of Chicago+15º as a supplement preheat method to the water heater. It is also recommended for this case that 100% of hardwired and plug-in lighting be converted to fluorescent, this is also a very common energy reduction strategy.

For the case involving the optimization of a MSHP system, BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

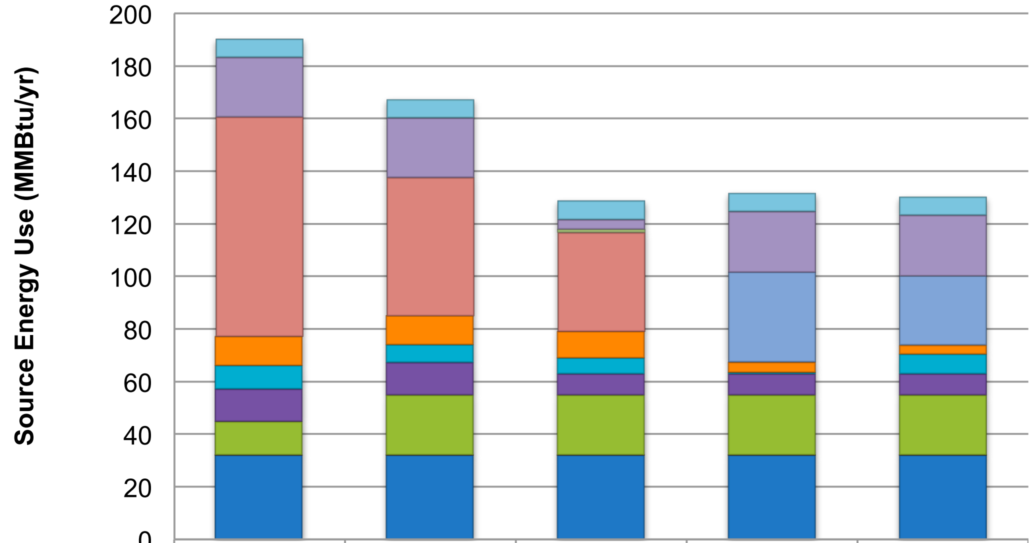
BEopt simulated that the optimal GSHP unit to be EER 20.2, COP 4.2, High-k soil, Enh grout between the pipes and the ground. BEopt recommends for installation to be relocated to finished space. An upgrade to the water heater was not recommended. As with all other cases, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 68 shows estimated site energy usage of the packages listed in Tables 16 and 17 while Figure 69 shows estimated source energy usage. It can be observed that both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 68) and that the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 69).



	Today	Enclosure: Iter 14, Pt 65	Furnace-Central A/C: Iter 14, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 21, Pt 58**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	20.74	20.82	3.63	21.10	21.07
Hot Water (E)	0.00	0.00	0.00	0.00	0.00
Heating (G)	76.24	48.26	34.48	0.00	0.00
Heating (E)	0.00	0.00	0.37	10.82	8.33
Cooling (E)	3.56	3.53	3.19	1.28	1.16
HVAC Fan/Pump (E)	2.81	2.13	1.97	0.23	2.39
Lights (E)	3.91	3.91	2.53	2.53	2.53
Lg. Appl. (E)	4.07	7.20	7.20	7.20	7.20
Vent Fan (E)	0.06	0.06	0.06	0.06	0.06
Misc. (E)	10.10	10.10	10.10	10.10	10.10

Figure 68. Group 12: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 14, Pt 65	Furnace-Central A/C: Iter 14, Pt 24**	MSHP: Iter 6, Pt 7**	GSHP: Iter 21, Pt 58**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	22.61	22.69	3.96	22.99	22.97
Hot Water (E)	0	0	1.15	0	0
Heating (G)	83.1	52.6	37.59	0	0
Heating (E)	0	0	0	34.11	26.27
Cooling (E)	11.24	11.12	10.04	4.05	3.66
HVAC Fan/Pump (E)	8.85	6.71	6.22	0.71	7.52
Lights (E)	12.31	12.31	7.98	7.98	7.98
Lg. Appl. (E)	12.83	22.71	22.72	22.72	22.72
Vent Fan (E)	0.19	0.19	0.18	0.18	0.18
Misc. (E)	31.84	31.84	31.84	31.84	31.84

Figure 69. Group 12: Source energy use of critical optimal iteration points

Figure 70 illustrates the simple payback periods for each of the cases. It can be inferred that the cases involving the MSHP having the lowest expected payback period of less than 40 years and may be more desirable retrofit packages than the Furnace-Central A/C with a payback period just under 50 years and the GSHP case which has an expected payback period of more about years.

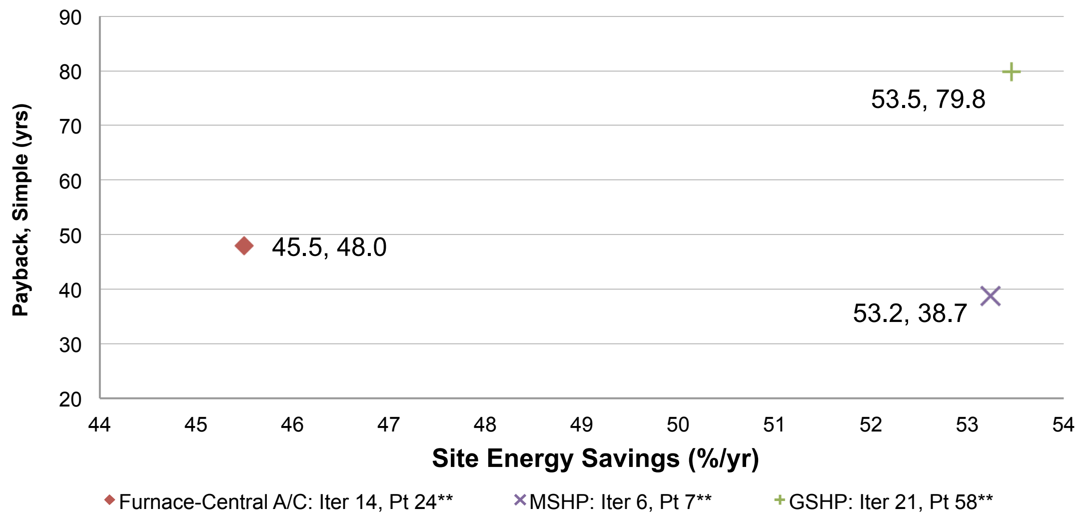


Figure 70. Group 12: Simple Payback of critical optimal iteration points

Figure 71 illustrates the Modified Internal Rate of Return (MIRR) for each of the cases for Group 12. It can be deduced that the case that is expected to have the highest MIRR is the Furnace-Central A/C and the MSHP cases.

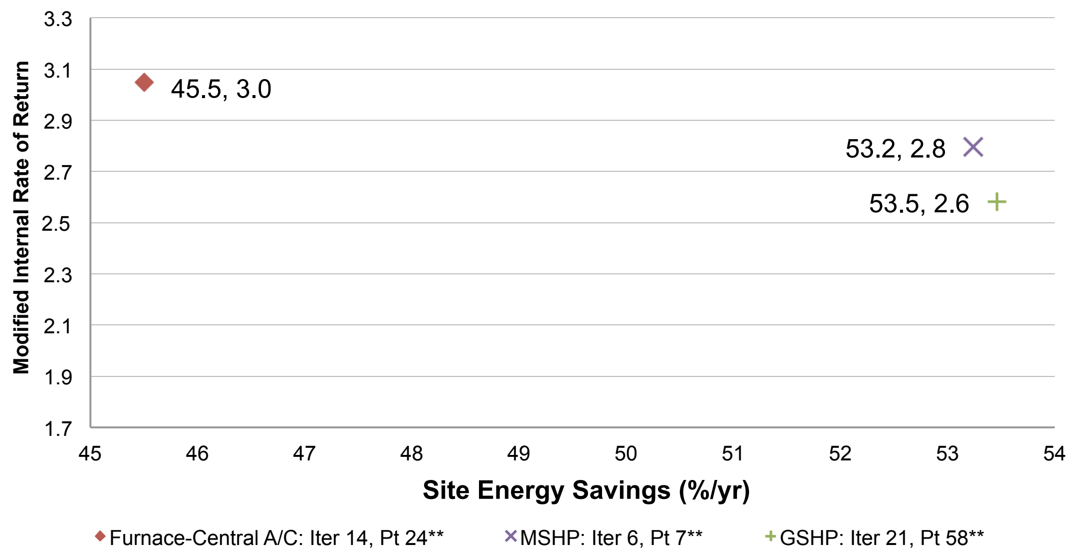


Figure 71. Group 12: Modified Internal Rate of Return of critical optimal iteration points

Through analyses of all the figures given for Group 12 it is concluded that a conversion to a MSHP system is the most cost effective option toward a 50% site energy reduction, representing one of the most site energy saving while also having the lowest payback period and a high MIRR.

Group 13: Frame, 1942-1978, 2 stories Group 13 has measured mean square footage of 1586 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 1584 ft^2. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 72.

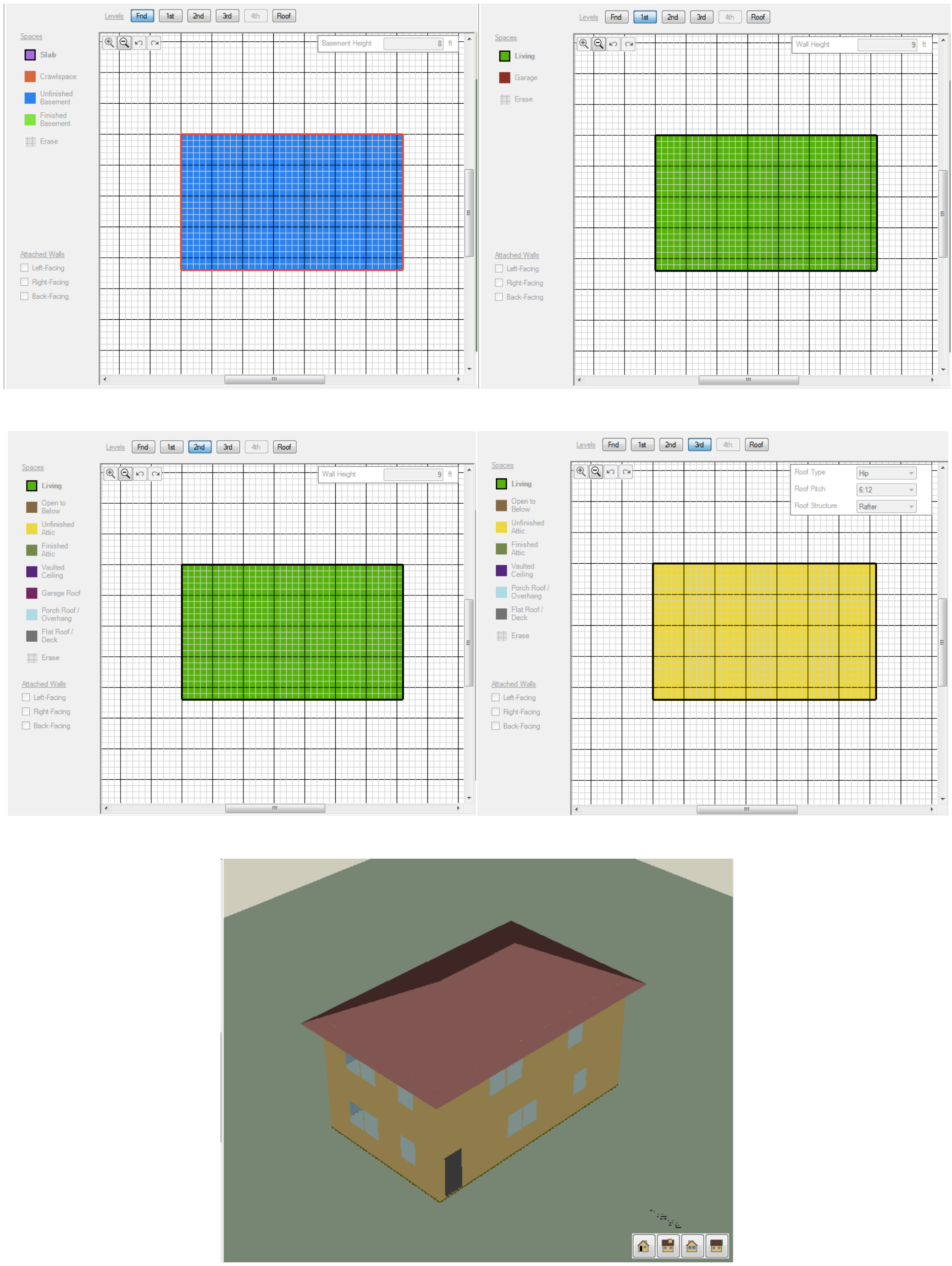


Figure 72. Group 13: BEopt model: foundation, first, second, and third (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 73 and 74 respectively It can be observed that a site energy savings of about 26% (least cost option) simply by updating the enclosure and keep existing HVAC systems. This translates to about a 20% source energy savings. Also, the least cost iteration point is representing has having an AERC of about $100/yr less than the existing.

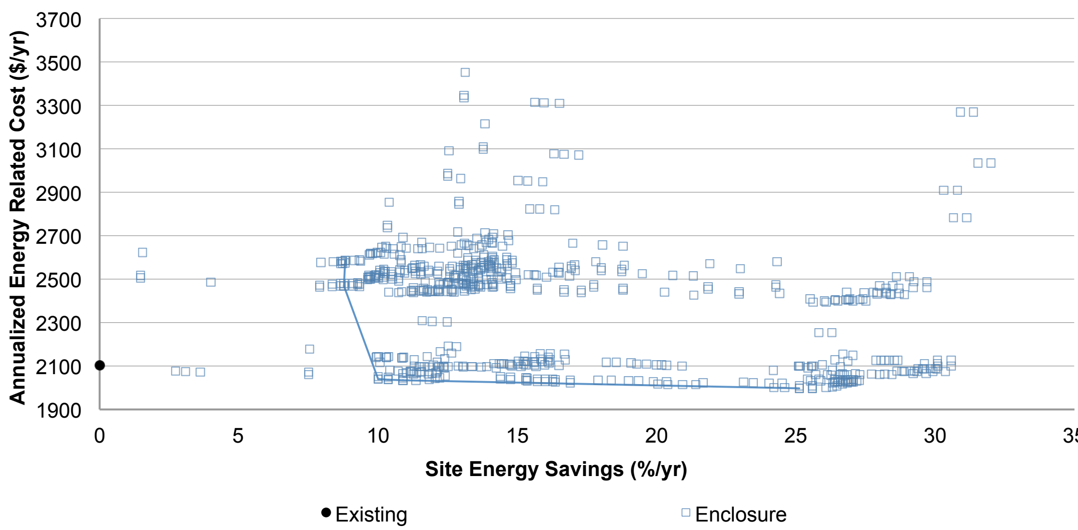


Figure 73. Group 13: Building Enclosure optimization results in terms of sites energy savings

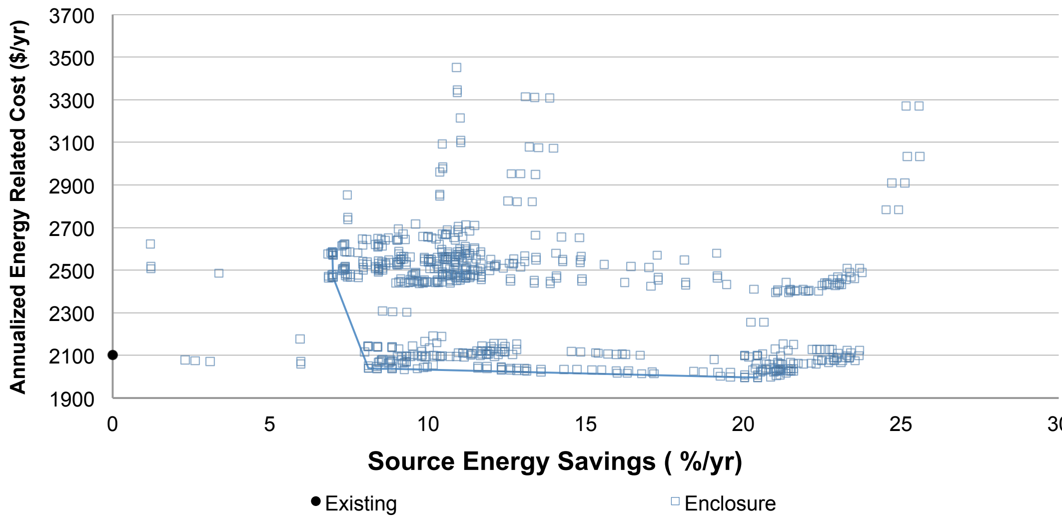


Figure 74. Group 13: Building Enclosure optimization results in terms of source energy savings.

