Residential Stretch Energy Code Analysis

Task 2: Conduct Building Energy Modeling Analysis

Prepared by Performance Systems Development

For Massachusetts Department of Energy Resources

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Task 2 Objective

The goal of Task 2 was to build an iterative building model analysis for the model scenarios defined in Task 1. To accomplish this, Task 2 was divided into multiple steps with each building off the previous step. These are listed below:

1) **Step 1**: Define properties and generate models representing the code baseline scenarios.
2) **Step 2:** Define potential improvements to be applied to each baseline scenario and add costing information to improvement parameters.
3) **Step 3**: Develop optimized packages for achieving Energy Rating Index 47 / 42 performance.
4) **Step 4**: Screen potential improvements/packages for Energy Rating Index 47 / 42 achievement potential.
5) **Step 5**: Develop and screen optimized packages for achieving PHIUS+ performance.
6) **Step 6**: Evaluate impact of new industry standard and software on case scenarios
7) **Step 7**: Develop new HERS 52 baseline scenarios
8) **Step 8**: Develop new HERS 42 target scenarios

Step 1 - 4 utilize the same code baseline models created in BEopt and REM/Rate software and share the same set of building component improvement options. Step 5 uses improved code baseline models derived from Step 1 with its own set of building component improvement options in line with Passive House standards and has final modeling results generated from WUFI software. Step 6 considers the recent software updates and new standards implemented across HERS rating software, and Step 7 adjusts the scenario baselines to meet the new HERS minimum targets. Step 8 examines the results from steps 3, 4, and 7 and proposes target scenarios that meet a HERS score of 42.

Software

Multiple software was utilized to accomplish each step, including BEopt, REM/Rate, Ekotrope, and WUFI. A brief overview of the capabilities of each software is described below:

BEopt[1]

The BEopt™ (Building Energy Optimization Tool) software provides capabilities to evaluate residential building designs and identify cost-optimal efficiency packages at various levels of whole-house energy savings along the path to zero net energy. BEopt can be used to analyze both new construction and existing home retrofits, as well as single-family detached and multi-family buildings, through evaluation of single building designs, parametric sweeps, and cost-based optimizations. BEopt provides detailed simulation-based analysis based on specific house characteristics, such as size, architecture, occupancy, vintage, location, and utility rates. Discrete envelope and equipment options, reflecting realistic construction materials and practices, are evaluated. BEopt uses EnergyPlus, the Department of Energy's flagship simulation engine. Simulation assumptions are based on the Building America Housing Simulation Protocols. BEopt has been developed by the National Renewable Energy Laboratory in support of the U.S. Department of Energy Building America program, with a goal to develop market-ready energy solutions for new and existing homes.

REM/Rate[2]

REM/Rate™ is a user-friendly, sophisticated, residential energy analysis, code compliance and Home Energy Rating (HERS®) software developed specifically for the needs of HERS® Providers and Home Energy Raters. REM/Rate™ software calculates heating, cooling, hot water, lighting, and appliance energy loads, consumption and costs for new and existing single and multi-family homes. Climate data is available for cities and towns throughout the U.S. and Canada. As a home energy rating tool, REM/Rate™ meets the following requirements:

- Complies with RESNET® National Home Energy Rating Standards as promulgated by the Residential Energy Services Network (RESNET®), including an hourly HERS simulation engine option.
- Calculates energy loads, consumption and costs as well as sizes mechanical equipment and performs automatic International Energy Conservation Code compliance analysis.

HERS® Providers throughout the U.S. use REM/Rate™ Software. The Software has a User Defined Reference Home feature which enables the HERS® Provider to create other reference homes (local construction practice, local code) that can be compared to the rated home. It also has an Export Database feature that creates a database of inputs and outputs for statistical analysis, archiving ratings and custom report generation.

Ekotrope RATER[3]

Ekotrope is a RESNET-accredited home energy rating software in the US. In addition to HERS, it also actively supports building standards for Energy Star, DOE, EPA, ASHRAE, LEED, IECC, and many others. Powered by a proprietary hourly energy algorithm, the software streamlines and automates every step of energy modeling, from design to certification.

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[1] https://beopt.nrel.gov/home
[2] http://www.remrate.com/
[3] https://www.ekotrope.com/

WUFI[4]

WUFI® Passive allows a double assessment of buildings based on the same building model:

- A monthly energy balance method is used for the design and verification of buildings meeting the passive house criteria following EN 13790
- The dynamic building simulation of WUFI® Plus is used for the detailed dynamic assessment of the hygrothermal behavior of buildings meeting the passive house criteria, as well as individual components.

Combining monthly balance and the dynamic method allows designers to optimize passive buildings for local climate conditions while maintaining indoor comfort. Passive houses are characterized by extremely low energy consumption. Dynamic hygrothermal models are necessary to accurately model the hygrothermal behavior of buildings in dynamically changing climates or climates where cooling and dehumidification of the indoor air play an important role. Thermal and hygric inertia can be considered in detail to further reduce energy demand and to eliminate limitations in indoor comfort (overheating, for example).

In many climate zones, the use of highly insulated components presents risks—such as moisture issues, for example—to designers and construction professionals. Managing this risk requires a dynamic hygrothermal assessment under real climatic conditions. To meet this need, the Fraunhofer-Institute for Building Physics (IBP) and Passive House Institute US (PHIUS) developed WUFI® Passive combining the WUFI® Plus building simulation tool with the PHIUS+ passive house verification criteria.

[4] https://wufi.de/en/software/wufi-passive/

Step 1: Baseline Model Development

The goal of Step 1 was to take the MA 2020 Stretch Code baseline scenarios developed in Task 1 and create BEopt models that represented each building type with the baseline target of HERS 55 to represent the current 2021 in-place Stretch Code in MA, and HERS 52 to represent compliance with the performance path of the IECC 2021. To accomplish this, the modeling inputs defined in Tables 3, 4, and 5 of the Task 1 memo were used to build the geometry, envelope, and HVAC components for each building type model.

Each model was run in BEopt to evaluate whether the Energy Rating Index (ERI) output aligned with the HERS 55 and HERS 52 targets. Since ERI and HERS are not a direct relation, the BEopt initial baseline inputs were then entered into REM to identify the level of correlation between BEopt's ERI and REM's HERS. The initial baseline inputs did not result in exact alignment and were then adjusted in REM until the target was met. The baseline inputs for BEopt were then updated based on these adjustments. The results of these adjustments can be seen in **Table 1** below.

Table 1. BEopt baseline ERI compared to HERS.

Building Type	ERI	HERS Index
SFD Small	60	55
SFD Large	59	55
Townhouse	61*	55
6-unit MF	68*	55
4-story MF	65*	55

**Discrepancy between ERI and HERS Index for multifamily buildings is likely due to the BeOpt software only modeling whole building ERI rather than unit level ERI.*

The BEopt inputs and geometry for each of the five building types can be seen in **Figure** 1 through **Figure** 5.

Figure 1. SFD Small baseline inputs.

Finished Floor Area	2,144 ft²
Dimensions	38 ft x 28 ft
Stories	2
Bedrooms	3
Bathrooms	2
Wall Height	8 ft
Roof Type	Gable
Roof Slope	7:12
Roof Structure	Truss, Cantilever
Foundation Type	Unfinished Basement

Parameter	Baseline Value
Orientation	West
Neighbors	None
Wood Stud	DOER_R-21 Fiberglass, 2x6, 16 in o.c.
Wall Sheathing	OSB
Exterior Finish	Vinyl, Light
Interzonal Walls	DOER_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Unfinished Attic	Ceiling R-49 Fiberglass, Vented
Finished Roof	R-30C Fiberglass Batt, 2x10
Roof Material	Asphalt Shingles, Medium
Radiant Barrier	None
Unfinished Basement	Ceiling R-30 Fiberglass Batt
Carpet	80% Carpet
Floor Mass	Wood Surface
Exterior Wall Mass	1/2 in. Drywall
Partition Wall Mass	1/2 in. Drywall
Ceiling Mass	1/2 in. Drywall
Window Areas	DOER_Window Areas
Windows	DOER_Low-E, Double, Non-metal, Air, L-Gain U-0.28
Interior Shading	Summer = 0.7, Winter = 0.7
Door Area	40 ft^2
Doors	DOER_Steel-polyurethane
Eaves	2 ft
Overhangs	None
Air Leakage	3 ACH50
Mechanical Ventilation	2013, Exhaust (94.8 cfm; 14.2 W)
Natural Ventilation	None
Central Air Conditioner	DOER_SEER 14.2
Furnace	Gas, 95% AFUE
Ducts	DOER_4 CFM25 per 100ft2, R-6
Ceiling Fan	National Average
Dehumidifier	None
Cooling Set Point	78 F Programmable
Heating Set Point	68 F Programmable
Humidity Set Point	None
Water Heater	DOER_Gas Tankless 0.95 EF
Distribution	DOER_R-3, TrunkBranch, PEX
Lighting	75% LED
Refrigerator	DOER_633 kWh
Cooking Range	DOER_Gas
Dishwasher	DOER_244 Rated kWh
Clothes Washer	DOER_Standard
Clothes Dryer	DOER_Gas, Standard

Figure 2. SFD Large baseline inputs.

Finished Floor Area	4,024 ft²
Dimensions	48 ft x 38 ft
Stories	2
Bedrooms	5+
Bathrooms	3+
Wall Height	8 ft
Roof Type	Gable
Roof Slope	7:12
Roof Structure	Truss, Cantilever
Foundation Type	Unfinished Basement

Parameter	Baseline Value
Orientation	West
Neighbors	None
Wood Stud	DOER_R-21 Fiberglass, 2x6, 16 in o.c.
Wall Sheathing	OSB
Exterior Finish	Vinyl, Light
Interzonal Walls	DOER_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Unfinished Attic	DOER_Ceiling R-49 Cellulose, Vented
Finished Roof	DOER_R-30C Fiberglass Batt, 2x10
Roof Material	Asphalt Shingles, Medium
Radiant Barrier	None
Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt
Interzonal Floor	R-30 Fiberglass Batt
Carpet	80% Carpet
Floor Mass	Wood Surface
Exterior Wall Mass	1/2 in. Drywall
Partition Wall Mass	1/2 in. Drywall
Ceiling Mass	1/2 in. Drywall
Window Areas	DOER_SFDL_Window Areas
Windows	DOER_Low-E, Double, Non-metal, Air, L-Gain U-0.28
Interior Shading	Summer = 0.7, Winter = 0.7
Door Area	40 ft^2
Doors	DOER_Steel-polyurethane
Eaves	2 ft
Overhangs	None
Air Leakage	DOER_3 ACH50

Mechanical Ventilation	DOER_2013, Exhaust (166.2 cfm; 24.9 W)
Natural Ventilation	None
Central Air Conditioner	DOER_SEER 14.2
Furnace	Gas, 95% AFUE
Ducts	DOER_4 CFM25 per 100ft2, R-6
Ceiling Fan	National Average
Dehumidifier	None
Cooling Set Point	78 F Programmable
Heating Set Point	68 F Programmable
Humidity Set Point	None
Water Heater	DOER_Gas Tankless 0.94 EF
Distribution	DOER_R-3, TrunkBranch, PEX
Lighting	75% LED
Refrigerator	DOER_653 kWh
Cooking Range	DOER_Gas
Dishwasher	DOER_254 Rated kWh
Clothes Washer	DOER_Standard
Clothes Dryer	DOER_Gas, Standard

Figure 3. Townhouse baseline inputs.

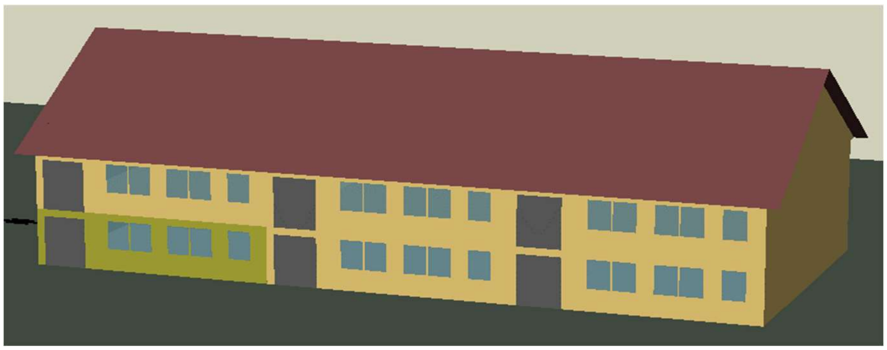
Finished Floor Area	2,096 ft²
Dimensions	23 ft x 36 ft
Stories	2
Bedrooms	3
Bathrooms	2
Wall Height	8 ft
Roof Type	Gable
Roof Slope	7:12
Roof Structure	Truss, Cantilever
Foundation Type	Unfinished Basement

Parameter	Baseline Value
Orientation	West
Neighbors	None
Wood Stud	DOER_R-21 Fiberglass, 2x6, 16 in o.c.
Wall Sheathing	OSB
Exterior Finish	Vinyl, Light
Interzonal Walls	DOER_R-21 Fiberglass Batt, 2x6, 16 in o.c.

Unfinished Attic	DOER_Ceiling R-49 Cellulose, Vented
Roof Material	Asphalt Shingles, Medium
Radiant Barrier	None
Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt
Interzonal Floor	R-30 Fiberglass
Carpet	80% Carpet
Floor Mass	Wood Surface
Exterior Wall Mass	1/2 in. Drywall
Partition Wall Mass	1/2 in. Drywall
Ceiling Mass	1/2 in. Drywall
Window Areas	DOER_townhome_Window Areas
Windows	DOER_Low-E, Double, Non-metal, Air, L-Gain U-0.28
Interior Shading	Summer = 0.7, Winter = 0.7
Door Area	40 ft^2
Doors	DOER_Steel-polyurethane
Eaves	2 ft
Overhangs	None
Air Leakage	DOER_3 ACH50
Mechanical Ventilation	DOER_2013, Exhaust (92.9 cfm; 13.9 W)
Natural Ventilation	None
Central Air Conditioner	DOER_SEER 14.2
Furnace	Gas, 95% AFUE
Ducts	DOER_4 CFM25 per 100ft2, R-6
Ceiling Fan	National Average
Dehumidifier	None
Cooling Set Point	78 F Programmable
Heating Set Point	68 F Programmable
Humidity Set Point	None
Water Heater	DOER_Gas Tankless 0.94 EF
Distribution	DOER_R-3, TrunkBranch, PEX
Lighting	75% LED
Refrigerator	DOER_633 kWh
Cooking Range	DOER_Gas
Dishwasher	DOER_254 Rated kWh
Clothes Washer	DOER_Standard
Clothes Dryer	DOER_Gas, Standard

Figure 4. 6-unit MF baseline inputs.