Table 18 lists the original 'Today' scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves. For this residential building group, the optimal option involves upgrades to the wall sheathing, unfinished attic insulation, and air leakage only.

Table 18. Group 13: Optimal Building Enclosure: Optimized Parameters, 'Today' scenario assumptions, and BEopt upgrades.

Parameter name	'Today'	Enclosure: Iter 8, Pt 63
Exterior Wall (Wood Stud)	R-7 Fiberglass Batt, Gr-3, 2x4, 16 in O.C.	No Change
Wall Sheathing	None****	R12- Polyiso
Exterior Finish	Wood Siding, Light	No Change
Unfinished Attic	Ceiling R-11 Fiberglass (Blown-in), Vented	Ceiling R-30 Fiberglass (Blown-in), Vented
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Leaky	Typical
Mechanical Ventilation	None	No Change

The parameters chosen to analyze any retrofit of insulation with a higher thermal resistance to the interior side of the wall were shown to be a more costly upgrade than the addition of insulation on the exterior side, therefore, the recommendation for R-12 Polyiso insulation underneath the sheathing is considered appropriate. Insulation retrofit unfinished attic to a R-30 blown-in insulation is considered appropriate as it is much more thermal resistant then the existing insulation (R-11) and the cost for the upgrade is offset by the energy savings it provides. The upgrade in envelope tightness from leaky to typical reflects about a 22% increase in enclosure tightness and is considered appropriate (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, & Weiger, 1988). The non-upgrades to other parameters are as expected as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

The results from the optimization of each of the HVAC cases after the implementation of the optimal enclosure are illustrated as AERC in terms of site energy savings and source energy savings and their respective least cost fit lines by Figures 75 and 76 respectively. Comparison of the two graphs shows differences in values between site and source energy savings especially in the cases involving the mini-split and ground-source heat pumps as expected

From the results shown in Figure 75, it can be seen that the options chosen for optimization all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated 60% site energy savings.

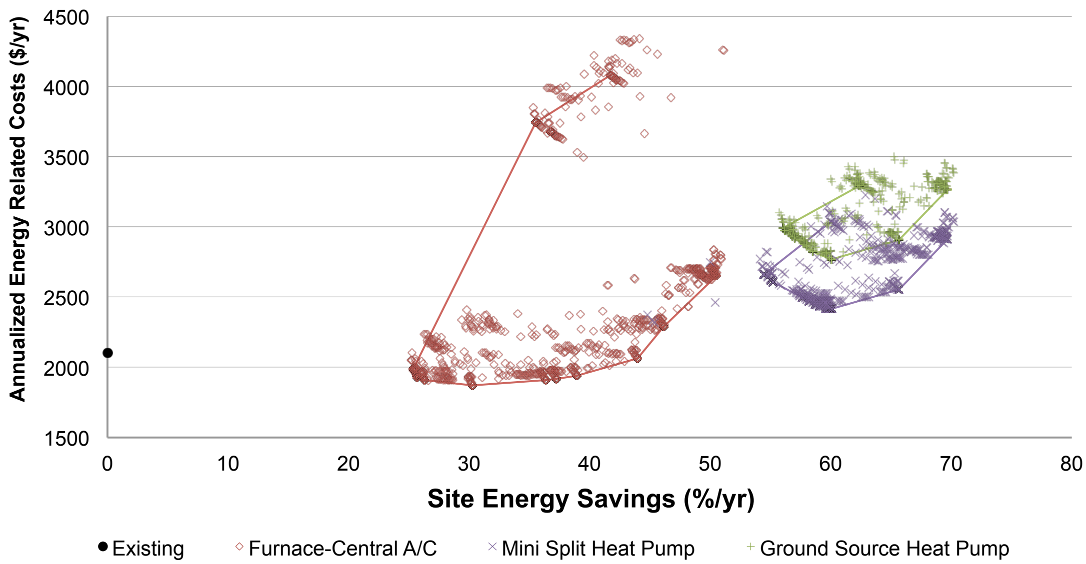


Figure 75. Group 13: HVAC optimization results in terms of site energy savings

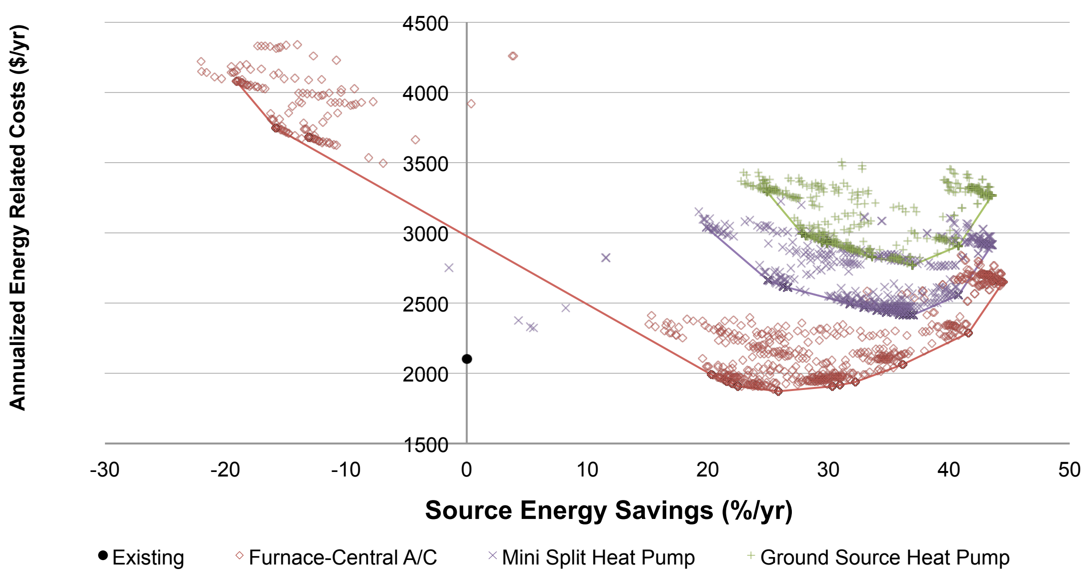


Figure 76. Group 13: HVAC optimization results in terms of source energy savings.

The iteration points chosen for further investigation and their associated parameter options, costs, and energy savings are reported in Table 19. It can be observed that the MSHP is estimated to have the lowest AERC and initial costs of all the systems. This is unexpected as further analysis determines that this is not the optimal retrofit package for this group as discussed later in this section

Table 19. Group 13: Frame, 1942-1978, 2 stories - Parameter options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Furnace-Central A/C: Iter 14, Pt 59**	MSHP: Iter 4, Pt 11**	GSHP: Iter 11, Pt 3**
Central A/C	SEER 10	SEER 24.5	None	None
Furnace	None	Gas, 98% AFUE	None	None
Electric Baseboard	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	Typical, Uninsulated, (Unfinished Basement)	In Finished Space	None	In Finished Space
Ceiling Fan***	None	None	None	None
Water Heater	Gas, 54% EF	Gas Tankless	No Change	No Change
Solar Water Heating	None	64 ft^2 Closed Loop	None	None
SWH Azimuth	N/A	Back Roof	N/A	N/A
SWH Tilt	N/A	30 Degrees	N/A	N/A
Lighting	Benchmark	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in
Initial Cost ($)	$0	$23,142	$10,721	$21,420
Annualized Energy Related Costs ($/yr)	$2,102	$2,625	$2,416	$2,769
% Site (Source) Savings	0	50.1(44.1)	60.1(37.0)	60.1(37.0)

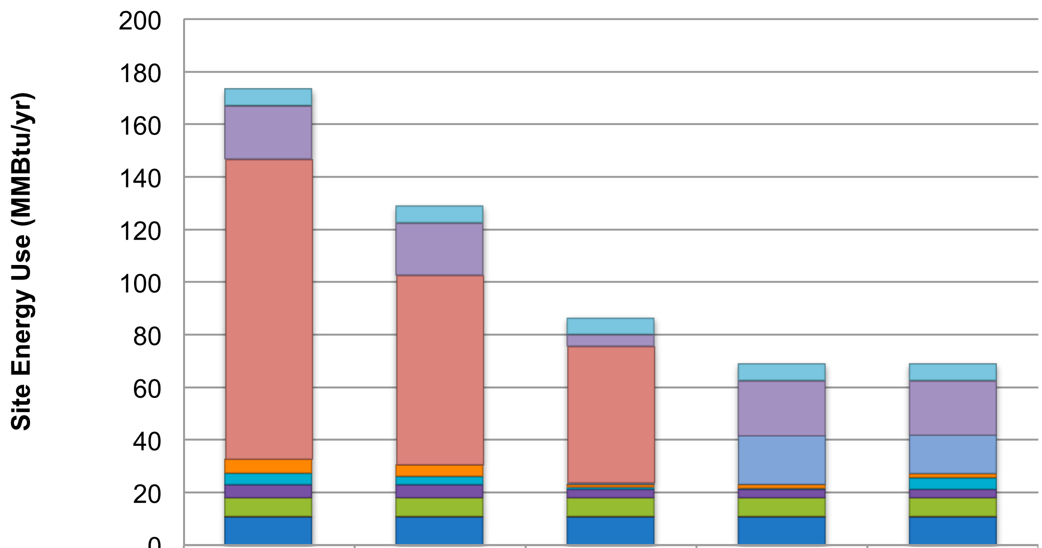
The addition of ceiling fans was not considered to be a cost effective upgrade for any of cases in this group.

The Furnace–Central A/C case, BEopt optimized the upgrade to a gas, 98% AFUE furnace from the existing and an upgrade to a 24.5 SEER central A/C are considered appropriate recommendations. It is recommended to relocate ducts in finished space. A 64 ft^2 closed loop solar water heating system, oriented on the back roof of the house (south side), and tilted to a degree that equals the latitude of Chicago+15^o was suggested as a supplement preheat method to the water heater. A tankless water heater is suggested as an upgrade from the existing water heater. User behavior may have to change to accommodate this upgrade and ensure the fulfillment of hot water loads.

For the MSHP case BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt did not suggest an upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

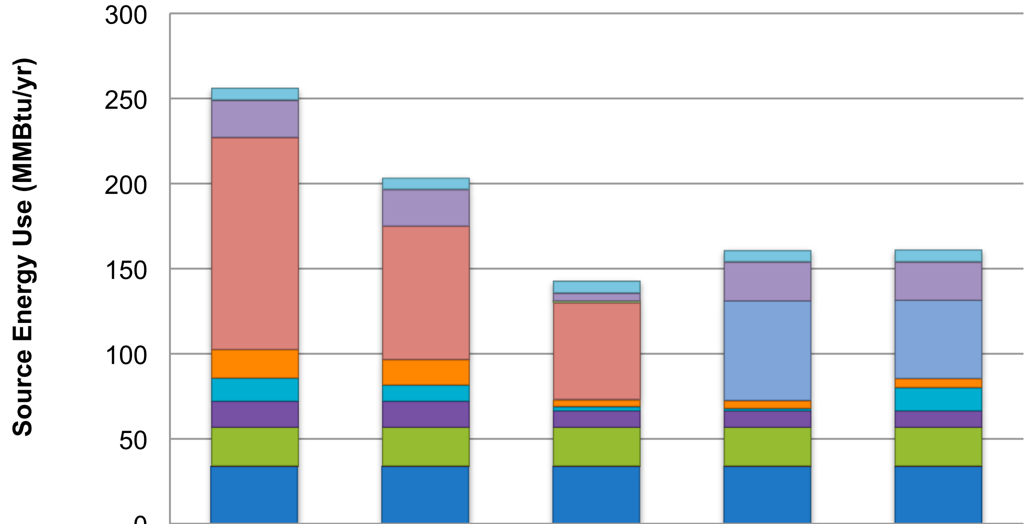
As with all previous groups BEopt simulated that the optimal GSHP unit as an EER of 20.2, COP 4.2 High-k soil, Enh grout the most efficient and largest sized unit for this parameter. BEopt recommends for installation of the ducts to be within the finished space. An upgrade to the water heater was not recommended because the initial cost to upgrade is not offset by energy related cost savings. Also a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 77 shows estimated site energy usage of the packages listed in Tables 18 and 19 while Figure 78 shows estimated source energy usage. It can be observed that both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 77) it is verified that the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 78).



	Today	Enclosure: Iter 8, Pt 63	Furnace-Central A/C: Iter 14, Pt 59**	MSHP: Iter 4, Pt 11**	GSHP: Iter 11, Pt 3**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	20.34	19.91	4.42	21.00	20.98
Hot Water (E)	0.00	0.00	0.00	0.00	0.00
Heating (G)	113.97	71.97	52.01	0.00	0.00
Heating (E)	0.00	0.00	0.36	18.53	14.53
Cooling (E)	5.38	4.69	1.33	1.59	1.71
HVAC Fan/Pump (E)	4.25	3.03	0.76	0.38	4.30
Lights (E)	4.86	4.86	3.15	3.15	3.15
Lg. Appl. (E)	7.20	7.20	7.20	7.20	7.20
Vent Fan (E)	0.07	0.07	0.07	0.07	0.07
Misc. (E)	10.67	10.67	10.67	10.67	10.67

Figure 77. Group 13: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 8, Pt 63	Furnace-Central A/C: Iter 14, Pt 59**	MSHP: Iter 4, Pt 11**	GSHP: Iter 11, Pt 3**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	22.16	21.7	4.82	22.88	22.86
Hot Water (E)		0	1.15	0	0
Heating (G)	124.22	78.44	56.69	0	0
Heating (E)	0	0	0	58.39	45.8
Cooling (E)	16.96	14.77	4.2	5	5.4
HVAC Fan/Pump (E)	13.41	9.54	2.41	1.2	13.56
Lights (E)	15.29	15.29	9.91	9.91	9.91
Lg. Appl. (E)	22.71	22.72	22.72	22.72	22.72
Vent Fan (E)	0.21	0.21	0.21	0.21	0.21
Misc. (E)	33.66	33.66	33.65	33.65	33.65

Figure 78. Group 13: Source energy use of critical optimal iteration points

Figure 79 illustrates the simple payback periods for each of the cases. It can be inferred that the cases involving the Furnace-Central A/C and MSHP cases have the expected payback period of less than 45 years and may be more desirable retrofit packages than the GSHP case which has an expected payback period of almost 90 years.