Finished Floor Area	1,408 ft²
Dimensions	32 ft x 44 ft
Stories	2
Number of Units	6
Bedrooms	3
Bathrooms	2
Wall Height	8 ft
Roof Type	Gable
Roof Slope	7:12
Roof Structure	Truss, Cantilever
Foundation Type	Slab

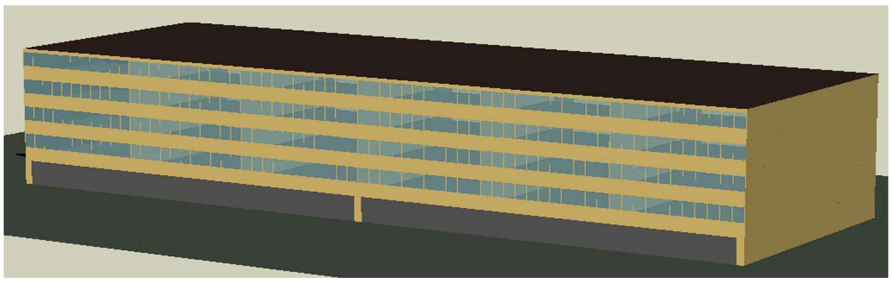


Parameter	Baseline Value
Orientation	West
Neighbors	None
Wood Stud	DOER_R-21 Fiberglass, 2x6, 16 in o.c.
Wall Sheathing	OSB
Exterior Finish	Vinyl, Light
Unfinished Attic	DOER_Ceiling R-30 Fiberglass, Vented
Roof Material	Asphalt Shingles, Medium
Radiant Barrier	None
Slab	2ft R10 Exterior XPS
Carpet	80% Carpet
Floor Mass	Wood Surface
Exterior Wall Mass	1/2 in. Drywall
Partition Wall Mass	1/2 in. Drywall
Ceiling Mass	1/2 in. Drywall
Window Areas	DOER_6unit_Window Areas (2)
Windows	DOER_Low-E, Double, Non-metal, Air, L-Gain U-0.28
Interior Shading	Summer = 0.7, Winter = 0.7
Door Area	40 ft^2
Doors	DOER_Steel-polyurethane
Eaves	2 ft
Overhangs	None
Air Leakage	DOER_3 ACH50
Mechanical Ventilation	DOER_2013, Exhaust (72.2 cfm; 10.8 W)
Natural Ventilation	None

Central Air Conditioner	DOER_SEER 13
Furnace	Gas, 95% AFUE
Ducts	In Finished Space
Ceiling Fan	National Average
Dehumidifier	None
Cooling Set Point	78 F Programmable
Heating Set Point	68 F Programmable
Humidity Set Point	None
Water Heater	DOER_Gas Tankless, Condensing
Distribution	DOER_R-3, TrunkBranch, PEX
Lighting	DOER_6unit_75% LED
Refrigerator	DOER_633 kWh
Cooking Range	DOER_Gas
Dishwasher	DOER_254 Rated kWh
Clothes Washer	DOER_Standard
Clothes Dryer	DOER_Gas, Standard

Figure 5. 4-story MF baseline inputs.

Finished Floor Area	1,155 ft²
Dimensions	35 ft x 33 ft
Stories	4
Number of Units	48
Bedrooms	2
Bathrooms	1
Wall Height	8 ft
Roof Type	Flat Roof/Deck
Roof Slope	-
Roof Structure	-
Foundation Type	Slab/Podium



Parameter	Baseline Value
Orientation	West
Neighbors	None
Wood Stud	DOER_R-21 Fiberglass, 2x6, 16 in o.c.
Wall Sheathing	OSB
Exterior Finish	Vinyl, Light
Finished Roof	DOER_R-30C Fiberglass Batt, 2x10
Roof Material	Asphalt Shingles, Medium

Radiant Barrier	None
Interzonal Floor	R-30 Fiberglass Batt
Carpet	80% Carpet
Floor Mass	Wood Surface
Exterior Wall Mass	1/2 in. Drywall
Partition Wall Mass	1/2 in. Drywall
Ceiling Mass	1/2 in. Drywall
Window Areas	DOER_4story_Window Areas (3)
Windows	DOER_Low-E, Double, Non-metal, Air, L-Gain U-0.28
Interior Shading	Summer = 0.7, Winter = 0.7
Door Area	40 ft^2
Doors	DOER_Steel-polyurethane
Eaves	2 ft
Overhangs	None
Air Leakage	DOER_3 ACH50
Mechanical Ventilation	DOER_2013, Exhaust (57.2 cfm; 8.6 W)
Natural Ventilation	None
Central Air Conditioner	DOER_SEER 13
Furnace	Gas, 94% AFUE
Ducts	In Finished Space
Ceiling Fan	National Average
Dehumidifier	None
Cooling Set Point	78 F Programmable
Heating Set Point	68 F Programmable
Humidity Set Point	None
Water Heater	DOER_Gas Tankless, Condensing
Distribution	DOER_R-3, TrunkBranch, PEX
Lighting	75% LED
Refrigerator	DOER_633 kWh
Cooking Range	DOER_Gas
Dishwasher	DOER_254 Rated kWh
Clothes Washer	DOER_Standard
Clothes Dryer	DOER_Gas, Standard

Step 2: Improvement Options and Pricing

BEopt has a total of eighty-eight building components that can be adjusted to improve the energy efficiency of a model. In this step, seventeen components were selected to investigate their effect on a building's efficiency in the hopes of reducing its ERI/HERS while minimizing the costs over baseline. These seventeen components, which vary across the building's envelope, HVAC, DHW, lighting, and appliances were selected by PSD based on industry experience and common construction practices.

Each building component had up to five alternative options with some either above or below the baseline performance option. The reasoning for this was to provide optimization options where increased energy performance in one area of the building could lead to using lower performance options in other areas to reduce overall incremental costs. The selected improvement options, along with the baseline options, are given in Table 2. These options were then created, or existing default options were modified, in BEopt to reflect the expected performance in terms of R-values, U-factors, kWh, Btu/hrs, etc.

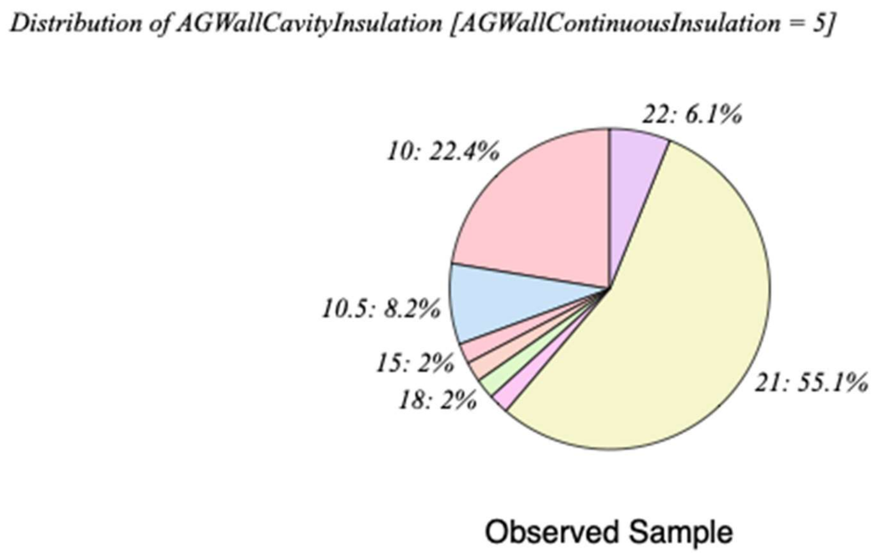
These options were then given to NORESCO so that material and labor costs could be applied. Multiple sources were consulted to develop typical industry pricing in 2020 for Massachusetts. The improvement options in BEopt were updated with this data. See Task 3 Memo for more details on costing and pricing methods.

Improvement Option Selection

Wall sheathing

Original Optimization Run

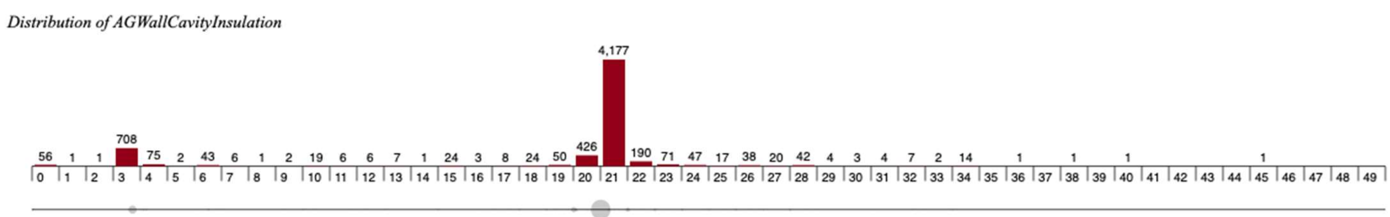
This category includes a baseline of standard OSB sheathing with three upgrades involving installation of rigid foam insulation over OSB sheathing. We increased the rigid foam by R-5, or 1 inch of XPS foam, the most common exterior insulation product, for each successive upgrade. DOER expressed concerns about the building science of R-20+5, but PSD notes that it will be an option in Climate Zone 5 under the 2021 IECC and has been an option for Climate Zones 6 through 8 since the 2012 IECC. Therefore, we assumed this option has been vetted as having acceptably low condensation risk. The most common continuous insulation application in the PSD Provider data (27 homes, 55% of homes with ci) was R-21+5. Up to four inches of foam is generally considered to be technically feasible. Twenty-five homes had R-15 or greater continuous insulation (8 had no cavity insulation, presumably SIP), so 17 homes had cavity plus continuous insulation of 15 or greater.



Cavity Insulation

Original Optimization Run

R-21 was chosen because more than two-thirds of the HERS Provider data. We did not include R-20 because of the very small impact on the HERS Index and will present the case studies as being applicable to R-20 cellulose. We did not include higher cavity insulation R-values because we did not want scenarios to include non-standard framing practices such as double-framed walls or SIPs construction.

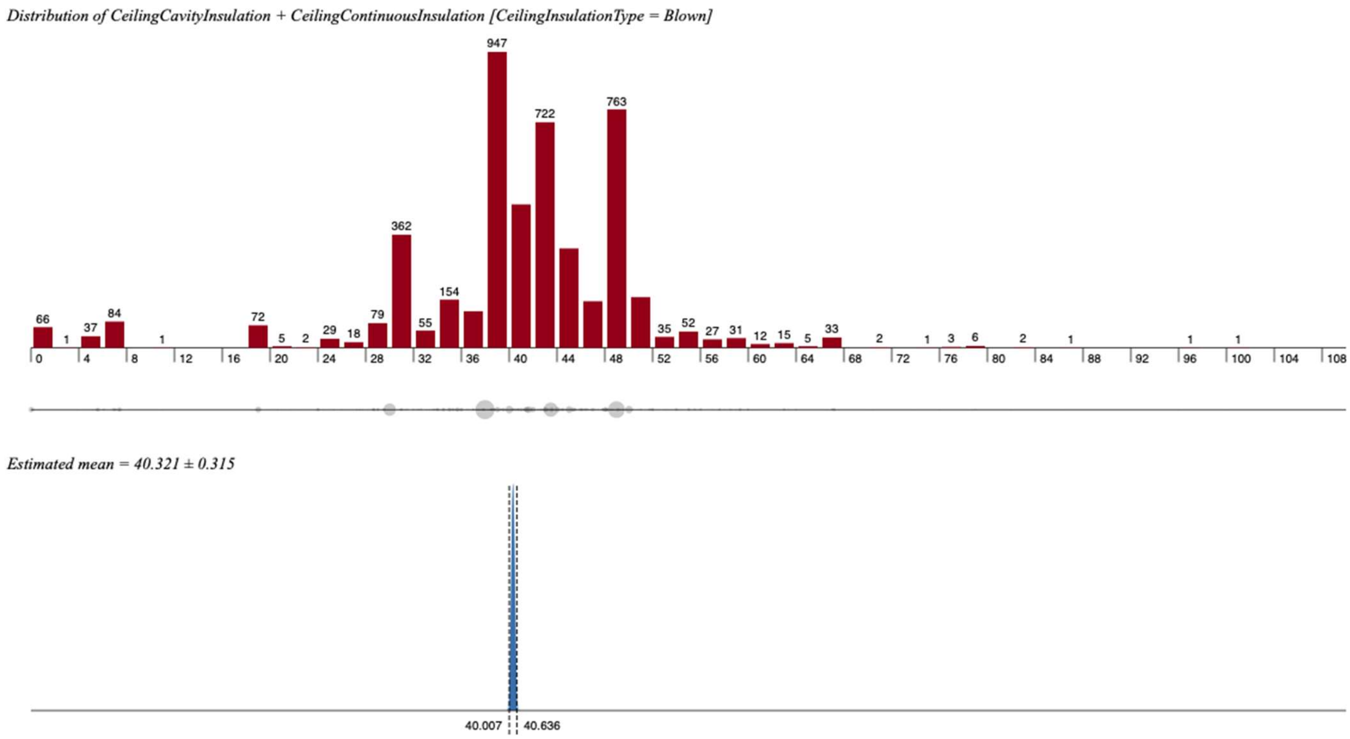


Unfinished attic

Original Optimization Run

This category includes the baseline of R-49 insulation installed on the attic floor (i.e. vented attic) and three upgrade options with the same insulation configuration. We also included two upgrade options where the thermal boundary is moved to the roof (i.e. unvented attics). R-49 was chosen because it is the prescriptive minimum R-value. Because of rapidly diminishing returns at high R-values, PSD included R-38 as an “improvement” option because it is the most common in the Provider data (the average is R-40). We also felt that the cost of additional insulation could be put into other upgrades that more substantially reduce the HERS Index.

For the unvented attics, we included R-30 and R-38 open cell spray foam because they were stock selections in BEopt and both R-values work with standard rafter design. The intent of including these options was to bring a portion of the ductwork inside the thermal envelope.



Finished roof (cathedral ceiling)

Original Optimization Run

For single-family detached models we included both unfinished attic areas and finished roof areas in the geometry of each model. In other words, the geometry of each model included mainly vented attic area and a smaller cathedral ceiling area. We did not include cathedral ceiling for townhouse and multifamily. R-30 and R-38 high-density fiberglass insulation were chosen because it fits in a standard 2x10 rafter.

Revised Optimization Run

The R-38+R-24 polyiso improvement option was intended for only the 4-story multifamily scenarios and was not a common construction type in provider data. This option was removed from all other scenarios.

Unfinished basement

Original Optimization Run

Unfinished basements are the most common basement type in Massachusetts (see Task 1 memo), so this, with R-30 floor insulation, was chosen as the baseline. Improving on R-30 would require significant design/framing changes, so the upgrades we chose involved including the basement within the thermal envelope. R-15 XPS and R-21 fiberglass batts are roughly equivalent in performance, but have different incremental costs, so we included both. We did not include higher R-values to stay within typical framing practices and wall thickness and builders' resistance to exterior foundation insulation.

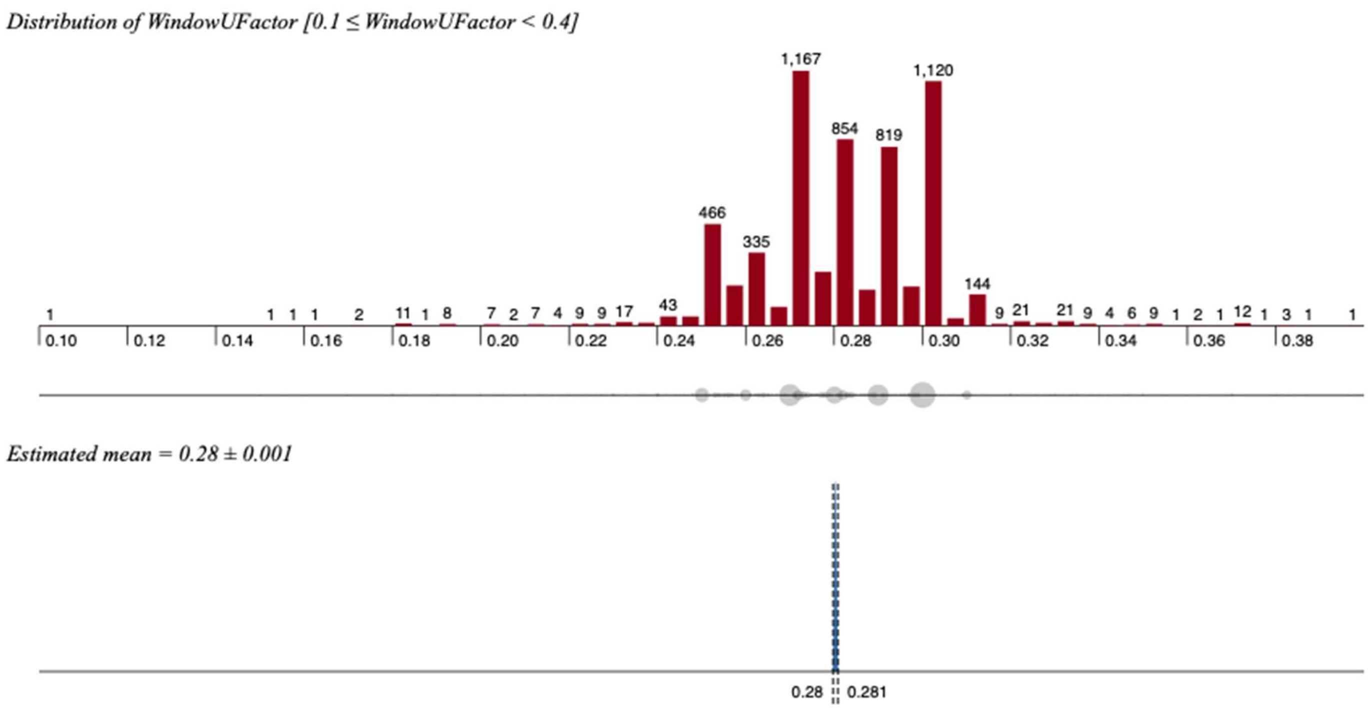
Windows

Original Optimization Run

U-0.28 was chosen for the baseline because it is the most common in the Provider data. U-0.18 was chosen as the upgrade because it is a common triple-pane glass U-factor.

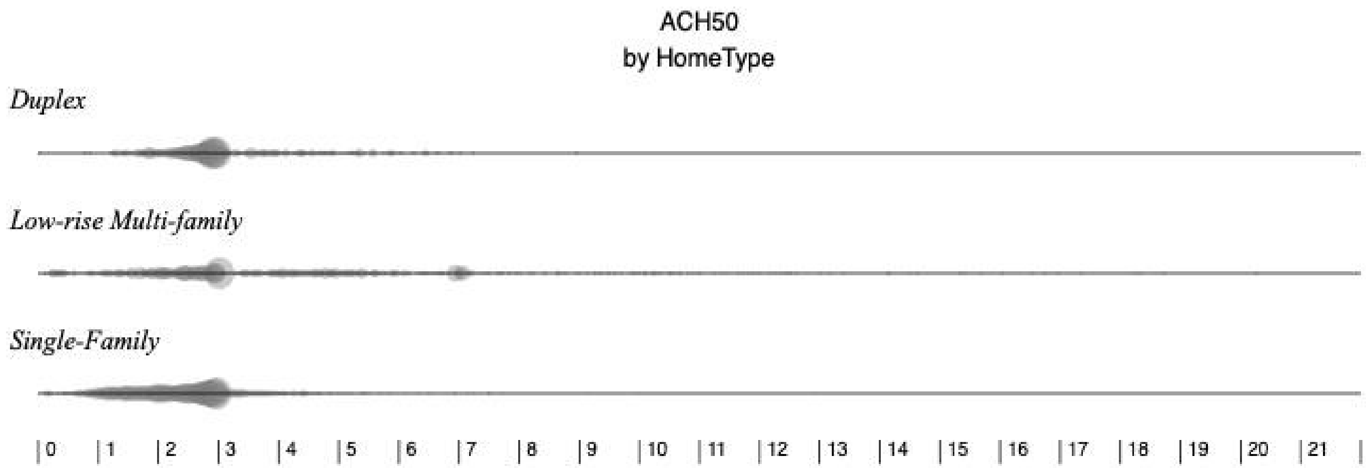
Revised Optimization Run

PSD added an intermediate option for windows. U-0.25 is common in the provider data; however, we did not believe the impact of a U-0.03 improvement would have a large impact on the HERS score. For example, we ran the small and large single-family baseline models once with a 0.28 and again with a U-0.25 and it lowered the HERS Index by one point in both cases. Although this does not have a significant impact on score, we understand the need for presenting flexibility in options for builders.



Air leakage

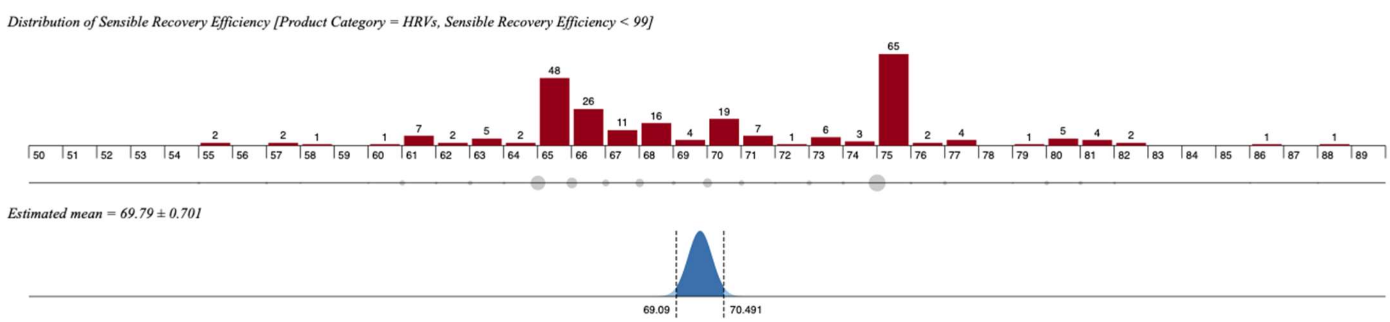
The baseline of 3.0 ACH50 was chosen because it is the code minimum and the Provider data average 2.8 ACH50. The upper limit of 0.6 was set at the minimum for Passive House, which is a difficult but achievable standard. The 2 ACH50 option was chosen simply because it is roughly halfway between the baseline and Passive House.



Mechanical ventilation

Original Optimization Run

Exhaust-only was chosen as the baseline because it is by far the most common in the Provider data (85%) and the only way to improve the energy efficiency is with an HRV or ERV. We did not consider HRV because we wanted to compare improved efficiencies and including HRVs and ERVs would have created four options. Data on HRV versus ERV was not available in the Provider data.



Revised Optimization Run

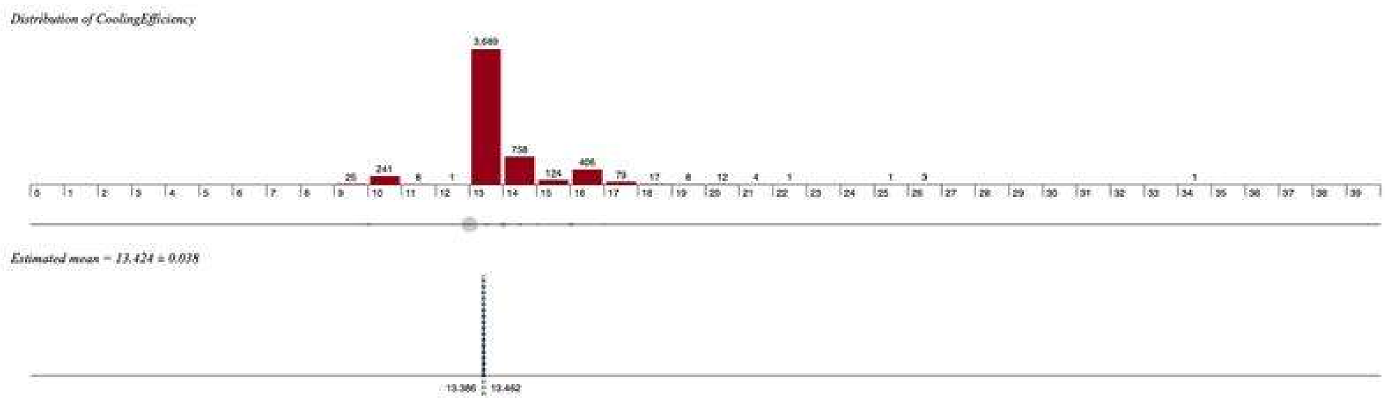
After additional research, PSD found that in the NMR RNC baseline study, 20% of stretch code homes had an ERV or HRV. Of those, 60% were HRVs and 40% were ERVs; therefore, we recommend including an HRV improvement option instead of an ERV.

In the image above, data from the Home Ventilating Institute (HVI) showing HRVs available in their certified products directory. Based on this information, PSD chose a 75% HRV for this revised run.

Central air conditioning

Original Optimization Run

We chose SEER 14 as the baseline because we had to adjust our models to exactly hit the HERS 55 target and SEER 14 was the most common among homes that achieved exactly a HERS 55. We included a SEER 13 as an option because it is the dominant system used in Massachusetts and the upgrade is not worth the cost in a heating-dominated climate. Adjusting the model from SEER 13 to 14 reduced the HERS index by one point in the small and large SFD.

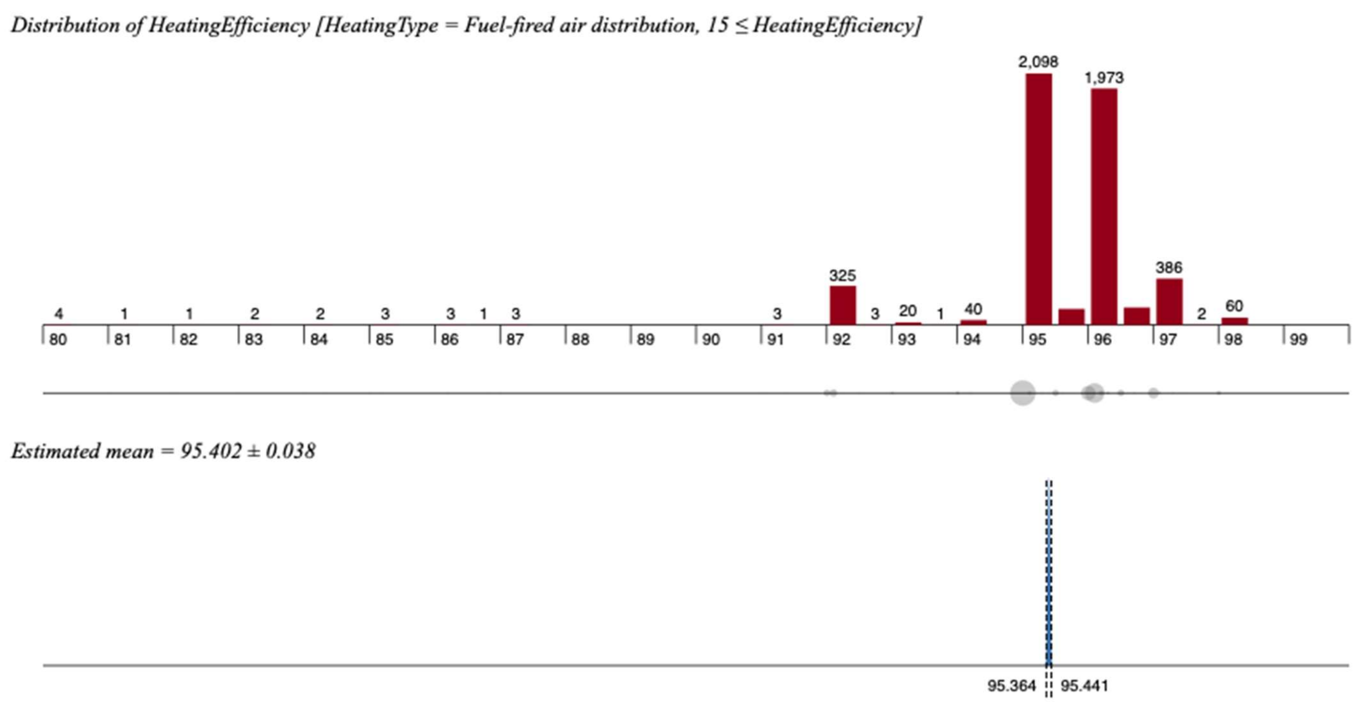


Furnace/heat pump

Original Optimization Run

The 8.2 HSPF was included as an option for the BEopt analysis, because BEopt requires an electric baseline to run an electric heat improvement.

For gas furnaces we chose 95 AFUE as the baseline because it is the most common and included 92 AFUE as a potential cost tradeoff.



Duct leakage and insulation

Options included reflected common tightness levels in provider data.

Water heaters

Original Optimization Run

On-demand water heaters were chosen for baseline as they are by far the most dominant in MA new homes according to provider and NMR baseline study data.

Upgrade options included a gas high efficiency storage option, and an electric on-demand and storage option for the all-electric scenarios. We also included a heat pump water heater as this option is gaining popularity in the industry.

Lighting & Appliances

Original Optimization Run

Lighting and appliance efficiency was adjusted to allow for cost and efficiency tradeoffs representing variations found in provider data.

Revised Optimization Run

All lighting was run as 100% LED as will be required by new MA code. All appliances were run as ENERGY STAR in the improved scenarios per DOER feedback.

Baseline/Improvement options by house type

Original Optimization Run

PSD did not find evidence that construction practices (insulation, HVAC, appliances) were different between the building types, and so the same improvement options were considered for all types.

Reviewing BEopt optimization output

Revised Optimization Run

The range of results was higher than anticipated in the original results. This happened for two reasons: The lower efficiency heat pump was unintentionally displayed as an improvement option and was removed from the results. Additionally, BEopt was configured with a lower bound on an ERI of 40 based on our initial understanding of the HERS to ERI translation. This was configured to optimize for a lower range of ERI results to shift the results lower.

Table 2

Revised Optimization Run

The table has been updated below to represent considerations described above.