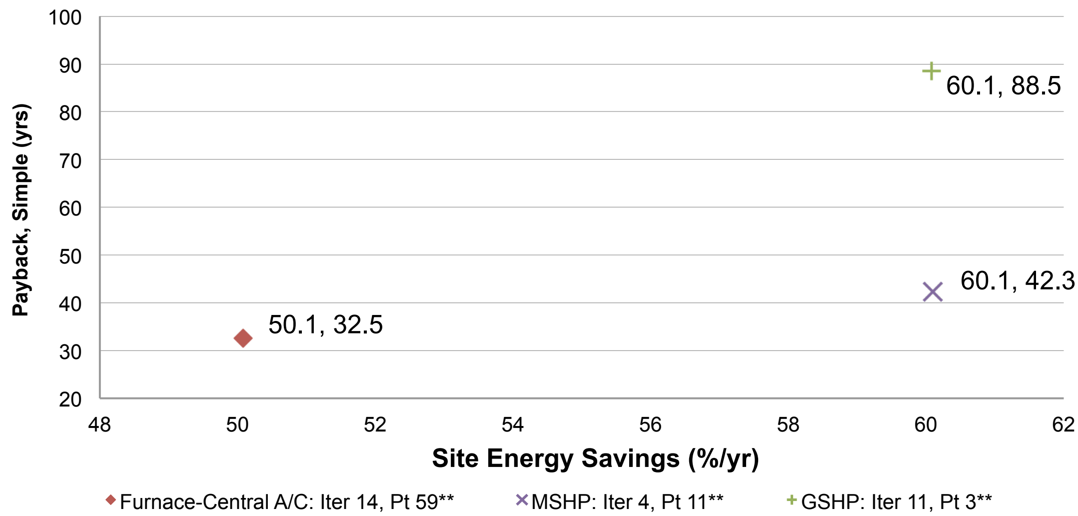


Figure 79. Group 13: Simple Payback of critical optimal iteration points

Figure 80 illustrates the Modified Internal Rate of Return (MIRR) for each of the HVAC cases. It can be deduced that the case that is expected to have the highest MIRR is the Furnace-Central A/C case.

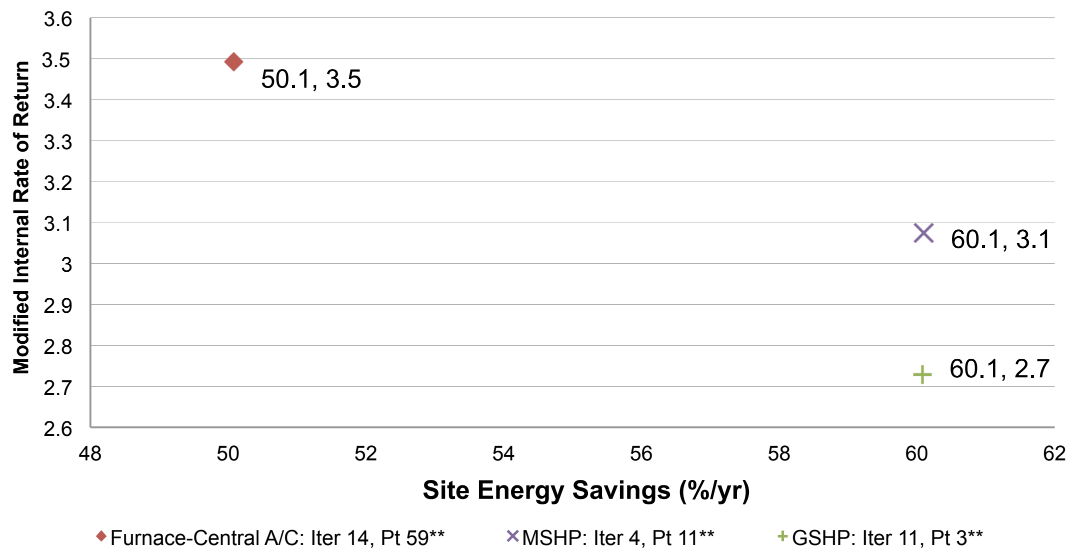


Figure 80. Group 13: Modified Internal Rate of Return of critical optimal iteration points

Through analyses of all the figures given for Group 13 it is concluded that an upgrade to the Furnace-Central A/C system is the most cost effective option toward a 50% site energy reduction while also having the lowest payback period and highest MIRR.

Group 14: Frame, Pre-1942, 1 to 1.5 stories Group 14 has measured mean square footage of 1254 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 1240 ft^2. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 81.

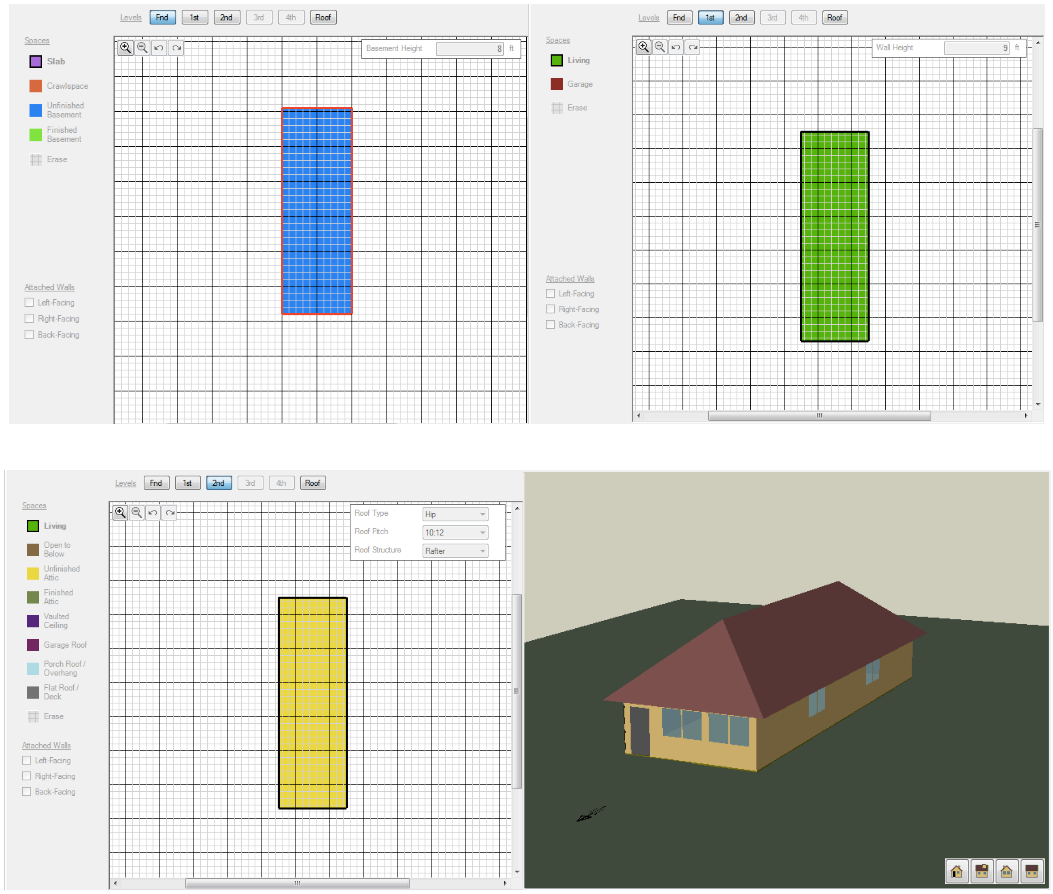


Figure 81. Group 14: BEopt model: foundation, first, and second (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 82 and 83 respectively. It can be observed that a site energy savings of about 41% (least cost option) simply by updating the enclosure and keep existing HVAC systems. This translates to about a 34% source energy savings. Also, the least cost iteration point is represented as having an AERC of about $250/yr less than the existing case.

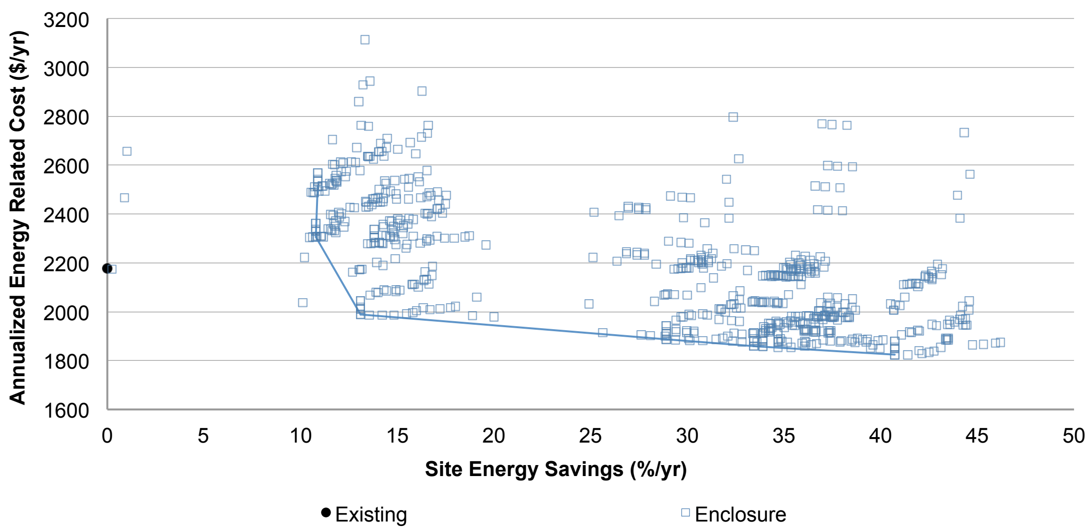


Figure 82. Group 14: Building Enclosure optimization results in terms of sites energy savings

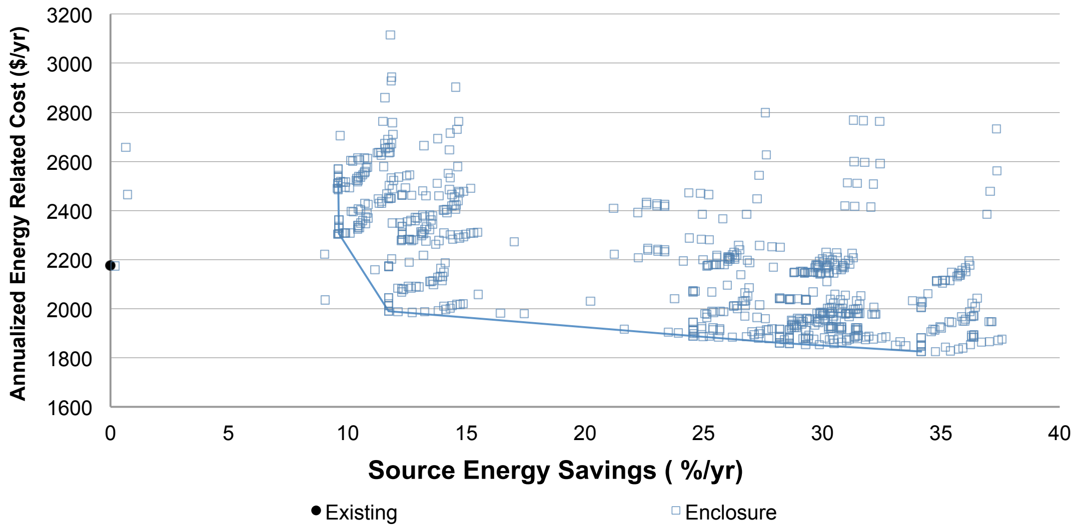


Figure 83. Group 14: Building Enclosure optimization results in terms of source energy savings.

Table 20 lists the original ‘Today’ scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves. For this residential building group, the optimal option involves upgrades to the wall sheathing, unfinished attic insulation, and air leakage only.

Table 20. Group 14: Optimal Building Enclosure: Optimized Parameters, 'Today' scenario assumptions, and BEopt upgrades.

Parameter name	'Today'	Enclosure: Iter 8, Pt 33
Exterior Wall (Wood Stud)	Uninsulated, 2x4, 16 in O.C.	No Change
Wall Sheathing	None****	R12- Polyiso
Exterior Finish	Wood Siding, Light	No Change
Unfinished Attic	Ceiling R-3 Fiberglass (Blown-in)	Ceiling R-25 Fiberglass (Blown-in), Vented
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Very Leaky	Leaky
Mechanical Ventilation	None	No Change

The parameters chosen to analyze any addition of insulation to the interior side of the wall were shown to be a more costly upgrade than the addition of insulation on the exterior side, therefore, the recommendation for R-12 Polyiso insulation underneath the sheathing is considered appropriate as determined by investigation for Group 10. Insulation retrofit unfinished attic to a R-25 blown-in insulation is considered appropriate as it is much more thermal resistant then the existing insulation (R-3) and the cost for the upgrade is offset by the energy savings it provides. The upgrade in envelope tightness from very leaky to leaky reflects about a 22% increase in enclosure tightness and is considered appropriate (Berry & Brown, 1994; Judkoff, Hancock, Franconi, Hanger, &

Weiger, 1988). The non-upgrades to other parameters are as expected as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

Using the optimized building enclosure parameters listed in Table 20 HVAC optimization simulations were performed in separate cases. The results form each of those cases are superimposed onto graphs illustrating the AERC in terms of site energy savings (see Fig. 84) and source energy savings (see Fig. 85) along side their respective least cost fit lines. Comparison of the two graphs shows critical differences in values between site and source energy savings especially in the cases involving the mini-split and ground-source heat pumps as expected.

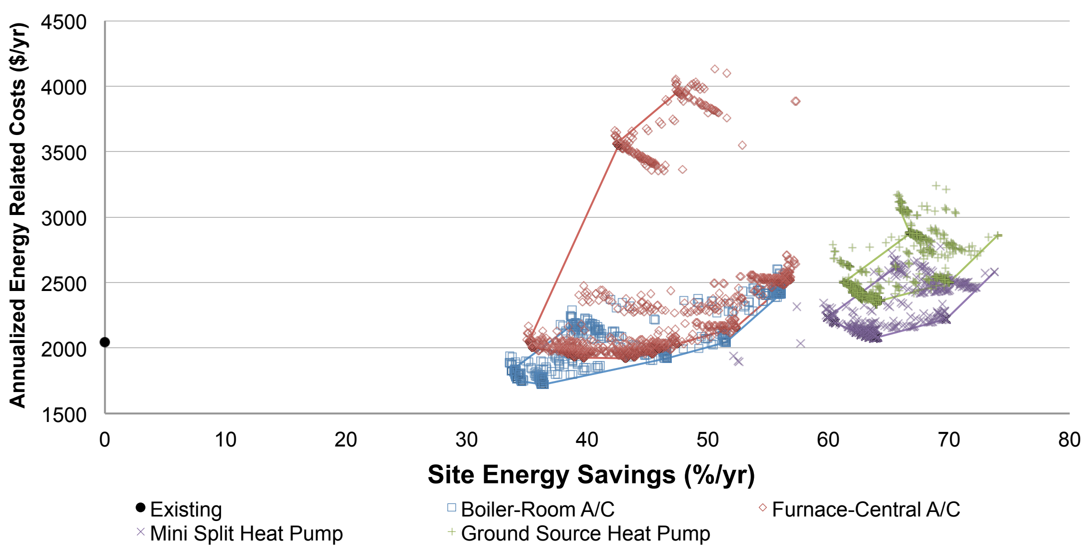


Figure 84. Group 14: HVAC optimization results in terms of site energy savings

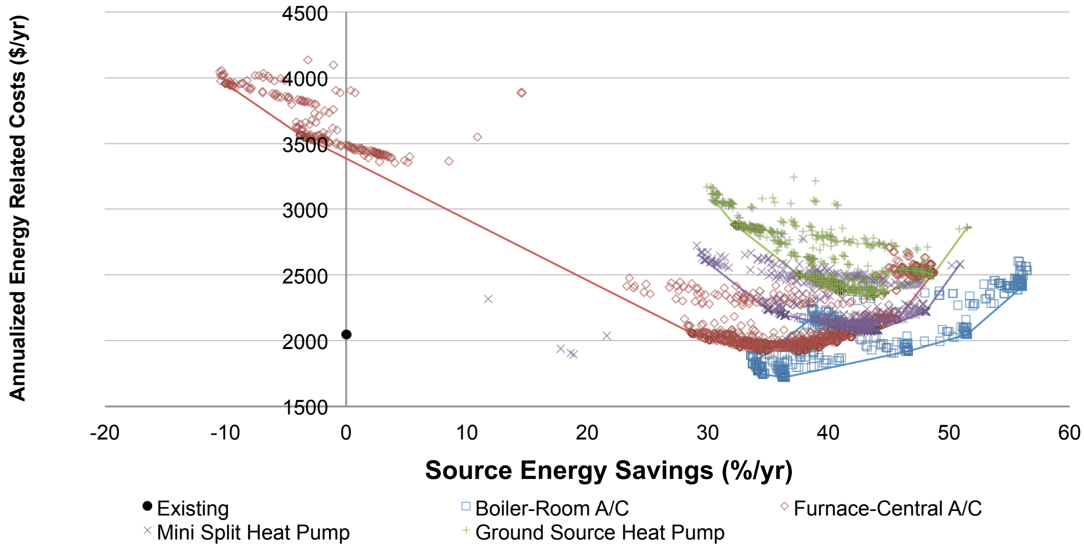


Figure 85. Group 14: HVAC optimization results in terms of source energy savings.

From the results shown in Figure 84 it can be seen that the options chosen for optimization all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case with an exception of the Boiler-Room A/C case. The iteration associated with 50% site energy savings for the Boiler-Room A/C case shows to have a slightly lower annualized energy related cost than the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated 63% site energy savings.

The parameter options of optimal iteration points chosen for continued investigation and their associated cost and energy savings are listed in Table 21. Note that the Boiler-Room A/C has the lowest AERC and is about $110/yr less than the existing, although it is not represented as having the lowest initial cost.

Table 21. (Page 1 of 2) Group 14: Frame, Pre-1942, 1 to 1.5 stories - Parameter options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 8, Pt 4**	Furnace-Central A/C: Iter 8, Pt 43**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 38**
Central A/C	None	None	SEER 16 (2 Stage)	None	None
Room A/C	EER 10	EER 10.7, 20% Conditioned	None	None	None
Furnace	None	None	Gas, 98% AFUE	None	None
Boiler	Gas, Hot Water, Forced, 80% AFUE	Gas, Hot Water, Condensing, 98% AFUE	None	None	None
Electric Baseboard	None	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	None	None	15% Leakage, R-6, 50% Surface Area, 1 Return (Unfinished Basement)	None	15% Leakage, R-6, 50% Surface Area, 1 Return (Unfinished Basement)

Table 21. (Page 2 of 2) Group 14: Frame, Pre-1942, 1 to 1.5 stories - Parameter options, costs, and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 8, Pt 4**	Furnace-Central A/C: Iter 8, Pt 43**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 38**
Ceiling Fan***	None	None	None	None	None
Water Heater	Gas, 54% EF	No Change	No Change	No Change	No Change
Solar Water Heating	None	None	None	None	None
SWH Azimuth	N/A	N/A	N/A	N/A	N/A
SWH Tilt	N/A	N/A	N/A	N/A	N/A
Lighting	Benchmark	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in
Initial Cost ($)	$0	$13,013	$14,560	$9,839	$19,059
Annualized Energy Related Costs ($/yr)	$2,047	$1,935	$1,968	$2,086	$2,344
% Site (Source) Savings	0	51.7(46.3)	50.4(43.8)	59.1(36.1)	59.4(36.6)

It is observed the addition of ceiling fans were not considered a cost effective upgrade for any of the cases. The addition of a solar water heating system was also not considered to be a cost effective upgrade for any of cases in this group.

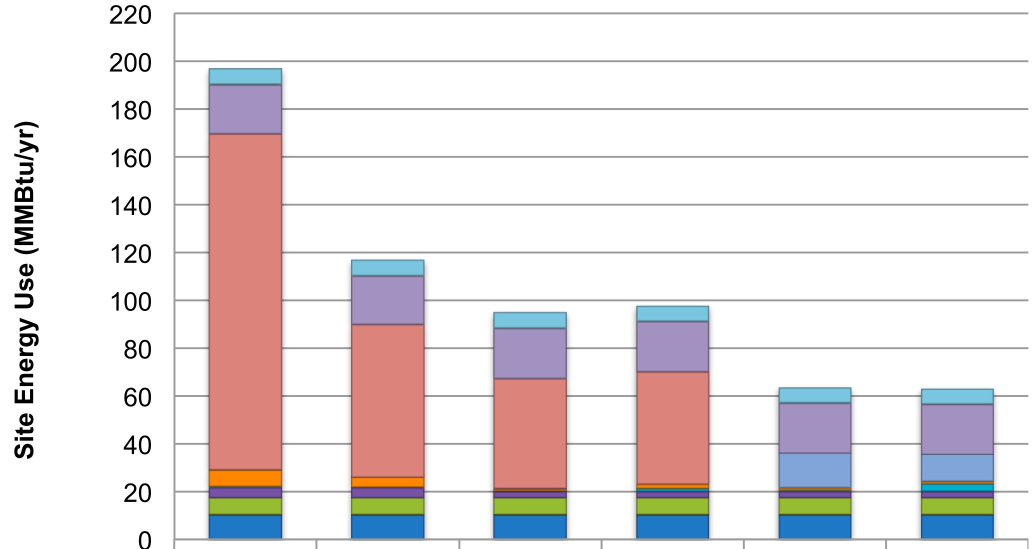
For the Boiler-Room A/C optimization case, the room air conditioner was upgraded from a EER 10, conditioning 100% of the home, to a EER 10.7 with only 20% of the home conditioned. The boiler was upgraded to a 98% AFUE condensing boiler. Note that existing radiators may not be compatible with this upgrade and the estimated costs associated may not reflect a need for replacements. No changes to the existing water heater were suggested.

For the Furnace–Central A/C case, BEopt optimized an upgrade to a gas, 98% AFUE furnace from the existing, and an upgrade to a 16 SEER (2 stage) central A/C are considered appropriate recommendations. BEopt recommends for installation to stay in its existing location and be insulated 15% Leakage (typical), R-6, 50% Surface Area, 1 Return (Unfinished Basement).

For the case involving the optimization of a MSHP system, BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

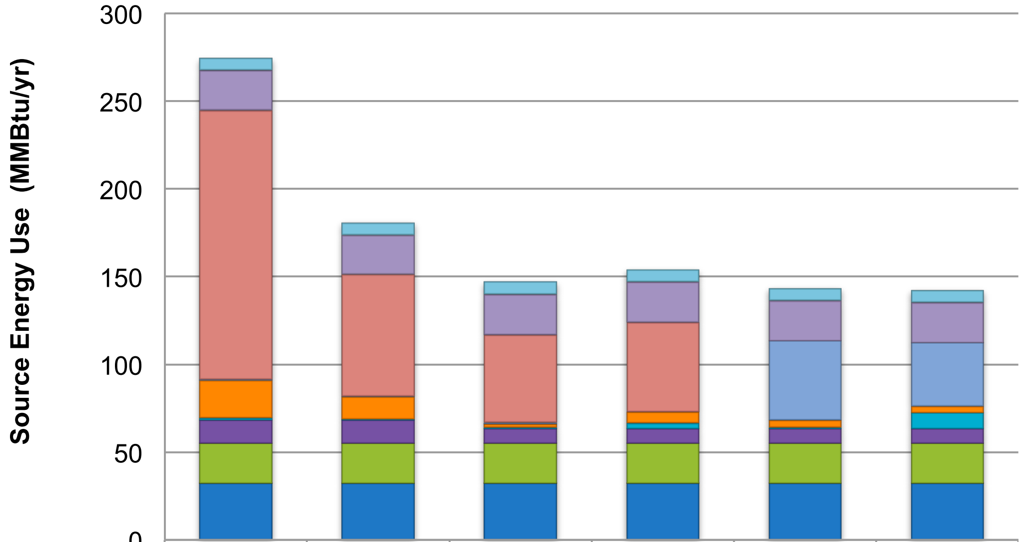
BEopt simulated that the optimal GSHP unit to be EER 20.2, COP 4.2, High-k soil, Enh grout between the pipes and the ground. BEopt recommends for installation to stay in its existing location and be insulated 15% Leakage (typical), R-6, 50% Surface Area, 1 Return (Unfinished Basement). An upgrade to the water heater was not recommended. As with all other cases for this group, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 86 shows estimated site energy usage of the packages listed in Tables 20 and 21 while Figure 87 shows estimated source energy usage. It can be observed that both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 86) and the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 87).



	Today	Enclosure: Iter 8, Pt 33**	Boiler-Room A/C: Iter 8, Pt 4**	Furnace-Central A/C: Iter 8, Pt 43**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 38**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	20.59	20.48	21.12	20.95	21.12	20.90
Hot Water (E)	0.00	0.00	0.00	0.00	0.00	0.00
Heating (G)	140.38	63.81	46.10	46.99	0.00	0.00
Heating (E)	0.29	0.13	0.13	0.00	14.32	11.55
Cooling (E)	6.69	4.08	0.75	1.95	1.27	1.15
HVAC Fan/Pump (E)	0.53	0.23	0.23	1.06	0.29	2.88
Lights (E)	4.05	4.05	2.62	2.62	2.62	2.62
Lg. Appl. (E)	7.20	7.20	7.20	7.20	7.20	7.20
Vent Fan (E)	0.06	0.06	0.06	0.06	0.06	0.06
Misc. (E)	10.18	10.18	10.18	10.18	10.18	10.18

Figure 86. Group 14: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 8, Pt 33**	Boiler-Room A/C: Iter 8, Pt 4**	Furnace-Central A/C: Iter 8, Pt 43**	MSHP: Iter 6, Pt 7**	GSHP: Iter 9, Pt 38**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	22.44	22.32	23.02	22.84	23.02	22.78
Hot Water (E)	0	0	0	0	0	0
Heating (G)	153.02	69.55	50.25	51.22	0	0
Heating (E)	0.93	0.4	0.4	0	45.13	36.41
Cooling (E)	21.08	12.87	2.35	6.15	3.99	3.6
HVAC Fan/Pump (E)	1.68	0.72	0.72	3.32	0.91	9.07
Lights (E)	12.76	12.76	8.27	8.27	8.27	8.27
Lg. Appl. (E)	22.72	22.72	22.72	22.72	22.72	22.72
Vent Fan (E)	0.18	0.18	0.18	0.18	0.18	0.18
Misc. (E)	32.11	32.11	32.11	32.11	32.11	32.11

Figure 87. Group 14: Source energy use of critical optimal iteration points

Figure 88 illustrates the simple payback periods for each of the cases. It can be inferred that the cases involving the Boiler-Room A/C and Furnace-Central A/C have the expected payback period of less than 20 years followed by MSHP at about 35 years, and may be more desirable retrofit packages than the GSHP case which has an expected payback period of more than 70 years.

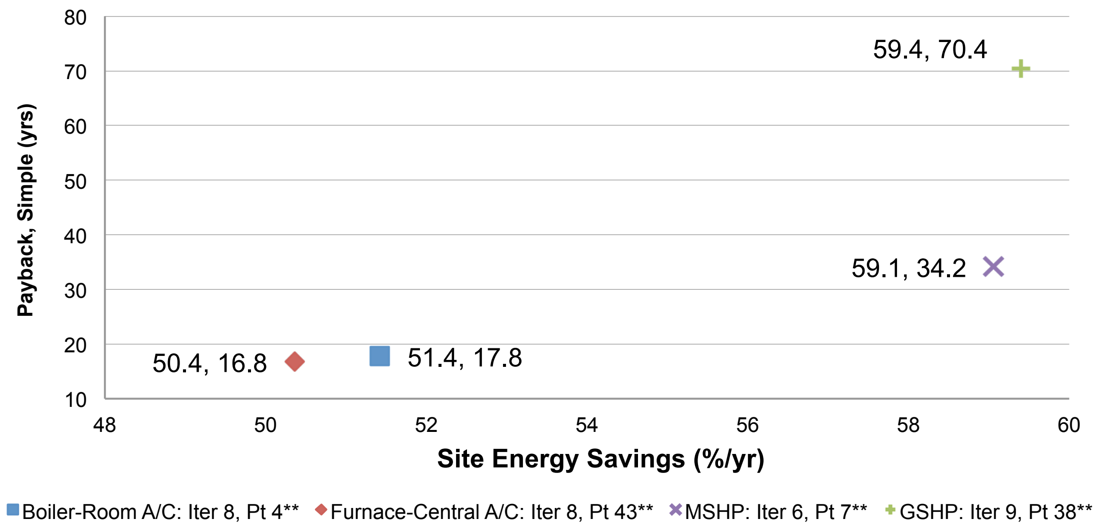


Figure 88. Group 14: Simple Payback of critical optimal iteration points

Figure 89 illustrates the Modified Internal Rate of Return (MIRR) for all the cases. It can be deduced that the case that is expected to have the highest MIRR is the Boiler-Room A/C case, followed by the Furnace-Central A/C and the MSHP cases.

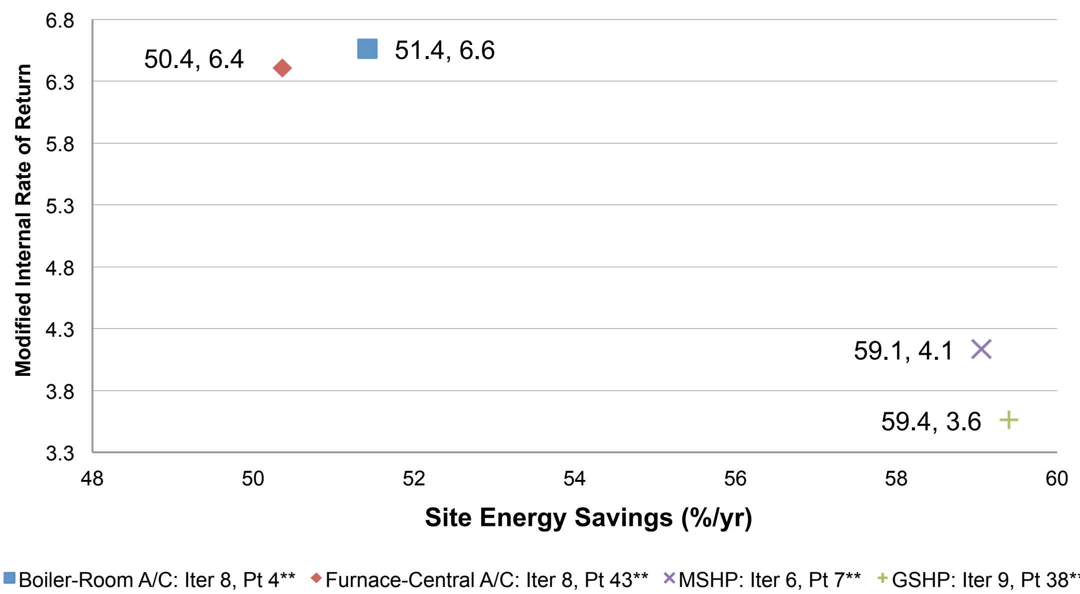


Figure 89. Group 14: Modified Internal Rate of Return of critical optimal iteration points

Through analyses of all the figures given for group 14 it is concluded that an upgrade to the Boiler system is the most cost effective option toward a 50% site energy reduction, having the lowest payback period and highest MIRR.