Single Family Table 2a. Baseline and improvement options

Component	Baseline	Improvement Options				
Wall Sheathing	OSB	R-5 XPS	R-10 XPS	R-15		
Wall Cavity Insulation	2 x 6 16" OC R-21 Fiberglass					
Attic	Ceiling R-49 Cellulose, Vented	Roof R-30 Open Cell Spray Foam, Unvented	Ceiling R-38 Fiberglass, Vented	Roof R-38 Open Cell Spray Foam, Unvented	Ceiling R-60 Cellulose, Vented	Ceiling R-80 Cellulose, Vented
Cathedral Ceiling	R-30 Fiberglass Batt, 2x10	R-38 Fiberglass Batt, 2x10				
Basement	Ceiling R-30 Fiberglass Batt	Whole Wall R-15 XPS	Whole Wall R-21 Fiberglass Batt, 2x6, 24 in o.c.			
Windows	U 0.28, 0.29 SHGC	U 0.25, 0.29 SHGC	U 0.18, 0.29 SHGC			
Air Leakage	3 ACH50	2 ACH50	0.6 ACH50			
Mechanical Ventilation	2013, Exhaust	HRV 75%				
Cooling	SEER 14.2	SEER 16 (2 Stage)	18 SEER ccHP Ductless	20 SEER ccHP Ductless	20 SEER ccHP Ducted	
Heating	Gas, 95% AFUE	Gas, 98% AFUE	11 HSPF ccHP Ductless	12 HSPF ccHP Ductless	12 HSPF ccHP Ducted	
Ducts	4 CFM25 per 100ft2, R-6[5]	2 CFM25 per 100ft2, R-6[6]	In Finished Space			
Water Heater	Gas Tankless 0.94 EF	Gas Premium, Condensing 0.82 EF	Electric Premium 0.95 EF	Electric Tankless 0.99 EF	HPWH, 50 gal	
Lighting	75% LED	100% LED (required for all scenarios)				
Refrigerator	633 kWh	550 kWh (required for all scenarios)				
Cooking Range	Gas / Electric	Electric, Induction	Gas			
Dishwasher	264 Rated kWh					
Clothes Washer	Standard	ENERGY STAR (required for all scenarios)				

[5] Ducts distributed between attic, cond space, and basement based on house configuration

Clothes Dryer	Gas / Electric	Gas, Premium / Electric Premium				

Multifamily Table 2b. Baseline and improvement options

Component	Baseline	Improvement Options					
Wall Sheathing	OSB	R-5 XPS	R-10 XPS	R-15			
Wall Cavity Insulation	2 x 6 16" OC R-21 Fiberglass						
Attic	Ceiling R-49 Cellulose, Vented	Roof R-30 Open Cell Spray Foam, Unvented	Ceiling R-38 Fiberglass, Vented	Roof R-38 Open Cell Spray Foam, Unvented	Ceiling R-60 Cellulose, Vented	Ceiling R-80 Cellulose, Vented
Flat Roof	R-30 Fiberglass Batt, 2x10	R-38C Fiberglass Batt, 2x10, R-24 Polyiso (MF ONLY)					
Slab	R-10, 2ft						
Windows	U-0.28, 0.29 SHGC	U 0.25, 0.29 SHGC	U-0.18, 0.29 SHGC				
Air Leakage	3 ACH50	2 ACH50	0.6 ACH50				
Mechanical Ventilation	2013, Exhaust	HRV 75%					
Cooling	SEER 14.2	SEER 16	18 SEER ccHP Ducted	20 SEER ccHP Ducted	20 SEER ccHP Ductless		
Heating	Gas, 95% AFUE	Gas, 98% AFUE	11 HSPF ccHP Ducted	12 HSPF ccHP Ducted	12 HSPF Ductless		
Ducts	4 CFM25 per 100ft2, R-6[6]	2 CFM25 per 100ft2, R-6[6]	In Finished Space				
Water Heater	Gas Tankless 0.94 EF	Gas Premium, Condensing 0.82 EF	Electric Premium 0.95 EF	Electric Tankless 0.99 EF	HPWH, 50 gal		
Lighting	75% LED	100% LED (required for all scenarios)					
Refrigerator	633 kWh	550 kWh (required for all scenarios)					
Cooking Range	Gas / Electric	Electric, Induction	Gas				
Dishwasher	264 Rated kWh						

[6] Ducts distributed between attic, cond space, and basement based on house configuration

Clothes Washer	Standard	ENERGY STAR (required for all scenarios)				
Clothes Dryer	Gas / Electric	Gas, Premium / Electric Premium				

Step 3: Modeling Optimization

Using the improvements options with their associated costs as defined in Step 2, multiple optimization-focused modeling runs were performed to evaluate which configurations of those improvements meet the target HERS rating at the lowest incremental cost. For reference, **Table 3** shows the target modeling scenarios.

Table 3. BEopt modeling scenarios.

Residential Unit Type	Building Type	MA 2020 Stretch Code (HERS 55), Gas heat*	2021 IECC (HERS 52 + prescriptive changes), Gas heat*	HERS 42 Electric heat	HERS 42 Gas heat	Passive House
Single-Family	2,100 sqft 3-bed	☑	☑	☑	☑	☑
	4,030 sqft 5-bed	☑	☑	☑	☑	☑
Townhouse	2,087 sqft 3-bed	☑	☑	☑	☑	☑
Multifamily unit	Small 6-unit building	☑	☑	☑	☑	☑
	Large (wood-frame) 4 story over podium	☑	☑	☑	☑	☑

For each building type, two optimization runs were necessary. The first run utilized gas heating with either gas or electric appliances and water heaters, while the second run was all electric. This was done to prevent BEopt's optimization algorithm from generating models that contained electric heating with gas appliances or water heaters. A target ERI is set at the beginning of each optimization run and BEopt cycles through all configurations for the most cost-effective designated improvement options at each sequential point along the path to the target ERI. Both the gas and electric runs were set with a target ERI of 0 so that BEopt would continue optimization until a limit of cost-effective options was found.

Modeling Outputs

At the completion of each run, a detailed output report contained in a .csv file is generated. This report contains various details on each model iteration including improvement option selections and initial costs for each improvement option over the 30-year analysis period. To assess cost-effectiveness for each model iteration, the incremental cost was calculated by comparing the cost of the improvement options to that of the options used in the baseline model.

These two metrics, ERI and incremental cost, were then used to determine the optimal configuration for each scenario. An overview of the combined output of the gas and electric modeling runs in each scenario are found in the following subsections. Additional analysis can be found in Appendix A1.

SFD Small

Figure 6. SFD Small modeling output, ERI vs. Incremental Cost.

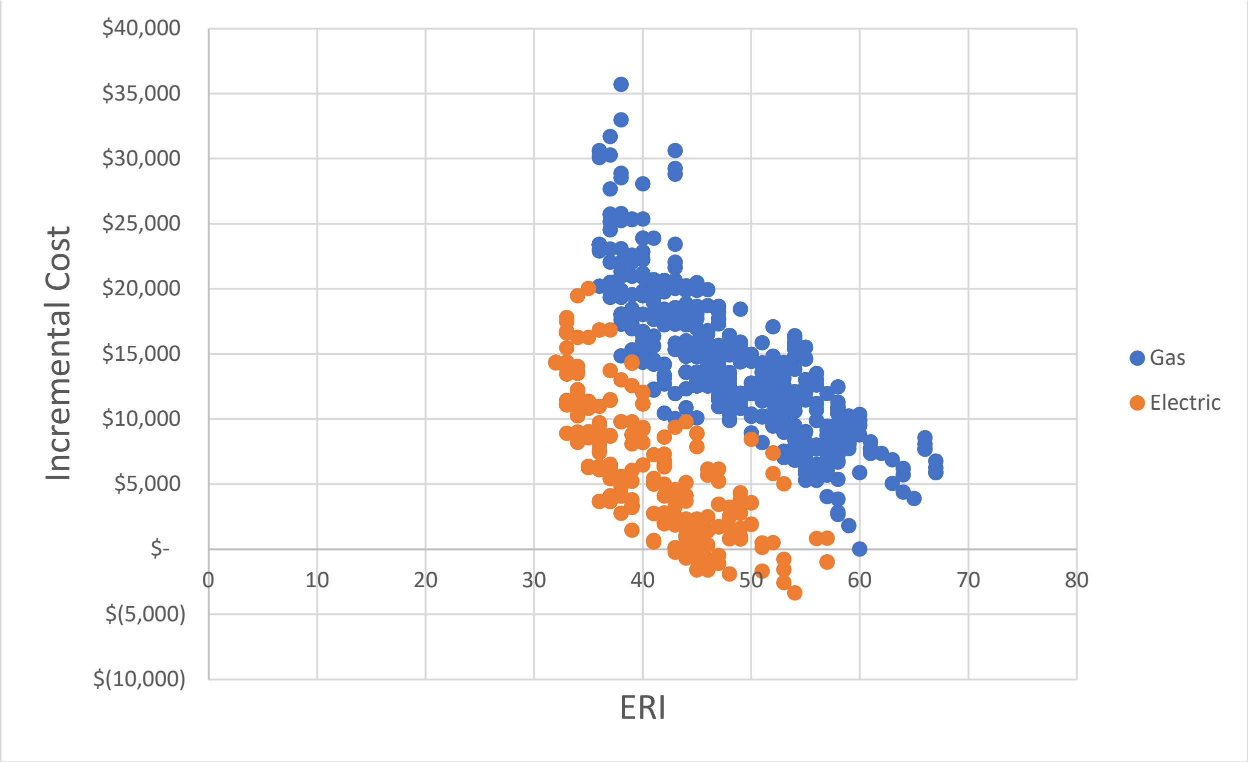


Figure 6 shows that the small SFD scenario generated 886 unique configurations with the minimum ERI at 32, the maximum at 67, and an average ERI of 45.6. Homes with gas heating saw higher ERIs with larger incremental costs with decreasing ERI.

Building features that generally result in an ERI within the target range ERI (<52) for the small single-family detached home include:

- Air leakage-- baseline value of 3 ACH_{50} when using a gas-fired HVAC system, and with an electric HVAC system 2 ACH_{50}.
- Ducts--duct leakage levels below 2 CFM_{25} per 100 ft² for all HVAC system cases.
- Wall Sheathing--exterior continuous insulation with an R-value of 5 or 10 for all HVAC systems.

A distribution of the improvement options can be found in **Table 4**, displaying the percentage of models containing each improvement and the effect on the ERI range.

Table 4. Small SFD modeling options distribution.

Wall Sheathing	Count	Percentage	Min ERI	Max ERI	Average ERI
DOER_OSB	276	31%	35	67	51.7
DOER_R-10 XPS	264	30%	33	58	41.6
DOER_R-15 XPS	88	10%	32	54	39.0
DOER_R-5 XPS	258	29%	33	61	45.4
Unfinished Attic	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Ceiling R-38 Fiberglass, Vented	577	65%	33	67	47.5
DOER_Ceiling R-60 Cellulose, Vented	106	12%	33	58	40.6
DOER_Ceiling R-80 Cellulose, Vented	91	10%	32	58	39.5
DOER_Roof R-30 Open Cell Spray Foam, Unvented	37	4%	33	60	45.7
DOER_Roof R-38 Open Cell Spray Foam, Unvented	37	4%	33	59	45.3
MA_Ceiling R-49 Cellulose, Vented	38	4%	33	60	45.4
Finished Attic	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_R-30 Fiberglass Batt, 2x10	407	46%	32	67	49.2
DOER_R-38 Fiberglass Batt, 2x10	479	54%	32	61	42.5
Unfinished Basement	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Ceiling R-30 Fiberglass Batt	684	77%	32	65	43.8
DOER_Whole Wall R-21 Fiberglass Batt, 2x6, 24 in o.c.	39	4%	34	58	45.7
Whole Wall R-15 XPS	163	18%	33	67	52.9
Windows	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_U-0.18, 0.29 SHGC	204	23%	32	56	38.3
MA_U-0.25, 0.29 SHGC	39	4%	33	58	44.4
MA_U-0.28, 0.29 SHGC	643	73%	34	67	48.0
Air Leakage	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_0.6 ACH50	437	49%	32	60	40.6
DOER_2 ACH50	156	18%	34	67	47.5
DOER_3 ACH50	293	33%	35	67	52.0
Mechanical Ventilation	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2013, Exhaust	385	43%	38	67	52.1
MA_2013, HRV, 75%	501	57%	32	55	40.6
Central Air Conditioner	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_SEER 14.2	169	30%	36	67	52.3
DOER_SEER 16 (2 Stage)	393	70%	36	67	47.0
Furnace	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Gas, 95% AFUE	364	65%	36	67	50.7
DOER_Gas, 98% AFUE	198	35%	36	59	44.8
Mini-Split Heat Pump	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_SEER 18, 11 HSPF, Ductless	94	29%	33	57	46.3
MA_SEER 20, 12 HSPF, Ducted	14	4%	35	53	43.5
MA_SEER 20, 12 HSPF, Ductless	216	67%	32	51	37.6
Ducts	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**

DOER_2 CFM25 per 100ft2, R-6	251	28%	40	63	49.3
DOER_4 CFM25 per 100ft2, R-6	157	18%	35	67	55.4
DOER_In Finished Space	168	19%	36	55	40.7
None	310	35%	32	57	40.2
Water Heater	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Electric Premium 0.95 EF	41	5%	39	66	51.5
DOER_Electric Tankless 0.99 EF	41	5%	39	67	51.9
DOER_Gas Premium, Condensing 0.82 EF	41	5%	33	60	45.3
DOER_Gas Tankless 0.94 EF	722	81%	32	60	44.9
DOER_HPWH, 50 gal	41	5%	34	62	45.9

SFD Large

Figure 7. SFD Large modeling output, ERI vs. Incremental Cost.

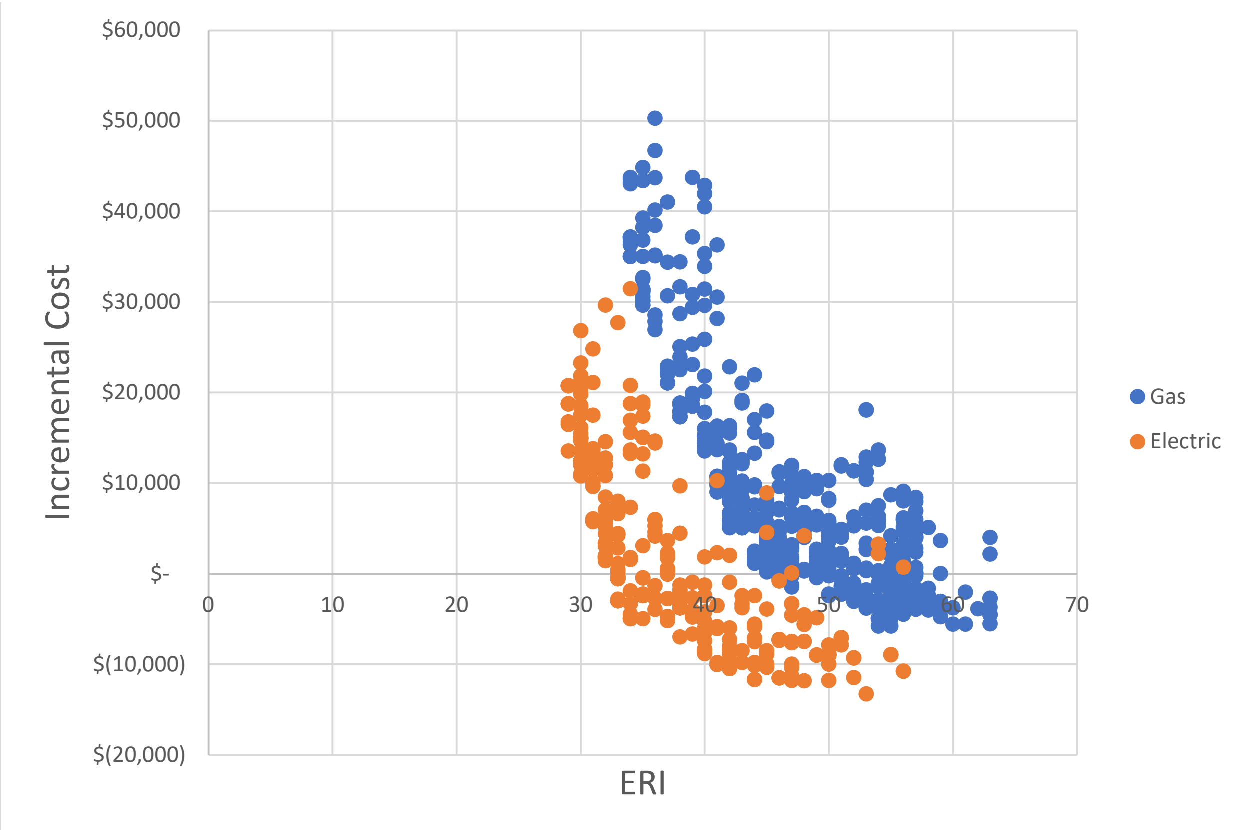


Figure 7 shows that the large SFD scenario generated 898 unique configurations with the minimum ERI at 29, the maximum at 63, and an average ERI of 44.2. This scenario indicates there are multiple configurations for both gas and electrically heated homes that are less expensive than the baseline scenario as well as having a lower ERI.

Building features that generally result in an ERI within the target range ERI (<52) for the large SFD include:

- Air Conditioner--SEER 16 (2 stage) unit
- Wall Sheathing—OSB with no continuous insulation
- Unfinished Attic—unvented open cell spray-foam on roof deck at a level of R-38

A distribution of the improvement options can be found in **Table 5**, displaying the percentage of models containing each improvement and the effect on the ERI range.

Table 5. Large SFD modeling options distribution.

Wall Sheathing	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_OSB	429	48%	32	63	49.2
DOER_R-10 XPS	145	16%	30	54	38.6
DOER_R-15 XPS	106	12%	29	53	36.2
DOER_R-5 XPS	218	24%	30	55	41.8
Unfinished Attic	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Ceiling R-38 Fiberglass, Vented	124	14%	30	63	48.0
DOER_Ceiling R-60 Cellulose, Vented	37	4%	30	57	43.5
DOER_Ceiling R-80 Cellulose, Vented	75	8%	29	56	38.6
DOER_Roof R-30 Open Cell Spray Foam, Unvented	123	14%	29	63	51.9
DOER_Roof R-38 Open Cell Spray Foam, Unvented	501	56%	29	60	42.2
MA_Ceiling R-49 Cellulose, Vented	38	4%	30	59	44.2
Finished Attic	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_R-30 Fiberglass Batt, 2x10	511	57%	29	63	47.3
DOER_R-38 Fiberglass Batt, 2x10	387	43%	29	57	40.0
Unfinished Basement	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Ceiling R-30 Fiberglass Batt	678	76%	29	61	42.1
DOER_Whole Wall R-21 Fiberglass Batt, 2x6, 24 in o.c.	40	4%	30	57	44.1
Whole Wall R-15 XPS	180	20%	30	63	51.8
Windows	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_U-0.18, 0.29 SHGC	153	17%	29	54	35.9
MA_U-0.25, 0.29 SHGC	40	4%	30	56	43.4
MA_U-0.28, 0.29 SHGC	705	79%	31	63	46.0
Air Leakage	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_0.6 ACH50	439	49%	29	57	39.3
DOER_2 ACH50	280	31%	32	62	47.0
DOER_3 ACH50	179	20%	34	63	51.7
Mechanical Ventilation	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2013, Exhaust	397	44%	34	63	50.1
MA_2013, HRV, 75%	501	56%	29	54	39.5
Central Air Conditioner	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_SEER 14.2	88	15%	34	63	50.4
DOER_SEER 16 (2 Stage)	485	85%	34	63	46.8
Furnace	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Gas, 95% AFUE	264	46%	34	63	51.9
DOER_Gas, 98% AFUE	309	54%	34	58	43.5
Mini-Split Heat Pump	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_SEER 18, 11 HSPF, Ductless	110	34%	30	56	45.2
MA_SEER 20, 12 HSPF, Ducted	14	4%	32	56	42.6
MA_SEER 20, 12 HSPF, Ductless	201	62%	29	48	34.5
Ducts	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**

DOER_2 CFM25 per 100ft2, R-6	264	29%	38	59	46.8
DOER_4 CFM25 per 100ft2, R-6	210	23%	32	63	52.5
DOER_In Finished Space	113	13%	34	53	38.6
None	311	35%	29	56	38.3
Water Heater	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Electric Premium 0.95 EF	42	5%	34	63	48.7
DOER_Electric Tankless 0.99 EF	42	5%	34	63	49.0
DOER_Gas Premium, Condensing 0.82 EF	42	5%	30	58	44.0
DOER_Gas Tankless 0.94 EF	730	81%	29	59	43.6
DOER_HPWH, 50 gal	42	5%	30	59	44.2

Townhouse

Figure 8. Townhouse modeling output, ERI vs. Incremental Cost.

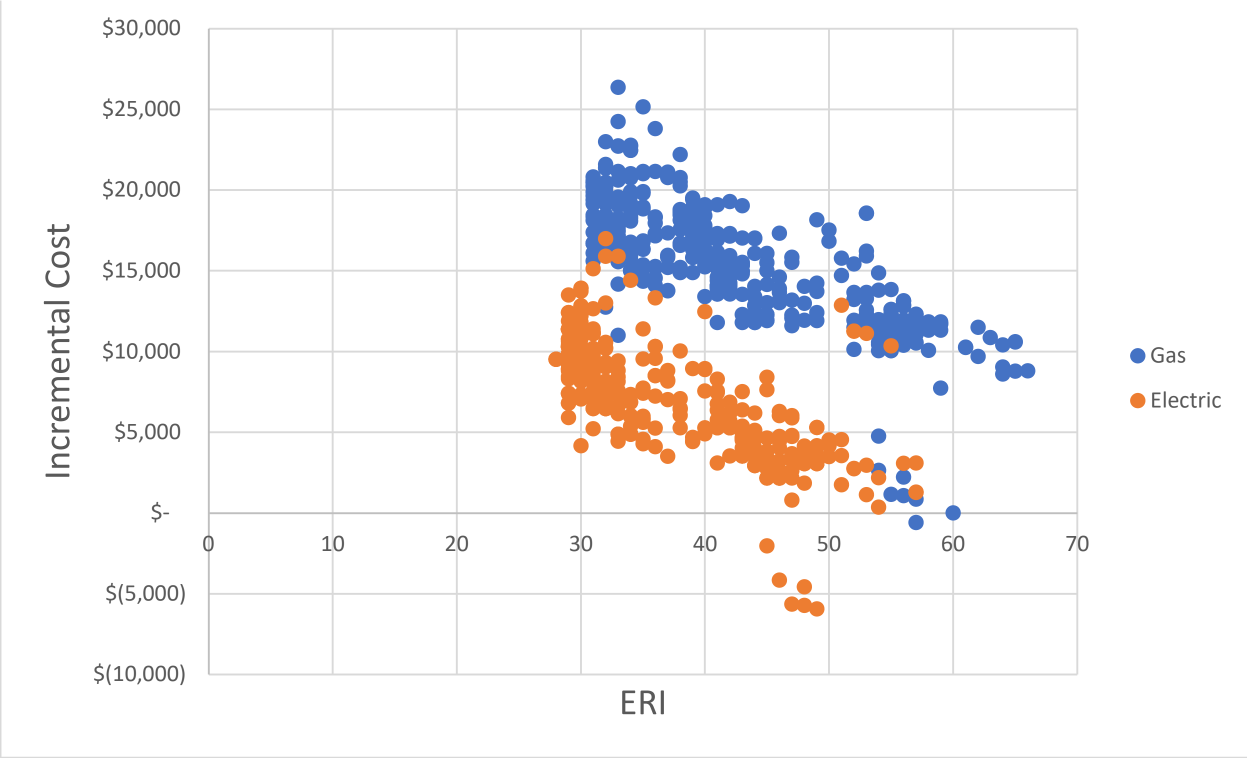


Figure 8 shows that the townhouse scenario generated 714 unique configurations with the minimum ERI at 28, the maximum at 66, and an average ERI of 40.4. This scenario continues the trend that electrically heated homes have lower incremental costs than gas heated homes. There are a limited set of configurations that give an incremental cost that's less than the baseline design.

Building features that generally result in an ERI within the target range (<52) for the townhouse include:

- Unfinished Attic--R-38 fiberglass, vented attic for all HVAC systems
- Windows--using double-pane U-0.28
- Unfinished Basement--using R-30 fiberglass in basement ceiling

A distribution of the improvement options can be found in **Table 6**, displaying the percentage of models containing each improvement and the effect on the ERI range.

Table 6. Townhouse modeling options distribution.

Wall Sheathing	Count	Percentage	Min ERI	Max ERI	Average ERI
DOER_OSB	320	45%	30	66	46.2
DOER_R-10 XPS	174	24%	29	54	35.2
DOER_R-15 XPS	102	14%	28	54	34.3
DOER_R-5 XPS	118	17%	29	55	38.0
Unfinished Attic	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Ceiling R-38 Fiberglass, Vented	396	55%	29	66	43.6
DOER_Ceiling R-60 Cellulose, Vented	95	13%	29	56	35.3
DOER_Ceiling R-80 Cellulose, Vented	129	18%	28	56	34.5
DOER_Roof R-30 Open Cell Spray Foam, Unvented	31	4%	30	59	41.0
DOER_Roof R-38 Open Cell Spray Foam, Unvented	31	4%	30	59	40.5
MA_Ceiling R-49 Cellulose, Vented	32	4%	29	60	40.2
Unfinished Basement	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Ceiling R-30 Fiberglass Batt	517	72%	28	64	38.5
DOER_Whole Wall R-21 Fiberglass Batt, 2x6, 24 in o.c.	32	4%	29	57	39.3
Whole Wall R-15 XPS	165	23%	29	66	46.8
Windows	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_U-0.18, 0.29 SHGC	179	25%	28	57	34.2
MA_U-0.25, 0.29 SHGC	33	5%	29	57	39.2
MA_U-0.28, 0.29 SHGC	502	70%	29	66	42.8
Air Leakage	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_0.6 ACH50	408	57%	28	56	35.1
DOER_2 ACH50	160	22%	30	64	45.1
DOER_3 ACH50	146	20%	32	66	50.3
Mechanical Ventilation	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2013, Exhaust	248	35%	37	66	50.4
MA_2013, HRV, 75%	466	65%	28	52	35.2
Central Air Conditioner	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_SEER 14.2	351	90%	31	66	43.5
DOER_SEER 16 (2 Stage)	40	10%	31	57	37.2
Furnace	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Gas, 95% AFUE	330	84%	31	66	44.2
DOER_Gas, 98% AFUE	61	16%	31	56	35.8
Mini-Split Heat Pump	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_SEER 18, 11 HSPF, Ductless	124	38%	29	57	41.9
MA_SEER 20, 12 HSPF, Ducted	13	4%	31	55	41.0
MA_SEER 20, 12 HSPF, Ductless	186	58%	28	51	34.3
Ducts	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2 CFM25 per 100ft2, R-6 (2)	37	5%	36	62	49.2
DOER_4 CFM25 per 100ft2, R-6 (2)	194	27%	31	66	48.5

DOER_In Finished Space	173	24%	31	53	35.1
None	310	43%	28	57	37.4
Water Heater	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Electric Premium 0.95 EF	35	5%	35	65	45.8
DOER_Electric Tankless 0.99 EF	35	5%	35	66	46.1
DOER_Gas Premium, Condensing 0.82 EF	35	5%	29	58	39.7
DOER_Gas Tankless 0.94 EF (2)	574	80%	28	60	39.8
DOER_HPWH, 50 gal	35	5%	29	61	40.6

6-unit Multifamily

Figure 9. 6-unit multifamily modeling output, ERI vs. Incremental Cost.

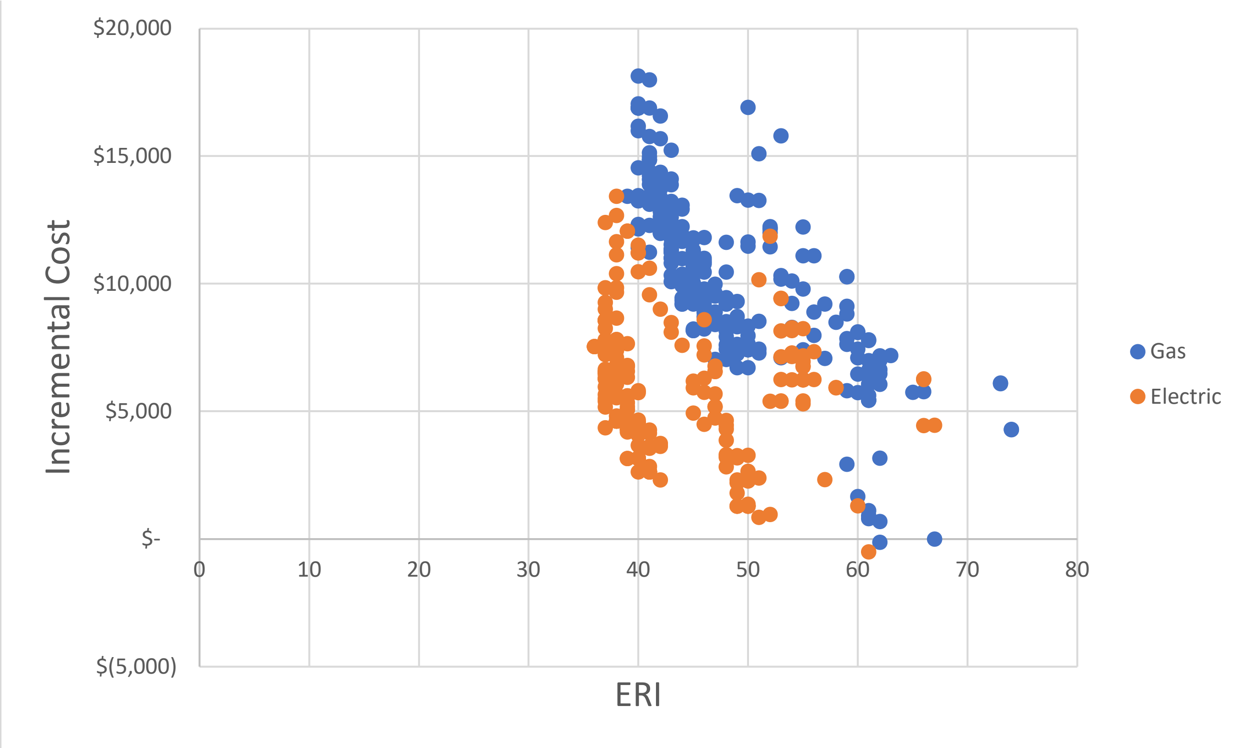


Figure 9 shows that the 6-unit multifamily scenario generated 470 unique configurations with the minimum ERI at 36, the maximum at 74, and an average ERI of 46.2. This scenario shows a larger overlap of optimal configurations for both gas and electric heating than the previous scenarios.

Building features that generally result in an ERI within the target range (<52) 6-unit multifamily include:

- Furnace--95% AFUE furnace
- Mechanical Ventilation--HRV becomes necessary to achieve a low ERI in this scenario
- Ducts—leakage to outside of 4 CFM25 per 100 ft²

A distribution of the improvement options can be found in **Table 7**, displaying the percentage of models containing each improvement and the effect on the ERI range.

Table 7. 6-unit multifamily modeling options distribution.