Group 15: Frame, Pre-1942, 2 stories Group 15 has measured mean square footage of 2058 ft^2 and was modeled in BEopt in accordance to the limitations of the lot size assumptions made by PARR (Spanier, Scheu, Brand, & Yang, 2012) to have a square footage of 2064 ft^2. The floor layouts and exterior 3d image of the BEopt model for this group are shown in Figure 90.

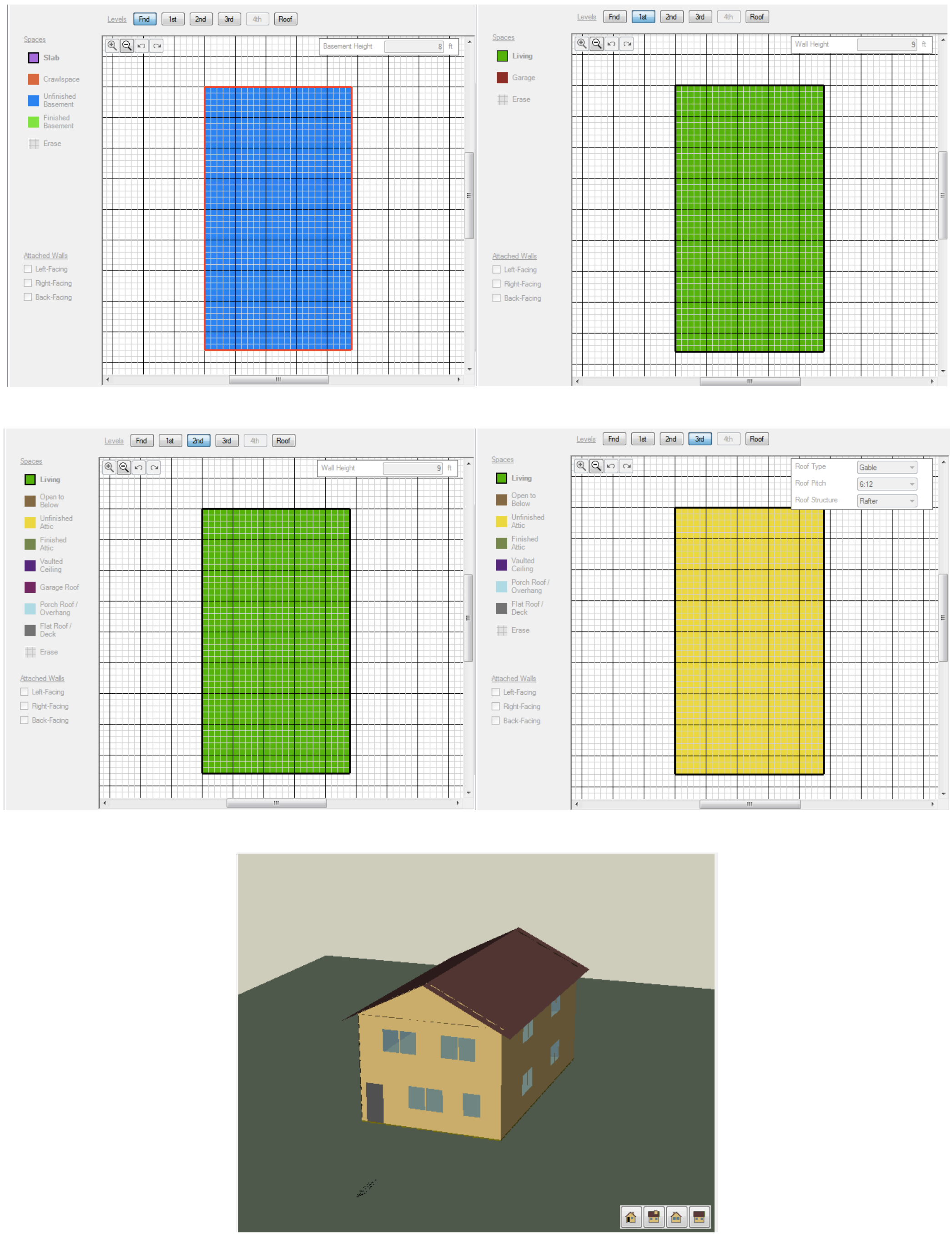


Figure 90. Group 15: BEopt model: foundation, first, and second (attic) floor layouts and 3d view

The iteration points resulting from the building enclosure optimization shown in terms of annualized energy related cost versus site energy savings and their corresponding positions in terms of annualized energy related cost versus source energy savings along with their least cost lines can be seen in Figures 91 and 92 respectively. It can be observed that a site energy savings of about 38% (least cost option) simply by updating the enclosure and keep existing HVAC systems. This translates to about a 32% source energy savings. Also, the least cost iteration point is reported as having an AERC of about $300/yr less than the existing.

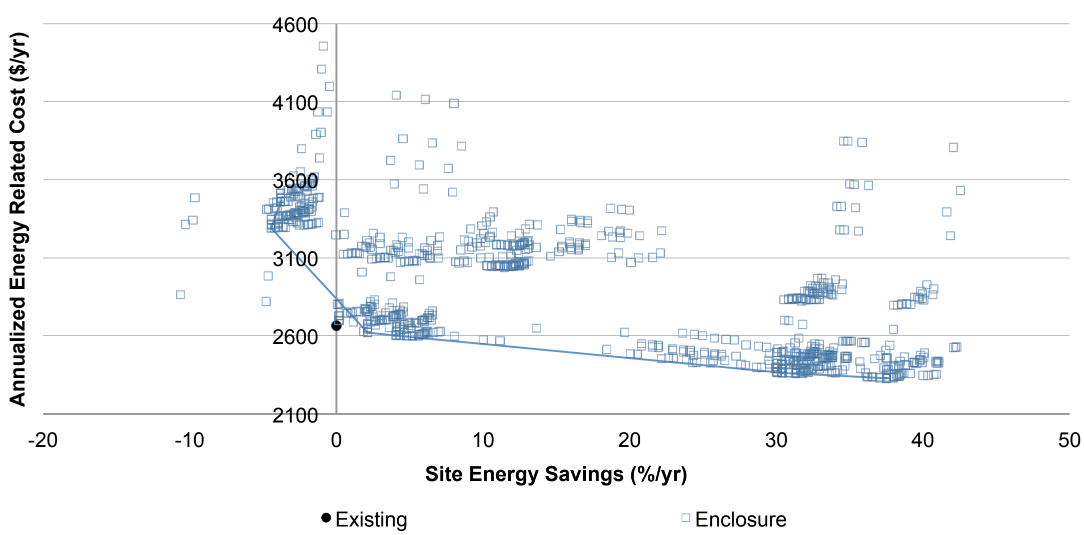


Figure 91. Group 15: Building Enclosure optimization results in terms of sites energy savings

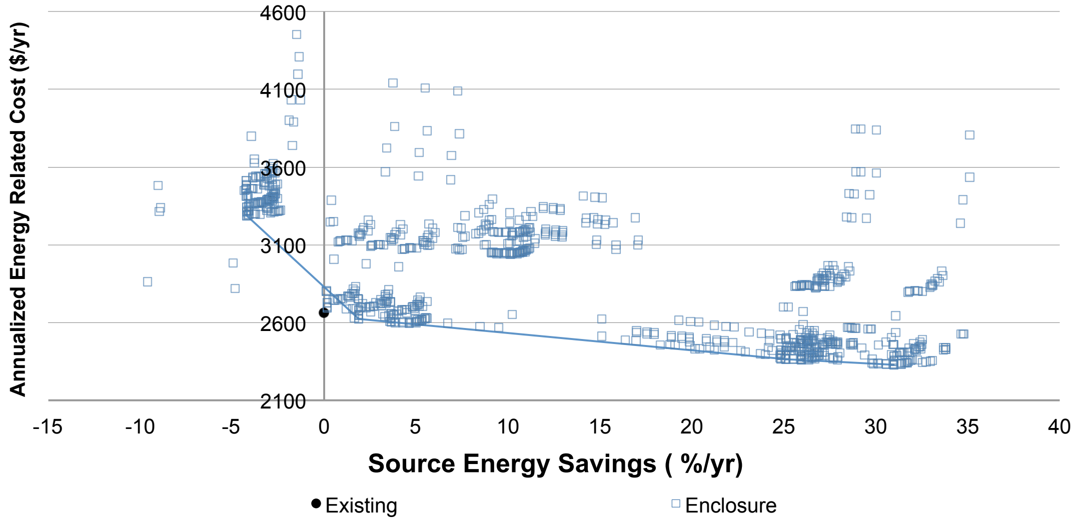


Figure 92. Group 15: Building Enclosure optimization results in terms of source energy savings.

Table 22 lists the original 'Today' scenario assumptions for the optimized building enclosure parameters and the upgrades associated with the option that provided the maximum energy savings and least cost for both site and source energy savings curves. For this residential building group, the optimal option involves upgrades to the wall sheathing, unfinished attic insulation, and air leakage only. The parameters chosen to analyze any addition of insulation to the interior side of the wall were shown to be a more costly upgrade than the addition of insulation on the exterior side, therefore, the recommendation for the installation of R-12 Polyiso insulation underneath the exterior siding is considered appropriate. An upgrade to R-30 insulation is cost effective as it is more thermal resistant than the existing (R-7). The upgrade in envelope tightness from leaky to typical reflects about a 22% increase in enclosure tightness. The non-upgrades to other parameters are as expected as the costs to upgrade these parameters are not offset by the minimal energy savings they provide.

Table 22. Group 15: Optimal Building Enclosure: Optimized Parameters, 'Today' scenario assumptions, and BEopt upgrades.

Parameter name	'Today'	Enclosure: Iter 9, Pt 57
Exterior Wall (Wood Stud)	Uninsulated, 2x4, 16 in O.C.	No Change
Wall Sheathing	None****	R12- Polyiso
Exterior Finish	Wood Siding, Light	No Change
Unfinished Attic	Ceiling R-7 Fiberglass (Blown-in), Vented	Ceiling R-30 Fiberglass Batt, Vented
Roof Material	Asphalt Shingles, Medium	No Change
Radiant Barrier	None	No Change
Unfinished Basement	Uninsulated	No Change
Window Type	Double Clear (Window + Storm)	No Change
Air Leakage*	Leaky	Typical
Mechanical Ventilation	None	No Change

The results form the optimizations of each of HVAC systems after the implementation of the optimal enclosure are reported as graphs illustrating the AERC in terms of site energy savings (see Fig. 93) and source energy savings (see Fig. 94) and their respective least cost fit lines. Comparison of the two graphs shows critical differences in values between site and source energy savings especially in the cases involving the mini-split and ground-source heat pumps as expected.

From the results shown in Figure 93 it is observed that the options chosen for optimization all HVAC cases formulate packages that either reach and/or exceed an estimated 50% site energy savings at an additional annualized energy related cost to the existing case. The iterations that represent 50% site energy savings for the Boiler-Room A/C and Furnace-Central A/C cases are available at an annualized energy related cost lower than the existing case. Moreover, the cases involving the mini-split and ground-source heat pumps not only reach or exceed an estimated 50% site energy savings but both of their least cost options equate to about an estimated 60% site energy savings.

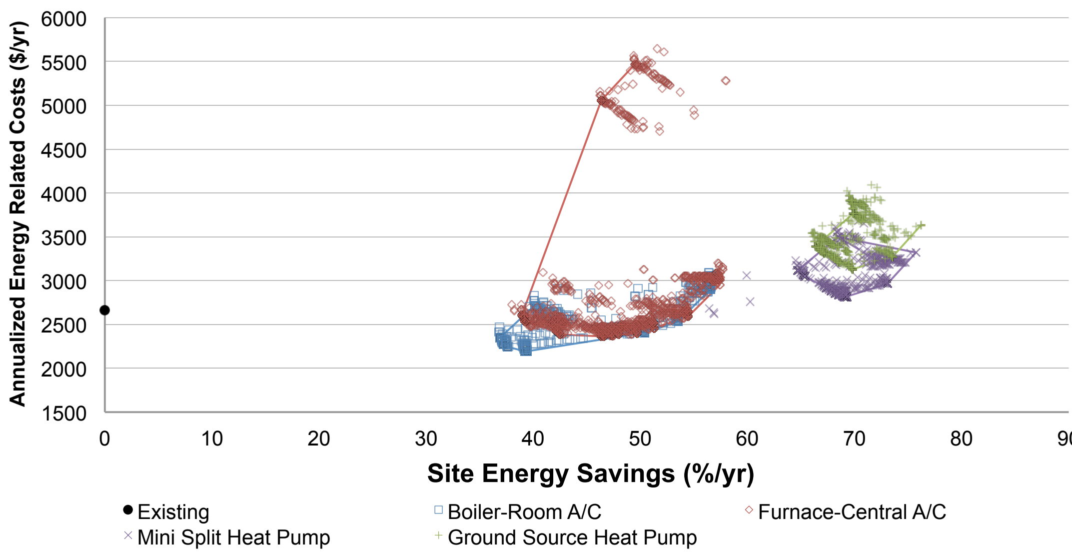


Figure 93. Group 15: HVAC optimization results in terms of site energy savings

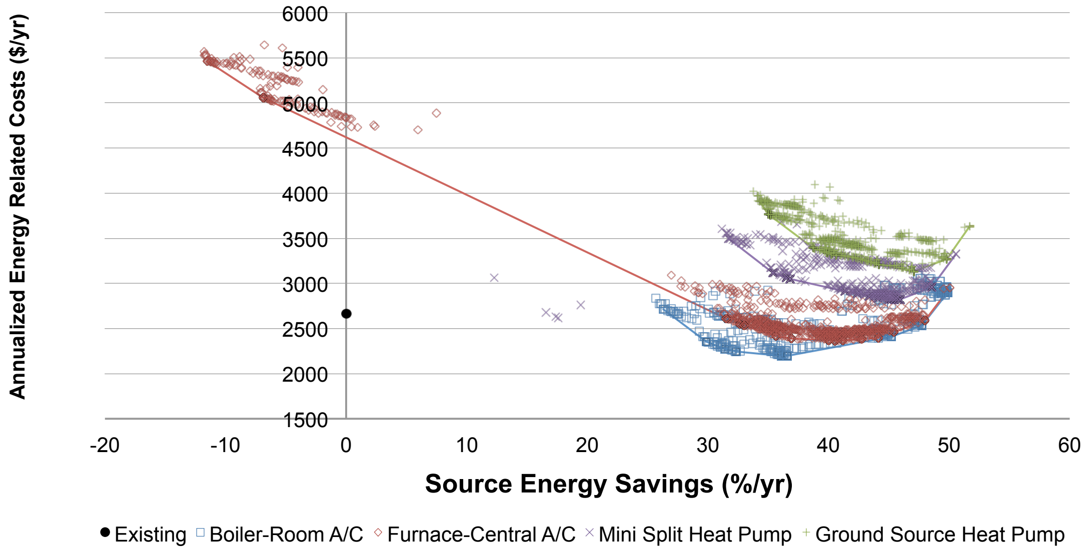


Figure 94. Group 15: HVAC optimization results in terms of source energy savings.