Wall Sheathing	Count	Percentage	Min ERI	Max ERI	Average ERI
DOER_OSB	192	41%	37	74	50.7
DOER_R-10 XPS	132	28%	37	60	42.8
DOER_R-15 XPS	84	18%	36	59	42.5
DOER_R-5 XPS	62	13%	37	61	44.9
Unfinished Attic	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Ceiling R-38 Fiberglass, Vented	204	43%	37	74	49.3
DOER_Ceiling R-60 Cellulose, Vented	87	19%	37	61	44.0
DOER_Ceiling R-80 Cellulose, Vented	112	24%	36	61	42.9
DOER_Roof R-30 Open Cell Spray Foam, Unvented	22	5%	37	62	45.3
DOER_Roof R-38 Open Cell Spray Foam, Unvented	22	5%	37	61	44.8
MA_Ceiling R-49 Cellulose, Vented	23	5%	37	67	45.9
Windows	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_U-0.18, 0.29 SHGC	159	34%	36	60	42.5
MA_U-0.25, 0.29 SHGC	24	5%	37	62	44.6
MA_U-0.28, 0.29 SHGC	287	61%	37	74	48.5
Air Leakage	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_0.6 ACH50	271	58%	36	61	42.8
DOER_2 ACH50	56	12%	38	62	45.3
DOER_3 ACH50	143	30%	39	74	53.2
Mechanical Ventilation	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2013, Exhaust	116	25%	45	74	56.6
MA_2013, HRV, 75%	354	75%	36	61	42.8
Central Air Conditioner	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_SEER 14.2	247	100%	39	74	48.5
Furnace	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Gas, 95% AFUE	216	87%	40	74	49.2
DOER_Gas, 98% AFUE	31	13%	39	61	43.9
Mini-Split Heat Pump	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_SEER 18, 11 HSPF, Ducted	48	22%	38	67	52.6
MA_SEER 20, 12 HSPF, Ducted	11	5%	37	54	42.1
MA_SEER 20, 12 HSPF, Ductless	164	74%	36	61	41.2
Ducts	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2 CFM25 per 100ft2, R-6	14	3%	41	62	48.2
DOER_4 CFM25 per 100ft2, R-6	229	49%	37	74	50.5
DOER_In Finished Space	63	13%	39	59	43.4
None	164	35%	36	61	41.2
Water Heater	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Electric Premium 0.95 EF	26	6%	46	73	54.1
DOER_Electric Tankless 0.99 EF	26	6%	46	74	54.7
DOER_Gas Premium, Condensing 0.82 EF	26	6%	38	63	45.2

DOER_Gas Tankless 0.94 EF	366	78%	36	67	45.2
DOER_HPWH, 50 gal	26	6%	37	66	46.1

4-story Multifamily

Figure 10. 4-story multifamily modeling output, ERI vs. Incremental Cost.

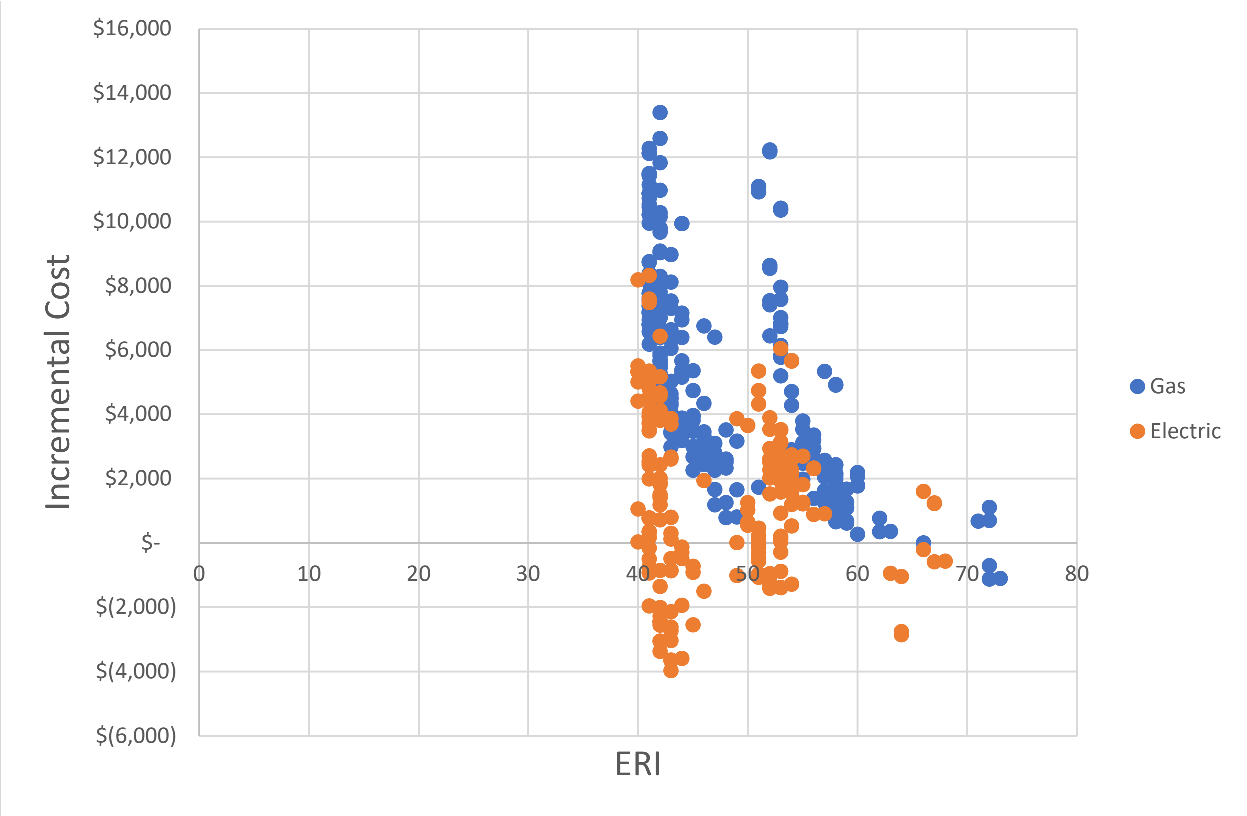


Figure 10 shows that the 4-story multifamily scenario generated 442 unique configurations with the minimum ERI at 40, the maximum at 73, and an average ERI of 48. Similar to the 6-unit scenario, the 4-story scenario also sees some overlap with lower ERI for both gas and electric heating.

Building features that generally result in an ERI within the target range ERI (<52) for the 4-story multifamily include:

- Ducts—leakage to outside of 4 CFM_{25} per 100 ft^2.
- Furnace—95% AFUE
- Wall Sheathing—OSB with no continuous insulation

A distribution of the improvement options can be found in **Table 8**, displaying the percentage of models containing each improvement and the effect on the ERI range.

Table 8. 4-story multifamily modeling options distribution.

Wall Sheathing	Count	Percentage	Min ERI	Max ERI	Average ERI
DOER_OSB	203	46%	41	73	51.6
DOER_R-10 XPS	61	14%	40	58	45.4
DOER_R-15 XPS	118	27%	40	58	44.5
DOER_R-5 XPS	60	14%	40	58	45.5
Finished Roof	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_R-30 Fiberglass Batt, 2x10	156	35%	41	73	52.2
DOER_R-38C Fiberglass Batt, 2x10, R-24 Polyiso	286	65%	40	66	45.7
Windows	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_U-0.18, 0.29 SHGC	162	37%	40	56	44.1
MA_U-0.25, 0.29 SHGC	27	6%	41	58	45.9
MA_U-0.28, 0.29 SHGC	253	57%	41	73	50.7
Air Leakage	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_0.6 ACH50	242	55%	40	58	44.4
DOER_2 ACH50	66	15%	42	64	47.9
DOER_3 ACH50	134	30%	43	73	54.6
Mechanical Ventilation	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2013, Exhaust	143	32%	49	73	56.1
MA_2013, HRV, 75%	299	68%	40	60	44.2
Central Air Conditioner	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_SEER 14.2	146	60%	41	73	49.3
DOER_SEER 16 (2 Stage)	99	40%	41	72	46.6
Furnace	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Gas, 95% AFUE	201	82%	41	73	49.0
DOER_Gas, 98% AFUE	44	18%	41	58	44.5
Mini-Split Heat Pump	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
MA_SEER 18, 11 HSPF, Ducted	54	27%	41	68	53.1
MA_SEER 20, 12 HSPF, Ducted	12	6%	40	53	45.2
MA_SEER 20, 12 HSPF, Ductless	131	66%	40	64	45.9
Ducts	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_2 CFM25 per 100ft2, R-6	45	10%	41	59	45.4
DOER_4 CFM25 per 100ft2, R-6	221	50%	40	73	50.4
DOER_In Finished Space	45	10%	41	58	45.1
None	131	30%	40	64	45.9
Water Heater	**Count**	**Percentage**	**Min ERI**	**Max ERI**	**Average ERI**
DOER_Electric Premium 0.95 EF	28	6%	51	72	57.5
DOER_Electric Tankless 0.99 EF	28	6%	52	73	58.0
DOER_Gas Premium, Condensing 0.82 EF	28	6%	42	60	47.3
DOER_Gas Tankless 0.94 EF	318	72%	40	66	46.7
DOER_HPWH, 50 gal	40	9%	40	63	45.6

Step 4: Selecting Optimal Packages

As stated in

Step 1: Baseline Model Development, the generated ERI from BEopt does not translate to an equivalent HERS rating. Therefore, the optimal configurations for each scenario HERS rating target were modeled in REM/Rate to ensure a RESNET-approved building configuration that was influenced by BEopt output.

To meet the targets that were described in Step 3: Modeling Optimization, **Table 3**, a selection of configurations that were expected to meet specified HERS ratings, based on the correlation with ERI found in Step 1, was chosen. These configurations were selected by sorting the model output data from BEopt first by ERI, then by the lowest incremental cost, for each scenario for each building type. This gave the most cost-effective configuration to achieve that ERI.

The baseline REM models that were created in Step 1 were modified based on the improvement options found in the optimal configuration. If the first selected optimal configuration did not achieve the target HERS rating in REM, then the second configuration was examined. This process was repeated until each scenario target was found. For some instances, an optimal configuration would be near the target HERS rating and a slight modification, such as switching the furnace, was considered. These modifications were then remodeled in BEopt to check if they still fell in the optimal selection window before deciding that configuration would be the optimal configuration for that scenario.

Table 9 shows the selected point, or modeled building improvement options configuration, from each scenario to meet the target HERS rating.

Table 9. Selected optimal BEopt configurations.

Building Types		**Gas**		**Electric**	
		REM/Rate		REM/Rate	
		HERS 47	HERS 42	HERS 52 CCHP	HERS 47 CCHP
Single-Family	2,100 sqft 3-bed	Iter 25, Pt 24 (Optimal 15)	Iter 3, Pt 1 (new run)	Iter 19, Pt 22 (Optimal #11)	Iter 24, Pt 5
	4,030 sqft 5-bed	Optimal #17	SFD_large_ERI40.xlsx Iter 3, Pt 1	Iter 20, Pt 2-rerun	Iter 20, Pt 21-rerun
Townhouse	2,087 sqft 3-bed	Iter 12, Pt 5 (modified with 92% AFUE)	Iter 11, Pt 7, Optimal #10	Iter 12, Pt 3-Opt#9 - rerun	Iter 12, Pt 4-rerun
Multifamily	Small 6-unit building	Iter 20, Pt 16 (with 2 cfm ducts and exhaust only)	Iter 17, Pt 6	Iter 6, Pt 16	Iter 10, Pt 16
	Large (wood-frame) 4-story over podium	Iter 16, Pt 22	Iter 5, Pt 16	Iter 14, Pt 7	Iter 15, Pt 10

The following subsections display what options were chosen for the optimal configuration for each scenario across each building type, along with the REM/Rate generated Home Energy Rating Certificate (HERC) to demonstrate how the BEopt configurations transferred over to REM. The full REM HERS Building Reports and Certificates are available in Appendix A2.

For additional comparison, the REM models were also created in Ekotrope, an alternative RESNET-accredited energy modeling software that provides HERS ratings. This was done to ensure that the optimal configurations generated from BEopt could result in HERS rating that meet the target rating for each scenario in more than one accredited software.
Table 10 shows a comparison of recreating the REM/Rate model for each scenario in Ekotrope.

Table 10. Comparison of HERS ratings in REM/Rate and Ekotrope software.

Building Type	Heating	REM/Rate	Ekotrope	Difference
Small SFD	Gas	47	44	3
Small SFD	Gas	42	39	3
Small SFD	Electric	52	42	10
Small SFD	Electric	47	38	9
Large SFD	Gas	42	41	1
Large SFD	Gas	47	45	2
Large SFD	Electric	52	49	3
Large SFD	Electric	52	55	-3
Large SFD	Electric	47	42	5
Townhouse	Gas	47	49	-2
Townhouse	Gas	47	47	0
Townhouse	Electric	52	53	-1
Townhouse	Electric	47	49	-2
6-unit Multifamily	Gas	47	46	1
6-unit Multifamily	Gas	42	44	-2
6-unit Multifamily	Electric	52	42	10
6-unit Multifamily	Electric	47	37	10
4-story Multifamily	Gas	47	44	3
4-story Multifamily	Gas	42	41	1
4-story Multifamily	Electric	52	42	10
4-story Multifamily	Electric	47	36	11

Table 10 shows that there are varying degrees of difference depending upon what software is used when determining a building's HERS rating through energy modeling. It is most apparent here in the multifamily cases, ranging between -2 to 10. There is widespread anecdotal evidence of the lack of alignment between results from various rating modeling tools; RESNET's Software Consistency Committee is currently investigating the issue.

SFD Small

Initial BEopt Option Selections

Table 11. Small SFD BEopt scenario selections.

Building Type	SFD Small - Baseline	SFD Small - Gas	SFD Small - Gas	SFD Small - Electric	SFD Small - Electric
Point	User-Defined	Iter 25, Pt 24	Iter 3, Pt 1	Iter 19, Pt 22	Iter 24, Pt 5
HERS Index	55	47	42	52	47
Wall Sheathing	OSB	R-10 XPS	R-10 XPS	R-5 XPS	R-5 XPS
Interzonal Walls	R-21 Fiberglass Batt, 2x6, 16 in o.c.	R-21 Fiberglass Batt, 2x6, 16 in o.c.	R-21 Fiberglass Batt, 2x6, 16 in o.c.	R-21 Fiberglass Batt, 2x6, 16 in o.c.	R-21 Fiberglass Batt, 2x6, 16 in o.c.
Unfinished Attic	Ceiling R-49 Cellulose, Vented	Ceiling R-38 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented	Ceiling R-38 Fiberglass, Vented	Roof R-38 Open Cell Spray Foam, Unvented
Finished Roof	R-30 Fiberglass Batt, 2x10	R-38C Fiberglass Batt, 2x10, R-24 Polyiso	R-38C Fiberglass Batt, 2x10, R-24 Polyiso	R-30 Fiberglass Batt, 2x10	R-30 Fiberglass Batt, 2x10
Unfinished Basement	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt
Windows	U-0.28, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC
Air Leakage	3 ACH50	3 ACH50	2 ACH50	2 ACH50	2 ACH50
Mechanical Ventilation	2013, Exhaust	2013, Exhaust	2013, ERV, 83%	2013, Exhaust	2013, Exhaust
Electric Baseboard	NA	NA	NA	100% Efficiency	100% Efficiency
Central Air Conditioner	SEER 14.2	SEER 13	SEER 13	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Furnace	Gas, 95% AFUE	Gas, 98% AFUE	Gas, 98% AFUE	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Ducts	4 CFM25 per 100ft2, R-6	2 CFM25 per 100ft2, R-6	2 CFM25 per 100ft2, R-6	4 CFM25 per 100ft2, R-6	2 CFM25 per 100ft2, R-6
Water Heater	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	HPWH, 50 gal	HPWH, 50 gal
Lighting	75% LED	100% LED	100% LED	90% LED	100% LED
Refrigerator	633 kWh	550 kWh	550 kWh	633 kWh	550 kWh
Cooking Range	Gas	Gas	Gas	Electric	Electric
Clothes Washer	Standard	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR
Clothes Dryer	Gas	Gas, Premium	Gas, Premium	Electric, Premium	Electric, Premium

SFD Large

BEopt Option Selections

Table 12. Large SFD BEopt scenario selections.