The iteration points considered for continued analysis and their associated AERC, initial costs, and energy savings, along side the ‘Today’ case are listed in Table 23. It is observed that the Boiler-Room A/C is reported to have the least initial costs and an AERC that is about $250/y less than the existing case

Table 23. (Page 1 of 2) Group 15: Frame, Pre-1942, 2 stories - Parameter options, costs and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 5, Pt 4**	Furnace-Central A/C: Iter 11, Pt 81**	MSHP: Iter 4, Pt 10**	GSHP: Iter 8, Pt 55**
Central A/C	None	None	SEER 24.5	None	None
Room A/C	EER 10	EER 10.7, 20% Conditioned	None	None	None
Furnace	None	None	Gas, 98% AFUE	None	None
Boiler	Gas, Hot Water, Forced Draft, 80% AFUE	Gas, Hot Water, Condensing, 98% AFUE	None	None	None
Electric Baseboard	None	None	None	100% Efficiency	None
Mini Split Heat Pump	None	None	None	SEER 23, 11.1 HSPF	None
Ground Source Heat Pump	None	None	None	None	EER 20.2, COP 4.2, High-k soil, Enh grout
Ducts	None	None	In Finished Space	None	In Finished Space

Table 23. (Page 2 of 2) Group 15: Frame, Pre-1942, 2 stories - Parameter options, costs and energy savings for critical iteration points for all cases

Parameter Name	'Today'	Boiler-Room A/C: Iter 5, Pt 4**	Furnace-Central A/C: Iter 11, Pt 81**	MSHP: Iter 4, Pt 10**	GSHP: Iter 8, Pt 55**
Ceiling Fan***	None	None	None	None	None
Water Heater	Gas, 54% EF	Gas Tankless, Condensing	Gas Tankless, Condensing	No Change	No Change
Solar Water Heating	None	None	None	None	None
SWH Azimuth	N/A	N/A	N/A	N/A	N/A
SWH Tilt	N/A	N/A	N/A	N/A	N/A
Lighting	Benchmark	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in	100% Fluorescent, Hardwired & Plug-in
Initial Cost ($)	$0	$16,647	$19,155	$16,434	$30,733
Annualized Energy Related Costs ($/yr)	$2,664	$2,407	$2,398	$2,820	$3,131
% Site (Source) Savings	0	50.2(44.7)	49.7(44.1)	69.2(45.7)	69.8(47.1)

It is observed the addition of ceiling fans were not considered a cost effective upgrade for any of the cases. The addition of a solar water heating system was also not considered to be a cost effective upgrade for any of cases in this group.

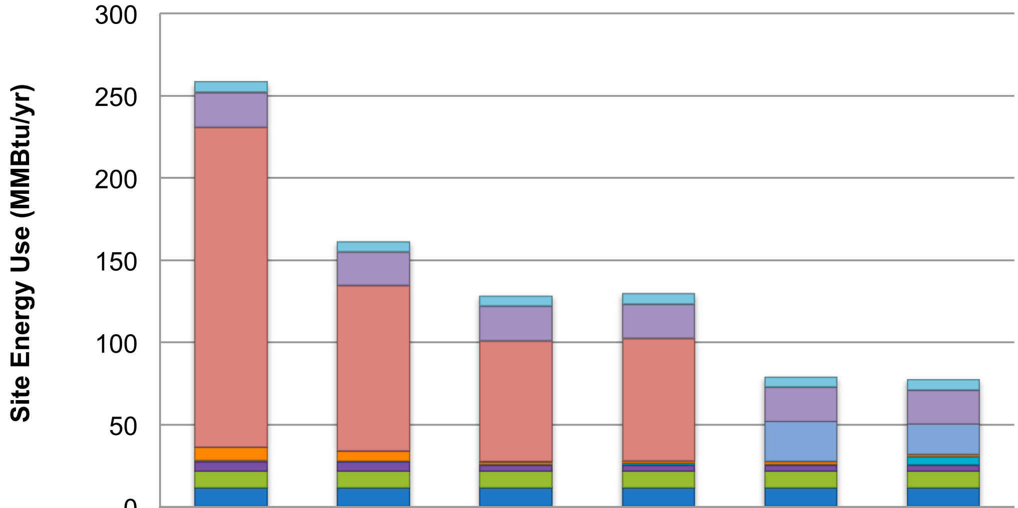
For the Boiler-Room A/C optimization case, the room air conditioner was upgraded EER 10, conditioning 100% of the home, to a EER 10.7 with only 20% of the home conditioned. The boiler was upgraded to a 98% AFUE condensing boiler. Note that existing radiators may not be compatible with this upgrade as a number of homes in this group are outfitted with standard cast iron radiators. BEopt optimized a tankless condensing water heater as an upgrade from the existing water heater. User behavior may need to adapt to accommodate this retrofit to ensure fulfillment of hot water loads.

The Furnace–Central A/C case optimized with the same upgrade to the hot water heating system and lighting parameters as the Boiler-Room A/C case. The installation of a gas, 98% AFUE furnace is an appropriate recommendation. The recommendation to install ducts in finished space is practical since installation within the walls is more difficult in homes without pre-conceived space dedicated for ductwork. As with the Boiler-Room A/C case, the Furnace-Central A/C case is optimized with a tankless condensing water heater as well.

For the case involving the optimization of a MSHP system, BEopt recommended the installation of a SEER 23, 11.1 HSPF, with 100% efficient electric baseboard heaters as supplemental heat. BEopt suggested no upgrade to the existing hot water heater as the cost to upgrade is not offset by the energy related cost savings.

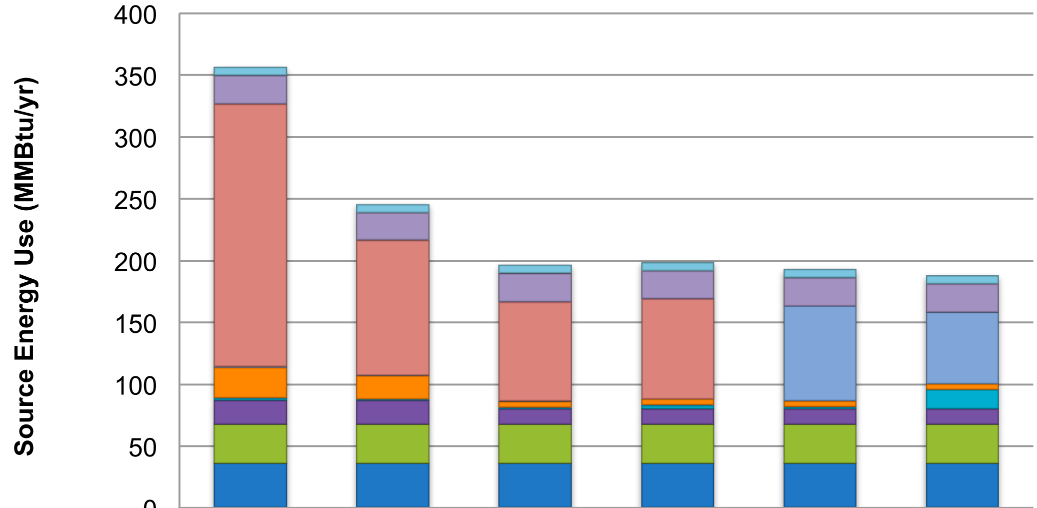
BEopt simulated that the optimal GSHP unit is an EER 20.2, COP 4.2, high-k soil, Enh grout unit. BEopt recommends for installation to be within the finished space. An upgrade to the water heater was not recommended because the initial cost to upgrade is not offset by energy related cost savings. As with all other cases, a conversion for 100% of hardwired and plug-in lighting to fluorescent is recommended.

Figure 95 shows estimated site energy usage of the packages listed in Tables 22-23 while Figure 96 shows estimated source energy usage. It can be observed that both heat pumps (i.e. mini-split and ground-source) are expected to consume less energy on site (see Fig. 95) and that the conversion of the heat load from gas consuming to electric consuming adds to energy consumption at the source (see Fig. 96).



	Today	Enclosure: Iter 9, Pt 57	Boiler-Room A/C: Iter 5, Pt 4**	Furnace-Central A/C: Iter 11, Pt 81**	MSHP: Iter 4, Pt 10**	GSHP: Iter 8, Pt 55**
Lg. Appl. (G)	6.52	6.52	6.52	6.52	6.52	6.52
Hot Water (G)	21.13	20.39	21.02	20.73	21.03	21.00
Hot Water (E)	0.00	0.00	0.00	0.00	0.00	0.00
Heating (G)	194.01	100.31	73.46	74.55	0.00	0.00
Heating (E)	0.30	0.15	0.15	0.00	24.30	18.32
Cooling (E)	7.84	6.05	1.66	1.52	1.67	1.67
HVAC Fan/Pump (E)	0.74	0.36	0.37	1.07	0.47	4.83
Lights (E)	5.98	5.98	3.88	3.88	3.88	3.88
Lg. Appl. (E)	10.03	10.03	10.03	10.03	10.03	10.03
Vent Fan (E)	0.08	0.08	0.08	0.08	0.08	0.08
Misc. (E)	11.36	11.36	11.36	11.36	11.36	11.36

Figure 95. Group 15: Site energy use of critical optimal iteration points



	Today	Enclosure: Iter 9, Pt 57	Boiler-Room A/C: Iter 5, Pt 4**	Furnace-Central A/C: Iter 11, Pt 81**	MSHP: Iter 4, Pt 10**	GSHP: Iter 8, Pt 55**
Lg. Appl. (G)	7.11	7.11	7.11	7.11	7.11	7.11
Hot Water (G)	23.02	22.22	22.91	22.59	22.91	22.89
Hot Water (E)	0	0	0		0	0
Heating (G)	211.47	109.33	80.07	81.26	0	0
Heating (E)	0.95	0.46	0.47	0	76.58	57.75
Cooling (E)	24.71	19.04	5.22	4.8	5.27	5.25
HVAC Fan/Pump (E)	2.33	1.14	1.16	3.36	1.5	15.23
Lights (E)	18.84	18.84	12.21	12.21	12.21	12.21
Lg. Appl. (E)	31.64	31.64	31.64	31.64	31.64	31.64
Vent Fan (E)	0.25	0.26	0.26	0.26	0.26	0.26
Misc. (E)	35.81	35.81	35.81	35.81	35.81	35.81

Figure 96. Group 15: Source energy use of critical optimal iteration points

Figure 97 illustrates the simple payback periods for each of the optimal packages for Group 15. It can be inferred that the cases involving the boiler, furnace, and MSHP have the expected payback period of less than 30 years and may be more desirable retrofit packages than the GSHP case which has an expected payback period of nearly 90 years.

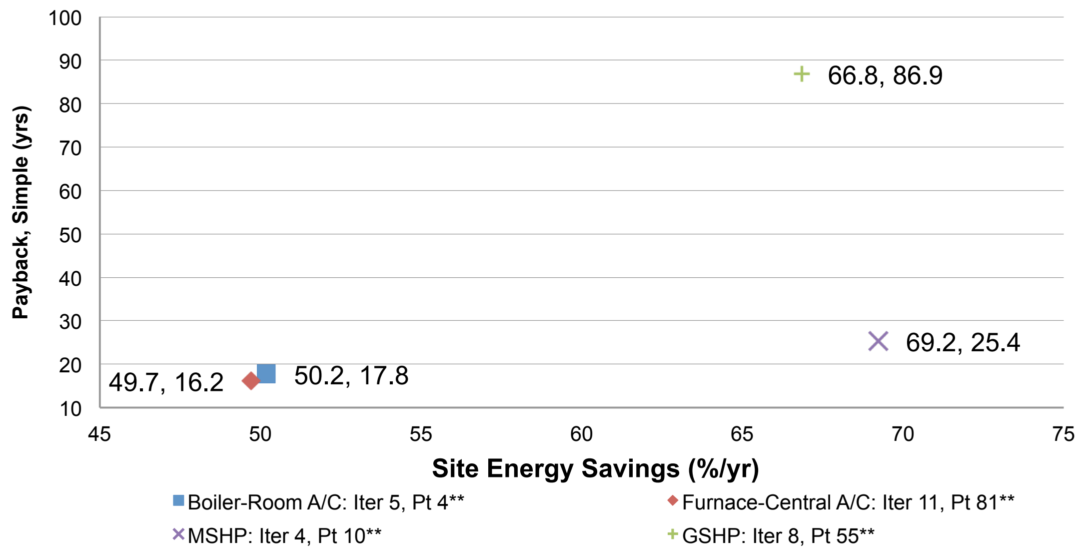


Figure 97. Group 15: Simple Payback of critical optimal iteration points

Figure 98 illustrates the Modified Internal Rate of Return for each of the optimal packages. It can be deduced that the case that is expected to have the highest MIRR is the Boiler-Room A/C case, followed by the Furnace-Central A/C and the MSHP cases.

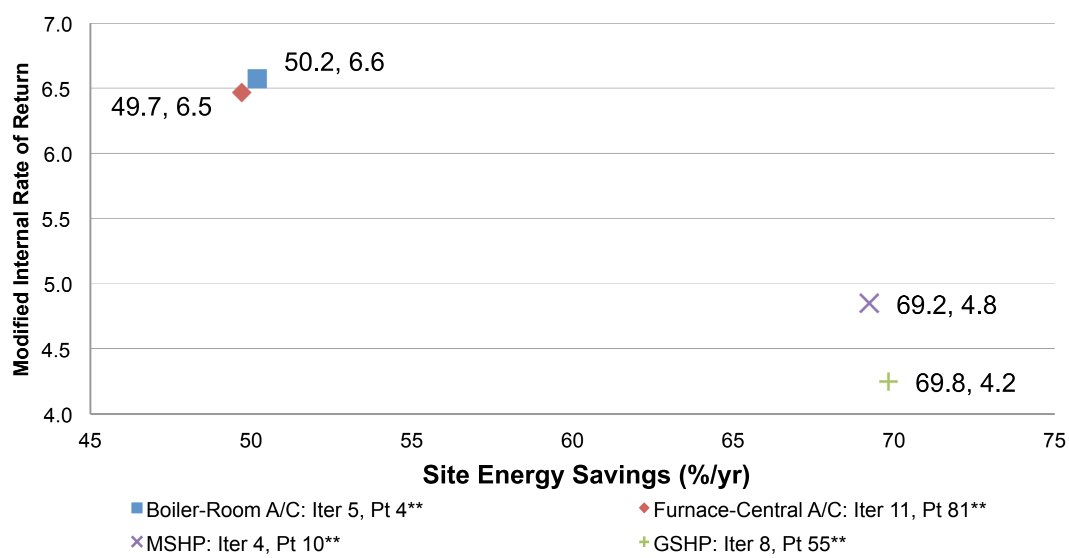


Figure 98. Group 15: Modified Internal Rate of Return of critical optimal iteration points

Through analyses of all the figures given for Group 15 it is concluded that an upgrade to the boiler system is the most cost effective option toward a 50% site energy reduction as it represents the option that has the lowest payback period and highest MIRR.

4.2 Generalizing the Data and Developing Standardized Retrofit Packages

Upon analyzing the various optimal packages for each of the groups, many similarities between several to all of the groups were observed. The parameters that were optimized for the appropriate groups and the classification of the results are listed and detailed in Table 24.

Table 24. (Page 1 of 2) Summary of parameter changes for each group.