Building Type	SFD Large - Baseline	SFD Large - Gas	SFD Large - Gas	SFD Large - Electric	SFD Large - Electric
Point	User-Defined	Iter 25, Pt 8	Iter 3, Pt 1	Iter 20, Pt 2-rerun	Iter 20, Pt 21-rerun
HERS Index	55	47	42	52	47
Wall Sheathing	OSB	OSB	R-5 XPS	R-10 XPS	OSB
Interzonal Walls	R-21 Fiberglass Batt, 2x6, 16 in o.c.	R-21 Fiberglass Batt, 2x6, 16 in o.c.	R-21 Fiberglass Batt, 2x6, 16 in o.c.	R-21 Fiberglass Batt, 2x6, 16 in o.c. (2)	R-21 Fiberglass Batt, 2x6, 16 in o.c. (2)
Unfinished Attic	Ceiling R-49 Cellulose, Vented	Roof R-38 Open Cell Spray Foam, Unvented	Roof R-38 Open Cell Spray Foam, Unvented	Roof R-30 Open Cell Spray Foam, Unvented (2)	Roof R-30 Open Cell Spray Foam, Unvented (2)
Finished Roof	R-30 Fiberglass Batt, 2x10	R-30 Fiberglass Batt, 2x10	R-30 Fiberglass Batt, 2x10	R-30 Fiberglass Batt, 2x10 (2)	R-30 Fiberglass Batt, 2x10 (2)
Unfinished Basement	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt	Whole Wall R-15 XPS (2)	Whole Wall R-15 XPS
Windows	U-0.28, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC
Air Leakage	3 ACH50	2 ACH50	2 ACH50	2 ACH50	2 ACH50
Mechanical Ventilation	2013, Exhaust	2013, Exhaust	2013, Exhaust	2013, Exhaust	2013, ERV, 70%
Electric Baseboard	NA	NA	NA	100% Efficiency	100% Efficiency
Central Air Conditioner	SEER 13	SEER 16 (2 Stage)	SEER 16 (2 Stage)	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Furnace	Gas, 92% AFUE	Gas, 98% AFUE	Gas, 98% AFUE	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Ducts	4 CFM25 per 100ft2, R-6	2 CFM25 per 100ft2, R-6	In Finished Space	4 CFM25 per 100ft2, R-6	2 CFM25 per 100ft2, R-6
Water Heater	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Electric Tankless 0.99 EF	HPWH, 50 gal
Lighting	75% LED	100% LED	100% LED	100% LED	100% LED
Refrigerator	633 kWh	550 kWh	550 kWh	633 kWh	633 kWh
Cooking Range	Gas	Gas	Gas	Electric	Electric
Dishwasher	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh
Clothes Washer	Standard	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR
Clothes Dryer	Electric, Standard	Gas, Premium	Gas, Premium	Electric, Premium	Electric, Premium

Townhouse

BEopt Option Selections

Table 13. Townhouse BEopt scenario selections.

Building Type	Townhouse - Baseline	Townhouse End Unit - Gas	Townhouse End Unit - Gas	Townhouse End Unit - Electric	Townhouse End Unit - Electric
Point	User-Defined	Iter 12, Pt 5 (adjusted 92% AFUE)	Iter 11, Pt 7	Iter 12, Pt 3-Opt#9 - rerun	Iter 12, Pt 4-rerun
HERS	55	47	42	52	47
Wall Sheathing	OSB	OSB	OSB	R-5 XPS	R-5 XPS
Unfinished Attic	Ceiling R-49 Cellulose, Vented	Ceiling R-60 Cellulose, Vented	Ceiling R-60 Cellulose, Vented	Ceiling R-60 Cellulose, Vented	Ceiling R-60 Cellulose, Vented
Unfinished Basement	Ceiling R-30 Fiberglass Batt	Ceiling R-30 Fiberglass Batt	Whole Wall R-15 XPS	Whole Wall R-15 XPS	Whole Wall R-15 XPS
Windows	U-0.28, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC
Air Leakage	3 ACH50	3 ACH50	2 ACH50	2 ACH50	2 ACH50
Mechanical Ventilation	2013, Exhaust	2013, ERV, 70%	2013, ERV, 83%	2013, ERV, 70%	2013, ERV, 83%
Electric Baseboard	NA	NA	NA	100% Efficiency	100% Efficiency
Central Air Conditioner	SEER 13	SEER 13	SEER 13	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Furnace	Gas, 92% AFUE	Gas, 92% AFUE	Gas, 95% AFUE	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Ducts	4 CFM25 per 100ft2, R-6	4 CFM25 per 100ft2, R-6	4 CFM25 per 100ft2, R-6	4 CFM25 per 100ft2, R-6	In Finished Space
Water Heater	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Electric Tankless 0.99 EF	Electric Tankless 0.99 EF
Lighting	75% LED	100% LED	100% LED	90% LED	100% LED
Refrigerator	633 kWh	550 kWh	550 kWh	633 kWh	633 kWh
Cooking Range	Gas	Gas	Gas	Electric	Electric
Dishwasher	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh
Clothes Washer	Standard	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR
Clothes Dryer	Electric, Standard	Gas, Premium	Gas, Premium	Electric, Standard	Electric, Standard

6-unit Multifamily

BEopt Option Selections

Table 14. 6-unit multifamily BEopt scenario selections.

Building Type	6-unit MF Top End - Baseline	6-unit MF Top End - Gas	6-unit MF Top End - Gas	6-unit MF Top End - Electric	6-unit MF Top End - Electric
Point	User-Defined	Iter 20, Pt 16 (mod w ducts 2 cfm & mech vent exh only)	Iter 17, Pt 6	Iter 6, Pt 16	Building: Iter 10, Pt 16
HERS	55	47	42	52	47
Wall Sheathing	OSB	OSB	OSB	OSB	OSB
Unfinished Attic	Ceiling R-38 Fiberglass, Vented	Ceiling R-60 Cellulose, Vented	Ceiling R-38 Fiberglass, Vented	Roof R-30 Open Cell Spray Foam, Unvented	Roof R-38 Open Cell Spray Foam, Unvented
Windows	U-0.28, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.28, 0.29 SHGC	U-0.18, 0.29 SHGC
Air Leakage	3 ACH50	2 ACH50	3 ACH50	3 ACH50	3 ACH50
Mechanical Ventilation	2013, Exhaust	2013, Exhaust	2013, ERV, 70%	2013, Exhaust	2013, Exhaust
Electric Baseboard	NA	NA	NA	100% Efficiency	100% Efficiency
Central Air Conditioner	SEER 13	SEER 13	SEER 13	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Furnace	Gas, 92% AFUE	Gas, 95% AFUE	Gas, 95% AFUE	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Ducts	4 CFM25 per 100ft2, R-6	2 CFM25 per 100ft2, R-6	4 CFM25 per 100ft2, R-6	4 CFM25 per 100ft2, R-6	4 CFM25 per 100ft2, R-6
Water Heater	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	HPWH, 50 gal	HPWH, 50 gal
Lighting	75% LED	100% LED	100% LED	90% LED	90% LED
Refrigerator	633 kWh	550 kWh	550 kWh	633 kWh	633 kWh
Cooking Range	Gas	Gas	Gas	Electric	Electric
Dishwasher	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh
Clothes Washer	Standard	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR
Clothes Dryer	Electric, Standard	Gas, Premium	Gas, Premium	Electric, Standard	Electric, Standard

4-story Multifamily

BEopt Option Selections

Table 15. 4-story multifamily BEopt scenario selections.

Building Type	4 story MF Inside Unit - Baseline	4 story MF Inside Unit - Gas	4 story MF Inside Unit - Gas	4 story MF Inside Unit - Electric	4 story MF Inside Unit - Electric
Point	User-Defined	Iter 5, Pt 16	ter 16, Pt 22	Iter 14, Pt 7	Iter 15, Pt 10
HERS	55	42	47	52	47
Wall Sheathing	OSB	OSB	OSB	OSB	OSB
Finished Roof	R-30 Fiberglass Batt, 2x10	R-38 Fiberglass Batt, 2x10	R-38 Fiberglass Batt, 2x10	R-38 Fiberglass Batt, 2x10	R-38 Fiberglass Batt, 2x10
Windows	U-0.28, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC	U-0.18, 0.29 SHGC
Air Leakage	3 ACH50	3 ACH50	2 ACH50	3 ACH50	3 ACH50
Mechanical Ventilation	2013, Exhaust	2013, ERV, 70%	2013, Exhaust	2013, ERV, 83%	2013, Exhaust
Electric Baseboard	None	None	None	100% Efficiency	100% Efficiency
Central Air Conditioner	SEER 14.2	SEER 13	SEER 13	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Furnace	Gas, 95% AFUE	Gas, 95% AFUE	Gas, 98% AFUE	SEER 19.95, 11 HSPF, Ducted	SEER 19.95, 11 HSPF, Ducted
Ducts	In Finished Space	In Finished Space	In Finished Space	In Finished Space	In Finished Space
Water Heater	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Gas Tankless 0.94 EF	Electric Tankless 0.99 EF	HPWH, 50 gal
Lighting	75% LED	100% LED	100% LED	90% LED	75% LED
Refrigerator	633 kWh	550 kWh	550 kWh	550 kWh	550 kWh
Cooking Range	Gas	Gas	Gas	Electric	Electric
Dishwasher	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh	264 Rated kWh
Clothes Washer	Standard	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR
Clothes Dryer	Gas	Gas, Premium	Gas, Premium	Electric, Premium	Electric, Premium

Step 5: PHIUS+ Scenario

Using the same baseline geometry of the five building types in the previous steps, these buildings were evaluated to determine what options are needed to meet PHIUS+ 2018 standards. A new set of building improvement options that are common to passive house designs were added to BEopt for modeling optimization. This included new options in the exterior wall construction, wall sheathing, roof, basement, windows, HVAC system, water heater, and some appliances. Additionally, three changes were made to the building geometry: conditioned basements, window areas and building orientation. Conditioned basements were added to each scenario, window areas were decreased in line with passive house design, and the front of each building is facing south where in the previous cases they all had a west-facing orientation.

The methodology for Step 5 relatively follows the same used in Steps 1 – 4. The difference being that the optimal configuration was selected by sorting the output data for each scenario by "Source Energy Consumption" on a kBtu/ft² basis, followed by the AERC to provide the most cost-effective configuration. The reasoning for this is that PHIUS+ does not use ERI or HERS for determining if a building meets their 2018 standards, but rather a set of criteria based on the kBtu/ft²-iCFA/year (iCFA - interior conditioned floor area) of the annual heat and cooling demand, as well as the peak heating and cooling load. Figure 11 through Figure 16 show the percent source energy savings over the baseline for each scenario. Percent source energy savings was chosen to be displayed as it gives a clearer insight on how each option configuration performed. The baseline in these cases are configurations using the lowest performance options of the passive house options.

Figure 11. Small SFD with conditioned basement AERC vs. % source energy savings over baseline.

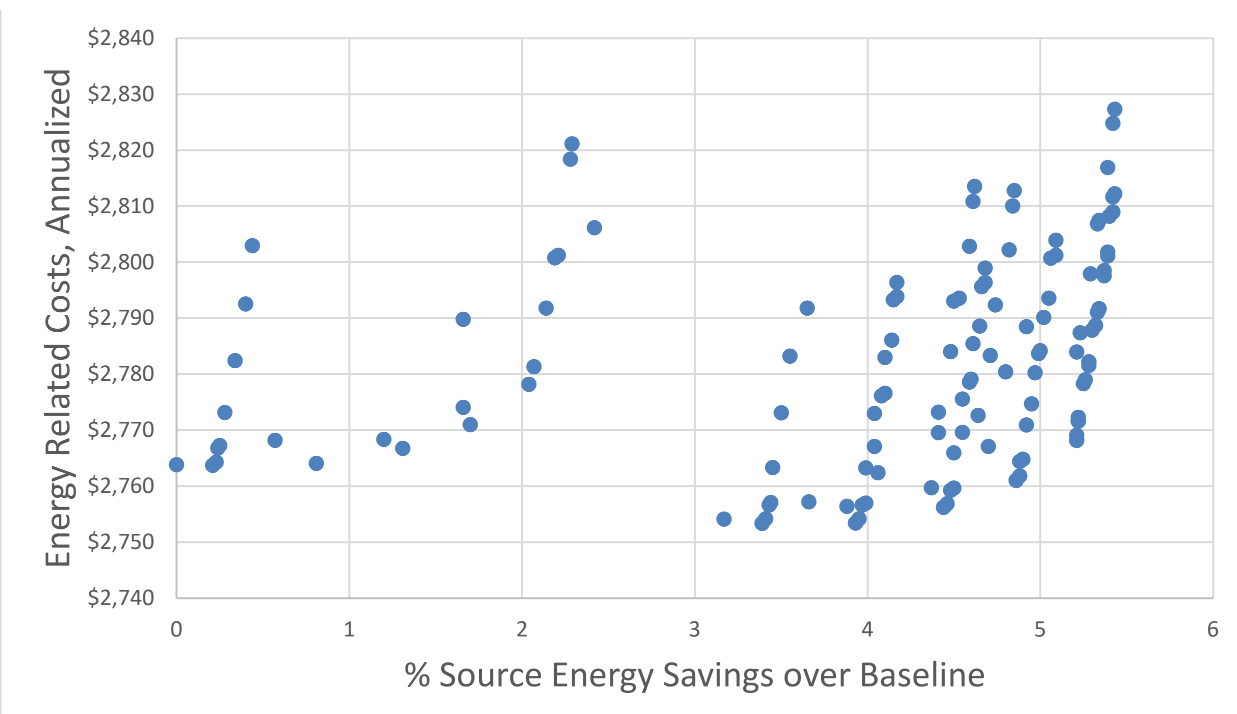


Figure 12. Small SFD with unconditioned basement AERC vs. % source energy savings over baseline.

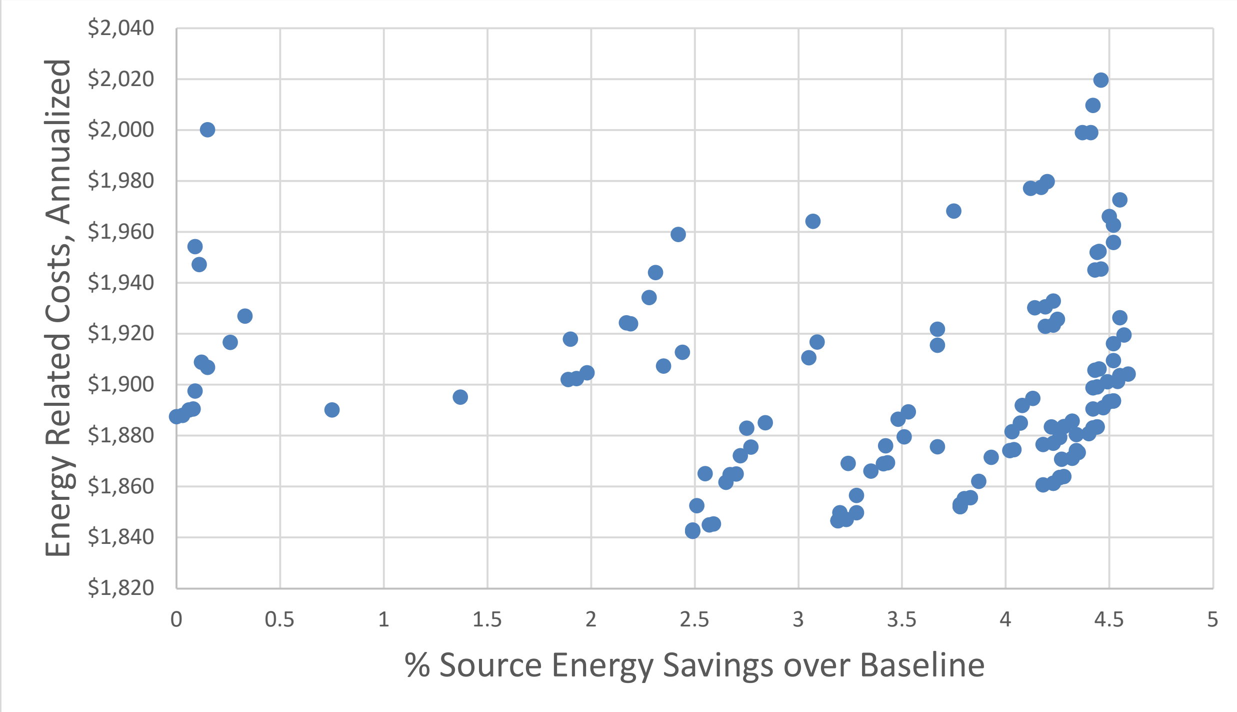


Figure 13. Large SFD AERC vs. % source energy savings over baseline.