Parameter Name	Group Number									
	Brick					Frame				
	4	5	6	7	8	10	12	13	14	15
Exterior Wall (Wood Stud)	N/A	N/A	N/A	N/A	N/A	--	--	--	--	--
Exterior Wall (Brick)	X	X	X	X	X	N/A	N/A	N/A	N/A	N/A
Wall Sheathing	N/A	N/A	N/A	N/A	N/A	X	X	X	X	X
Exterior Finish	--	--	--	--	--	--	--	--	--	--
Interzonal Walls	--	X	X	X	N/A	X	N/A	N/A	N/A	N/A
Unfinished Attic	X	X	X	X	X	X	X	X	X	X
Finished Roof	--	N/A	N/A	--	N/A	--	N/A	N/A	N/A	N/A
Roof Material	--	--	--	--	--	--	--	--	--	--
Radiant Barrier	--	--	--	--	--	--	--	--	--	--
Unfinished Basement	N/A	--	--	--	--	--	--	--	--	--
Interzonal Floor	N/A	--	N/A	--	N/A	N/A	--	N/A	N/A	N/A
Window Type	--	--	--	--	--	--	--	--	--	--
Air Leakage*	X	X	X	X	X	X	X	X	X	X
Mechanical Ventilation	--	--	--	--	--	--	--	--	--	--
Central A/C	/	/	/	/	/	/	/	/	/	/
Room A/C	N/A	N/A	N/A	/	/	/	N/A	N/A	/	/
Furnace	/	/	/	/	/	/	/	/	/	/
Boiler	N/A	N/A	N/A	/	/	/	N/A	N/A	/	/
Electric Baseboards	/	/	/	/	/	/	/	/	/	/
MSHP	/	/	/	/	/	/	/	/	/	/
GSHP	/	/	/	/	/	/	/	/	/	/

Table 24. (Page 2 of 2) Summary of parameter changes for each group.

Parameter Name	Group									
	Brick					Frame				
	4	5	6	7	8	10	12	13	14	15
Ducts	/	/	/	/	/	/	/	/	/	/
Ceiling Fan***	--	--	--	--	--	--	--	--	--	--
Water Heater	/	/	/	/	--	/	/	/	--	/
Solar Water Heating	--	/	--	/	--	--	/	/	--	--
SWH Azimuth	--	/	--	/	--	--	/	/	--	--
SWH Tilt	--	/	--	/	--	--	/	/	--	--
Lighting	X	X	X	X	X	X	X	X	X	X

N/A This parameter was not optimized for this group.
X This parameter was optimized and the result applies to all HVAC cases in this group.
/ This parameter was optimized and the result applies to only some of the HVAC cases in this group.
-- This parameter was optimized and resulted in no change from the existing for all HVAC cases in this group.

From this information, cross-referenced with Tables 4-23, several generalizations can be made about the retrofit suggestions that can be made to all groups regardless of optimal HVAC system and exterior wall construction; all groups for the same HVAC case regardless of exterior wall construction; all groups of brick exterior wall construction; or all groups of wood frame exterior wall construction.

The generalizations that can be made for all groups regardless of optimal HVAC system and exterior wall construction are as follows:

- No changes to the exterior finish, radiant barrier (roof), roof material, unfinished basement, window type, or presence of ceilings fans were suggested for any of the groups. This may be because either the cost to upgrade these parameters is not offset by potential energy savings or an upgrade to any of these parameters results a negative impact on the energy efficiency of the building. The lack of insulation in the basement is inconsistent with modern energy codes as R-13 continuous insulation on the interior or exterior of the home or R-19 cavity insulation at the interior of the basement wall is the requirement (International Code Council, 2011).

- An unfinished attic insulation upgrade or installation having a minimum R-value of 19 is recommended for all groups. This inconsistent with modern code requirements of R-49 for new residential ceiling (attic) (International Code Council, 2011). In some groups, insulation with a higher R-value was suggested. The installation of insulation with a high thermal resistance (R-Value) can dramatically increase the energy efficiency of a building as it reduces the heating and cooling load by mitigating heat transfer through the attic space.
- Where appropriate, an upgrade to the finished roof or interzonal floor insulations were not suggested for any group. This may be because the cost to upgrade insulation in these areas was not offset by the energy savings or the existing case was adequately insulated relative to the reduction target.
- An upgrade in air leakage in the form of a step up from each groups' corresponding existing enclosure tightness is recommended for all groups as it is an inexpensive way to improve the energy efficiency of a building as it reduces

the heating and cooling loads by mitigating some of the heat transfer through the enclosure.

- The conversion of 100% hardwired and plug-in lighting to fluorescent from benchmark lighting is recommended for all groups. This also has shown to be an inexpensive way to improve the energy efficiency of a building by reducing plug load.
-

The generalizations that can be made for all groups for the same HVAC case regardless of exterior wall construction include:

- The highest efficiency heating or combination heating units were chosen for the optimal packages for the Furnace-Central A/C, and GSHP cases, namely the Gas, 98% AFUE Furnace for the Furnace-Central A/C cases and the EER 20.2, COP 4.2, High-k soil, Enh grout unit for the GSHP cases. BEopt may have optimized these options because although some improvements would have been made to the enclosure to mitigate some thermal transfer, there still may be large heating and/or cooling loads that necessitate larger and more efficient units to not only meet such loads but use as little energy as possible while maintaining cost effectiveness. In fact, many of the groups were estimated to have unmet heating and cooling loads in all of their corresponding HVAC cases, indicating that the largest and most efficient units are undersized.
- Recommendations for ductwork to either be relocated to or installed in finished space, or insulated and sealed were made for all groups. Groups representing homes built between 1942-1978 resulted in the relocation of ductwork to finished

space. Existing ducts were initially located in the unfinished, uninsulated basement (Groups 5, 6, 12, and 13) or in the unfinished attic space (Group 4) alongside the presence of R-19 insulation. For the cases where initial ductwork was located in the unfinished, uninsulated basement, the cost to relocate ductwork was calculated by BEopt to be justified by the energy savings resultant of this retrofit. One explanation may be that since any potential leakage or heat loss from ductwork located in finished space terminates in its intended destination, thus the total leakage for this option is given as 0% of the total air flow rate. For the case of Group 4, the suggestion for ductwork to be relocated to finished space regardless of the presence of R-19 insulation in the attic is justified similarly in that any leakage of the newly located ducts terminates in its intended destination. For Groups representing homes built Pre-1942, it was recommended insulated and installed in the unfinished basement and having 15% Leakage and R-6 insulation for all GSHP simulation cases. However, instead of sealing and insulating the ducts, the relocation to finished space was recommended for the Furnace-Central A/C simulation cases for Groups 7, 10 and 15. The reason for this is undetermined and necessitates further investigation. However, it should be noted that all optimal packages chosen for each group that include ducts call for installation in finished space.

For all groups of brick exterior wall construction the following generalization can be made:

- Regardless of vintage, all exterior walls were recommended to be retrofitted with a 2x6, 24 in o.c. frame wall insulated with R-19 Fiberglass Batts on the interior side as this option was shown to be the least expensive and provides the highest thermal performance of all options that were simulated for this parameter. Note that this exceeds modern energy code requirements of R-17 mass walls (International Code Council, 2011).

For all groups of frame exterior wall construction the following generalization can be made:

- Regardless of vintage, no additional insulation was recommended within the exterior wall. Instead the addition of R-12 Polyisocyanurate rigid insulation to be installed on the exterior side underneath the siding as this provides the highest thermal performance at lower initial costs when compared to the cost to install insulation for the case of Pre-1942 homes or retrofit insulation for 1942-1978 homes. Modern energy codes as the R-20 or R-13 plus R-5 continuous is required for frame construction (International Code Council, 2011). For homes built prior to 1942 this upgrade is not compliant with the standard, but for 1942-1978 homes having R-7 insulation within existing exterior walls being the assumption, the addition of continuous R-12 Polyiso on the exterior side can be considered to be compliant with modern energy codes.

The vintage, exterior wall construction type, number of stories, and recommended retrofit package for each group is summarized in Table 25.

Table 25. Summary of group vintage, exterior wall construction type, and recommended optimal package

Group	Vintage	Exterior Wall Construction Type	# of Stories	Optimal Retrofit Package
4	1942-1978	Brick	1-1.5	MSHP Iter 6 Pt 7**
5	Pre-1978 (1924-1978)	Brick	1.5 (Split-Level)	MSHP Iter 6 Pt 9**
6	1942-1978	Brick	2	Furnace-Central A/C Iter 11 Pt 12** (Upgrade to existing)
7	Pre- 1942	Brick	1-1.5	MSHP Iter 6 Pt 7**
8	Pre- 1942	Brick	2	Boiler-Room A/C Iter 7 Pt 3** (Upgrade to existing)
10	All Years (Pre-1942)	Frame	1.5 (Split Level)	Boiler-Room A/C Iter 8 Pt 13** (Upgrade to existing)
12	1942-1978	Frame	1-1.5	MSHP Iter 6 Pt 7**
13	1942-1978	Frame	2	Furnace-Central A/C Iter 14 Pt 59** (Upgrade to existing)
14	Pre-1942	Frame	1-1.5	Boiler-Room A/C Iter 8 Pt 4** (Upgrade to existing)
15	Pre-1942	Frame	2	Boiler-Room A/C Iter 5 Pt 4** (Upgrade to existing)

It can be seen that the optimal retrofit package is either an upgrade to existing systems or the conversion to a MSHP system. Although there seems to be no relation between the type of optimal retrofit package and vintage, generalizations can be made based on exterior wall construction type and number of stories. It can be deduced that once the corresponding optimal enclosure is implemented, frame construction homes are more likely to benefit from an upgrade to existing HVAC systems (80% probability) whereas homes of brick construction are slightly more likely to benefit from a conversion to a MSHP system (60% probability). Also, 1-1.5 story homes, including split level homes are most likely to convert to MSHP systems (67% probability) whereas homes having 2 stories are most likely to upgrade existing HVAC systems (100% probability).

4.3 Summary of Predicted Energy and Monetary Savings of the Optimized Retrofit Solutions

The predicted energy savings for each group were estimated given that the optimum retrofit package was implemented. Using the resulting estimated savings, the potential energy savings for the entire Chicagoland Area was then calculated. A summary of both source and site energy savings in terms of percentage per home and MMBtu/yr per home for the optimal retrofit package for each group is listed in Table 26. An average of 53% and 42% for percentage of site and source savings, respectively, for each group can be deduced from the values in Table 26. This translates to an average of 99.7 and 110.2 MMBtu site and source savings respectively for each group. If the appropriate retrofit package was implemented in every one of home in every group in Chicagoland, the total estimated savings in terms of MMBtu/yr is detailed in Table 27 for each group.

Table 26. Summary of optimal packages and corresponding energy savings predicted for each group

Parameter Name	Group									
	Brick					Frame				
	4	5	6	7	8	10	12	13	14	15
Optimal Retrofit Package	MSHP Iter 6 Pt 7**	MSHP Iter 6 Pt 9**	Furnace-Central A/C Iter 11 Pt 12**	MSHP Iter 6 Pt 7**	Boiler-Room A/C Iter 7 Pt 3**	Boiler-Room A/C Iter 8 Pt 13**	MSHP Iter 6 Pt 7**	Furnace-Central A/C Iter 14 Pt 59**	Boiler-Room A/C Iter 8 Pt 4**	Boiler-Room A/C Iter 5 Pt 4**
Optimal Package Site Energy Savings (%)	58.2	61.6	49.9	60.6	49.9	48.9	53.3	50.1	51.7	50.2
Optimal Package Source Energy Savings (%)	39.9	40.7	45.5	37.6	45.3	42.5	30.7	44.1	46.3	44.1
Optimal Package Site Energy Savings (MMBtu/yr)	81.3	105.6	102.5	97.2	118.4	83.5	68.2	86.8	124.4	129.5
Optimal Package Source Energy Savings (MMBtu/yr)	86.5	103.4	138.8	87.6	149.6	104.9	58.4	112.8	100.5	159.3

Table 27. Summary of total energy savings predicted for each group and the Chicagoland Area

Group	% of Population†	Number of Homes	'Today' Total Site Consumption (MMBtu/yr)	'Today' Total Source Consumption (MMBtu/yr)	'Post-Retrofit' Total Site Savings (MMBtu/yr)	'Post-Retrofit' Total Source Savings (MMBtu/yr)
4	17.9	77,435	10,819,218	16,722,088	6,295,466	6,698,128
5	6.1	26,445	4,532,938	6,711,476	2,792,592	2,734,413
6	4.8	20,755	4,264,322	6,331,105	2,127,388	2,880,794
7	11.6	50,239	8,065,872	11,701,668	4,883,231	4,400,936
8	4.1	17,629	4,182,128	5,827,619	2,087,274	2,637,298
10	2.1	9,225	1,575,815	2,275,069	770,288	967,703
12	23.6	101,957	13,053,555	19,379,987	6,953,467	5,954,289
13	3.8	16,411	2,843,698	4,196,785	1,424,475	1,851,161
14	11.2	48,365	8,253,004	11,777,361	6,016,606	4,860,683
15	2.9	12,479	3,219,707	4,444,146	1,616,031	1,987,905
Chicagoland Total	88.1	380,940	60,810,255	89,367,305	34,966,816	34,973,309

† Relative to a dataset of 432,605 homes.

It can be deduced from Table 27, that by implementing the optimal retrofit packages, an estimated savings of about 35 Trillion Btu/yr can be achieved. This equates to a 58% site savings and 39% source savings for the entire pre-1978 vintage singe family residential stock of the Chicagoland area.

The monetary savings for per home in terms of site fuel type was calculated using values for average electricity and gas prices ($0.1177/kWh and $8.47/MMBtu respectively) obtained from the U.S. Energy Information Administration (U.S. Energy Information Administration, 2014; U.S. Energy Information Administration, 2014). Table 28 summarizes the results for both fuel types as well as total overall savings for each of the 10 groups (per home). If the appropriate optimal retrofit package is implemented the total average savings achievable per household is estimated to be about $906/yr.

Table 28. Summary of potential monetary savings for each home in terms of site fuel type

Group	Total Site Gas Savings (MMBtu/yr)	Total Site Gas Savings ($/yr)	Total Site Electricity savings (kWh/yr)	Total Site Electricity Savings ($/yr)	Total Savings ($/yr)
4	82.5	$699	(359)	($42)	$657
5	111.3	$943	(1,659)	($195)	$747
6	89.4	$757	3,845	$453	$1,210
7	106.1	$899	(2,604)	($306)	$592
8	108.5	$919	2,919	$344	$1,263
10	76.7	$650	1,978	$233	$882
12	75.9	$643	(2,261)	($266)	$377
13	77.8	$659	2,608	$307	$966
14	93.3	$790	2,119	$249	$1,040
15	120.7	$1,022	2,580	$304	$1,326

The potential monetary savings per group and the total for the Pre-1978 single-family residential sector (relative to the dataset of 432,605 homes) of the entire Chicagoland area is summarized in Table 29. Although an average site electricity usage savings of a negative $1,200,000/yr is observed, meaning that many groups are paying more for electricity when compared to the existing case, the average savings for site gas usage per group is $28,900,000/yr, for an overall average savings of $27,700,000/yr per group. The total potential monetary savings as a result of the total energy savings for the entire Pre-1978 single-family residential sector (relative to the dataset of 432,605 homes) of the Chicagoland area equates to about $280,000,000/yr.

Table 29. Summary of potential monetary savings for each group and the Chicagoland Area in terms of site fuel type

Group	% of Population[†]	Number of Homes	Total Site Gas Savings (MMBtu/yr)	Total Site Gas Savings ($/yr)	Total Site Electricity savings (kWh/yr)	Total Site Electricity Savings ($/yr)	Total Site Energy Savings ($/yr)
4	17.9	77,435	6,388,388	$54,109,642	(27,799,165)	($3,271,962)	$50,837,680
5	6.1	26,445	2,943,329	$24,929,992	(43,872,255)	($5,163,764)	$19,766,228
6	4.8	20,755	1,855,497	$15,716,060	79,802,975	$9,392,810	$25,108,870
7	11.6	50,239	5,330,358	$45,148,131	(130,822,356)	($15,397,791)	$29,750,340
8	4.1	17,629	1,912,747	$16,200,963	51,459,051	$6,056,730	$22,257,693
10	2.1	9,225	707,558	$5,993,012	18,247,050	$2,147,678	$8,140,690
12	23.6	101,957	7,738,536	$65,545,402	(230,524,777)	($27,132,766)	$38,412,636
13	3.8	16,411	1,276,776	$10,814,291	42,799,888	$5,037,547	$15,851,838
14	11.2	48,365	4,512,455	$38,220,490	102,485,435	$12,062,536	$50,283,025
15	2.9	12,479	1,506,215	$12,757,644	32,195,820	$3,789,448	$16,547,092
Chicagoland Total	88.1	380,940	34,171,857	$289,435,627	(106,028,334)	($12,479,535)	$276,956,092

CHAPTER 5

CONCLUSIONS

5.1 Summary of the Results

In this work, several typology groups of single-family homes in Chicagoland built prior to 1978 were considered for energy retrofit package optimization with a target of 50% site energy reduction. Simulations were conducted as a two-step process. First an optimization of the building enclosure was performed and the least cost package was applied to the model. Then optimization simulations of several HVAC system cases were performed. From the results of the second set of simulations, an optimal package was chosen for each group based on efficiency, payback period, and MIRR and the energy savings implications associated with each package was analyzed both on a single unit and Chicagoland area wide scales. Figure 99 illustrates a summary of the site energy usage values for all groups in three different scenarios (measured CNT Mean values, and the 'Today' and 'Post-Retrofit' scenarios developed in this work). It can be observed from the graph that the intentions for a minimum 50% site energy reduction were met through common retrofit measures for all groups with the optimal HVAC system being either an efficiency upgrade to the existing or a conversion to a MSHP system.

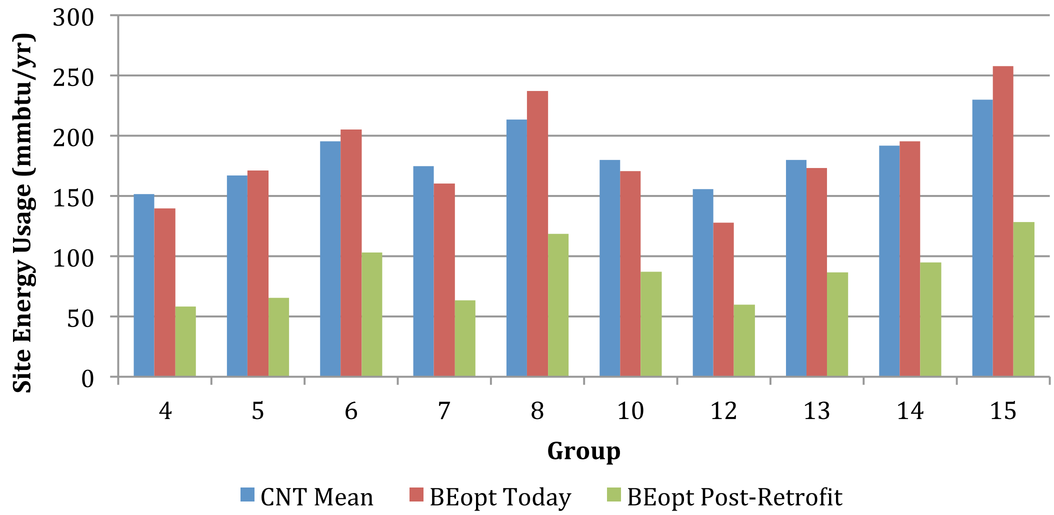


Figure 99. Summary of Site energy usage for all groups

A breakdown of site energy use by fuel type is summarized for each group across the same three scenarios is summarized in Figures 100 and 101.

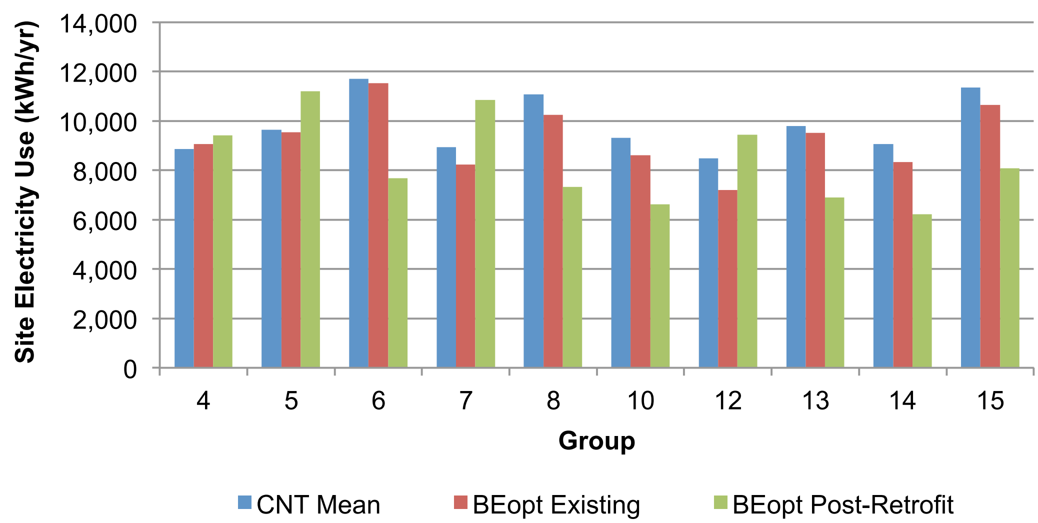


Figure 100. Summary of Site Electricity Usage for all groups

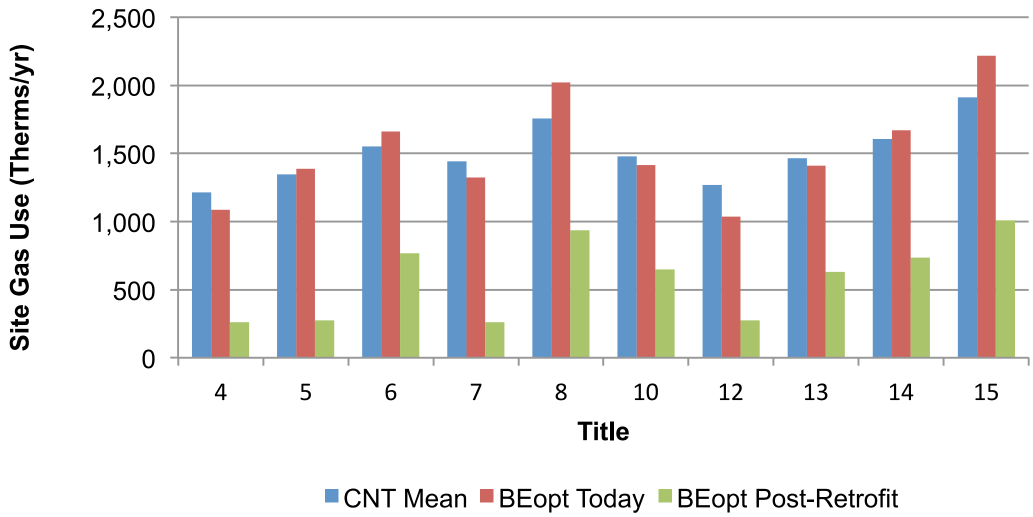


Figure 101. Summary of Site Gas Usage for all groups

Although, no significant reductions in electricity usage can be seen from Figure 100, a gross reduction in site gas usage is present for all groups indicating that for most groups a shift from gas powered heating to electric powered heating system has occurred. This shift may help facilitate a change to renewable energy sources in the future, which will further increase the sustainability of the retrofits.

5.2 Lessons Learned

In the wake of the extensive optimization processes, several lessons were learned. First, it was discovered that significant estimated energy savings could be obtained in this vintage of homes with the modifications to only a few parameters and common weatherization measures. It was also discovered that the type of HVAC retrofit could potentially be predicted as relationships between suggested retrofits and the buildings exterior construction type and/or number of stories were observed. This finding can possibly be used to quickly predict an expected optimal outcome for HVAC retrofit decisions based on building characteristics and aide in the development of standardized retrofit packages for implementation on a grand scale. Finally, the optimization process has provided insight on what could not be expected to be positive investments toward energy reduction in this particular subset of the Chicagoland building stock (e.g. the installation of newer windows, the insulating of the unfinished basement, the implementation of GSHPs, etc.)

5.3 Recommendations for Future Projects

Similar to those of the study comparing IHP measures to BEopt recommended packages (Yee, Milby, & Baker, 2014), there are concerns about the accuracy of the costs associated with the optimal retrofit packages developed in this work. There are also concerns that the default parameter option library in BEopt is rather limited and the accuracy of the costs associated with the custom options that were necessary for the modeling of this portion of the Chicagoland building stock can be considered questionable. Therefore, one recommended is for future researchers to work toward improving the accuracy of the costs associated with parameters in order to better reflect market costs and to develop a more extensive option library so that the concepts and processes detailed by this work can be applied toward the development of optimal retrofit packages more rapidly and with better accuracy. This could be done through a process that involves modeling an actual home of one or several of the groups based on the actual existing building characteristics, and conducting enclosure and HVAC system optimizations as was simulated in this work. After an appropriate optimal retrofit package is prescribed, it may then be sent to a contractor for bidding, and prices for the parameters can be compared and modified as needed.

This work did not involve a thorough sensitivity. For instance, sensitivity could be tested for to validate the use of RTP electricity pricing profiles for simulations by applying an hourly space conditioning setpoint schedule that would act as a “smart-thermostat” and re-optimizing the parameters with a target to minimize or eliminate unmet cooling an heating loads (particularly for the MSHP with electric baseboard HVAC cases) and comparing the least cost solutions of this set of simulations to the original packages prescribed herein. Another way to test sensitivity would be to apply a budget constraint to cost variables such as initial costs and AERC to explore the tangibility of deep-energy reductions for low-income single-family homes of this vintage.

Another limitation is that PVs were not considered in the simulations, but further investigation of the tangibility of a ZNE target for Pre-1978 vintage homes would be warranted, particularly for groups that were recommended to convert from gas furnace or boiler to electric MSHP systems (i.e., groups 4, 5, 7, and 12). Additionally, further exploration of the potential impacts that long-term climate change has on the original prescriptive retrofit packages can be conducted by applying various climate profiles to the models and comparing results. This process can also be used to determine if the same optimal retrofit packages could be applied to the same typologies in other locations. Finally, if money was no object, a recommendation for future work would be to verify a prescribed retrofit package by implementing it to the corresponding actual home and comparing the energy savings, and estimated costs, payback periods, and MIRR of the actual measures and BEopt results.

APPENDIX A

BEOPT MODELING ASSUMPTIONS

As-Built Assumptions

Building Lot size/ distance to neighbor	Size	Distance to Neighbor	Age	Notes	*Deviations From PARR Assumptions*
Pre-1942	25	5	90	25x125 Lot, house 20ft wide	
1942-1978	50	10	50		

Beds/Bath and Garage

Group	Garage	Bed	Bath
4	2 Car detached	3	1
5	2 Car Attached	3	1.5
6	2 Car Attached	4	2.5
7	2 Car detached	3	1
8	2 Car detached	4	2.5
10	2 Car detached	3	1.5
12	2 Car detached	3	1
13	2 Car detached	3	1.5
14	2 Car detached	3	1
15	2 Car detached	4	2.5

Operation	Setpoint Heating	Setpoint Cooling	MEL	MGL
Pre-1942	70	72	Baseline (1.0)	Baseline (1.0)
1942-1978	70	72	Baseline (1.0)	Baseline (1.0)

	Misc. HW Loads	Natural Ventilation	
Pre-1942	Sink Aerators	Benchmark	*Note: 'Sink aerators' option was not included in newer BEopt. A new option was made based on a former version.*
1942-1978	Sink Aerators	Benchmark	

As-Built Assumptions (cont.)

Walls/Ceilings/Roofs

Brick	**Wall Construction (Outside to Inside)**
Pre-1942	4-inch brick, I inch airspace, 4-inch brick, 1-inch lath (no insulation), 5/8 inch drywall
1942-1978	4-inch brick, I inch airspace, 4-inch brick, 1-inch lath (R-3 fiberglass), 5/8 inch drywall

Note: A structural brick wall was not a default option for this parameter. A custom option was made based on CMU structured walls but with physical specifications of brick. Costs associated with these options were carried over from the CMU base.

Frame	
Pre-1942	white wood siding, 1/2-inch wood sheathing, 2x4 stud wall (no insulation), 5/8 inch drywall
1942-1978	white wood siding, 1/2-inch wood sheathing, 2x4 stud wall (R-7 fiberglass insulation), 5/8 inch drywall

Insulation

Levels	**Brick Wall**	**Frame Wall**	**Ceiling Insulation**	**Interzonal Walls**	**Interzonal Floors**
Pre-1942	0	0	0	0	0
1942-1978	3	7	11	7	11

Foundation /Floors	**Basement**	**Crawl**	**Slab**
Pre-1942	Uninsulated	Uninsulated/ ventilated	
1942-1978	Uninsulated	Uninsulated/ ventilated	Uninsulated

Note: In certain cases, custom insulation options were needed and were created based on similar insulation types of slightly lesser or higher R-values. Physical properties were changed where appropriate but original cost values were kept.

Windows & Shading	
Pre-1942	Double Clear (window + storm)
1942-1978	Double Clear (window + storm)

Note: ‘Double Clear (Window + Storm)’ was not a default option in the newer version of BEopt. A custom option was created based on a former version’s.

Air Flow	**Infiltration**	**Infiltration 2 Story**	**Mechanical Ventilation**
Pre-1942	Very Leaky	Leaky	None
1942-1978	Leaky	Typical	Spot

Note: Infiltration options were based on ACH values in newer BEopt version. Custom options were created based on a former version’s.

Major Appliances	**Dryers**
Pre-1942	None
1942-1978	Gas

As-Built Assumptions (cont.)

Space Conditioning Heating (gas)	System	Ducts	
Pre-1942	Boiler 65%	None	*Note: Units with these particular efficiencies were not default options in the newer version of BEopt. New options were created based on units with slightly higher efficiencies. The value of the new parameter options were changed to reflect those listed but costs were not changed.*
1942-1978	Forced Air 70%	Typical/uninsulated	

Cooling	
Pre-1942	None
1942-1978	None

Water Heating (gas)		
Pre-1942	48% EF	*Note: Units with these particular efficiencies were not default options in the newer version of BEopt. New options were created based on units with slightly higher efficiencies. The value of the new parameter options were changed to reflect those listed but costs were not changed.*
1942-1978	48% EF	

'Today' Assumptions Upgrades/Changes from As-builts

Operation	MEL
Pre-1942	1.5
1942-1978	1.5

Insulation Levels	Brick Wall	Frame Wall	Ceiling Insulation	Interzonal Walls	Interzonal Floors
Pre-1942	0	0	7 Blown-in	0	0
1942-1978	3	7	19 Blown-in	7	11

Major Appliances	Dryers
Pre-1942	Gas
1942-1978	Gas

'Today' Assumptions Upgrades/Changes from As-Built (cont.)

Space Conditioning

Heating (gas)	System	Ducts
Pre-1942	Boiler, 80% AFUE	None
1942-1978	Furnace, 78% AFUE	Typical/ uninsulated

Cooling

Pre-1942	SEER 10- Window Units
1942-1978	SEER 10 Central A/C

Water Heating (gas)

Pre-1942	54% EF
1942-1978	54% EF

Special Cases

Group 4	Slab construction, Changed to floored attic R-19 in roof for both 'As-Built' and 'Today'
Group 7	Bungalow with upper half story. Added Floored attic, no insulation. Uninsulated interzonal walls
Group 14	Only Building with a full, unfinished attic. Added floored attic As-built and flooring + R-3 roof for today

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