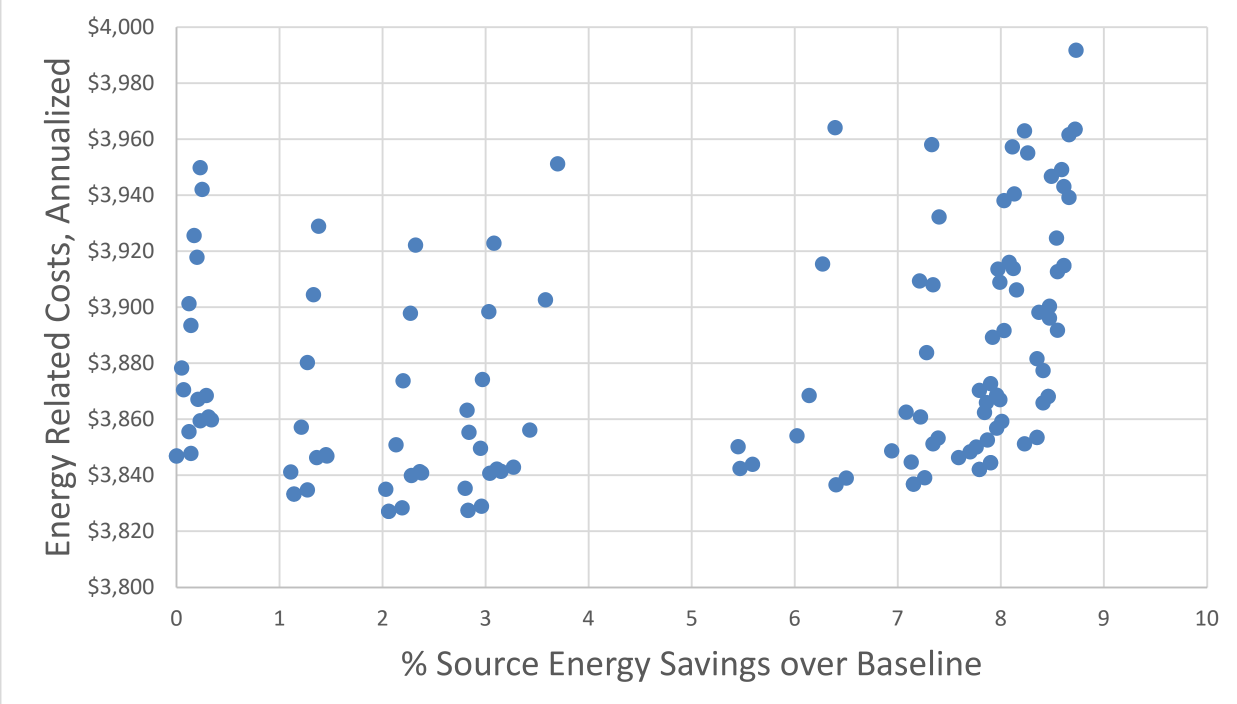


Figure 14. Townhouse AERC vs. % source energy savings over baseline.

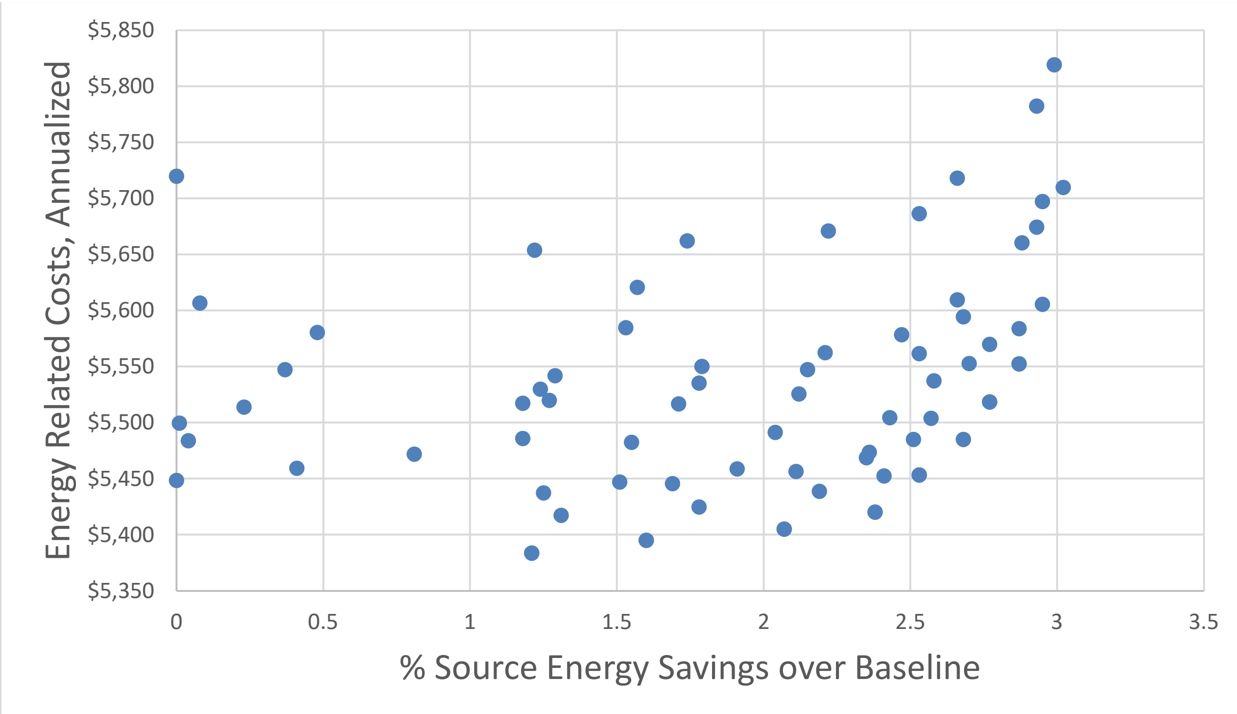


Figure 15. 6-unit multifamily AERC vs. % source energy savings over baseline.

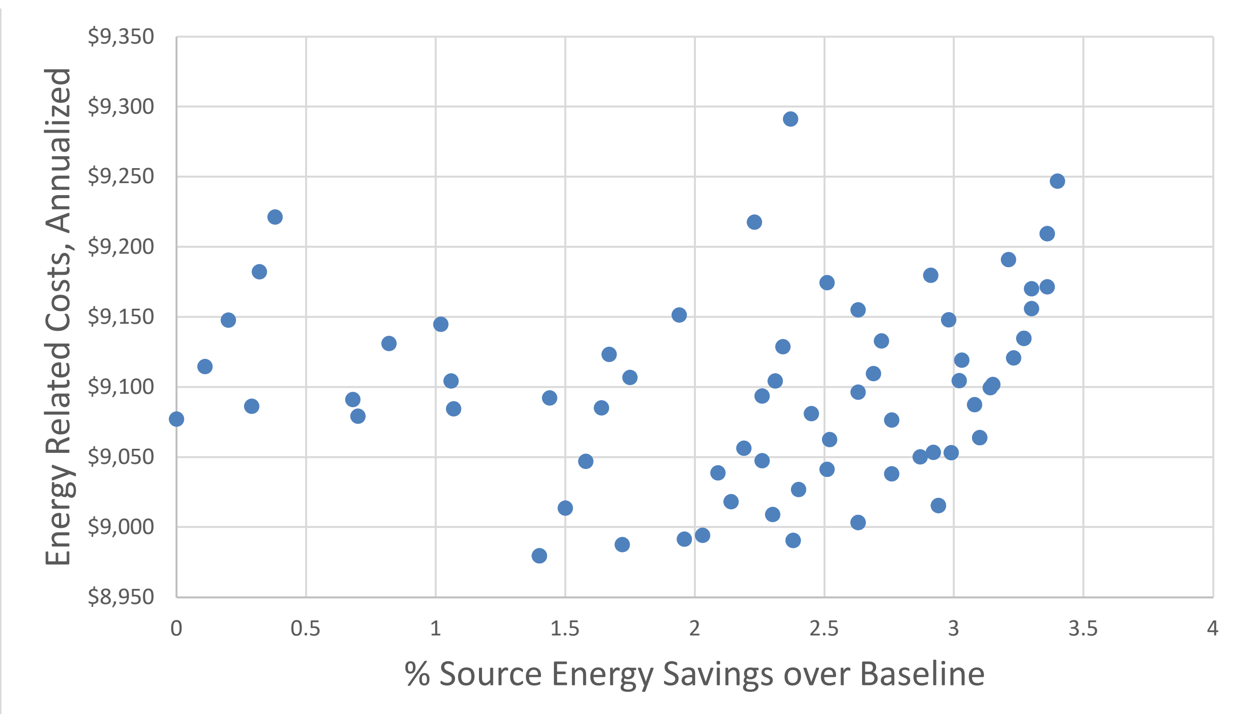
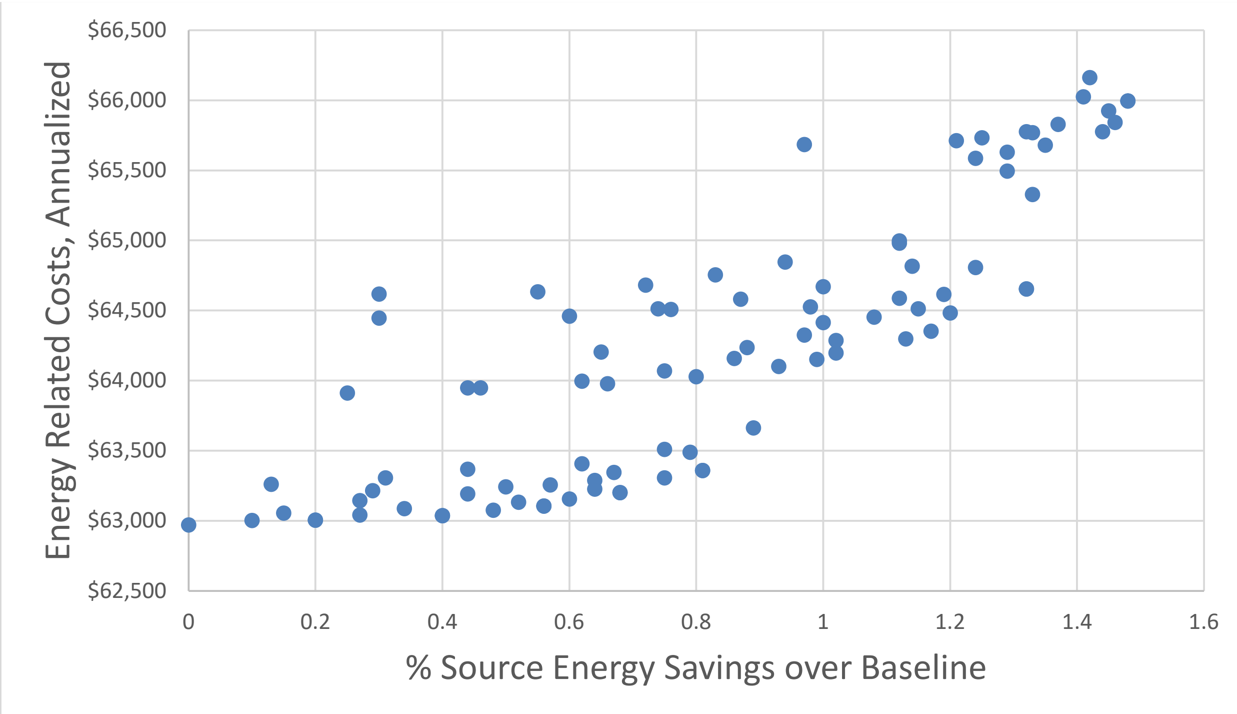


Figure 16. 4-story multifamily AERC vs. % source energy savings over baseline.



A selection of optimal BEopt configurations for each scenario were then entered in the WUFI software to evaluate if they met the passive house criteria. Due to differences in software designs, building options were not completely transferrable between BEopt and WUFI and therefore some modifications to the optimal BEopt options were needed, mainly the envelope assemblies of the roof and basement. These optimal configurations are given in Table 16, and these options translated into WUFI are given in Table 17.

Table 18 gives the PHIUS+ 2018 criteria for meeting passive house standards in Worchester, MA and where the building modeled in WUFI stand in relation to those standards. All scenarios were able to meet the annual heating and cooling demand as well as the peak heating and cooling load based on the inputs from Table 17. The data for Table 18 comes from the output reports from WUFI. Full WUFI reports, as well as the source energy requirements used are included in Appendix A.

Table 16. Optimal BEopt chosen configurations

Option	SFD - Conditioned	SFD - Unconditioned	Townhouse	Large SFD	6-unit Multifamily	4-story Multifamily
Point	Optimal #2	Iter 2, Pt 4	Building: Optimal #1	Iter 3, Pt 8	Building: User-Defined	Building: Iter 3, Pt 5
Orientation	South	South	South	South	South	South
Wood Stud	R-19 Cellulose, 2x6, 24 in o.c.	R-19 Cellulose, 2x6, 24 in o.c.	R-19 Cellulose, 2x6, 24 in o.c.	R-19 Cellulose, 2x6, 24 in o.c.	R-19 Cellulose, 2x6, 24 in o.c.	R-19 Cellulose, 2x6, 24 in o.c.
Wall Sheathing	R-6 Polyiso 2 in	R-6 Polyiso 4 in	R-6 Polyiso 2 in	R-6 Polyiso 2.5 in	R-6 Polyiso 2 in	R-6 Polyiso 3 in
Unfinished Attic	Ceiling R-60 Cellulose, Vented 19 in	Ceiling R-60 Cellulose, Vented 19 in	Ceiling R-60 Cellulose, Vented 19 in	Ceiling R-60 Cellulose, Vented 19 in	Ceiling R-60 Cellulose, Vented 19 in	None
Finished Roof	R-36 Cellulose, 14 TJI, R-24 4 in Polyiso	R-36 Cellulose, 14 TJI, R-24 4 in Polyiso	None	R-36 Cellulose, 14 TJI, R-24 4 in Polyiso	None	10 in Polyiso R-60
Finished Basement	Whole Wall R-13 Fiberglass Batt, 2x4, 16 in o.c., R-10 XPS	None	5 in polyiso R-30	Whole Wall R-19 Fiberglass Batt, 2x6, 24 in o.c.	None	None
Unfinished Basement	None	5 in polyiso R-30	None	None	None	None
Slab	None	None	None	None	Whole Slab EPS 4 in R-16.8	None
Interzonal Floor	R-30 Fiberglass	None	R-30 Cellulose	None	None	6 in Polyiso R-36
Windows	U-0.14, 0.5 SHGC	U-0.14, 0.5 SHGC	U-0.14, 0.5 SHGC	U-0.14, 0.5 SHGC	U-0.14, 0.3 SHGC	U-0.14, 0.3 SHGC
Air Leakage	0.6 ACH50	0.6 ACH50	0.6 ACH50	0.6 ACH50	0.6 ACH50	0.6 ACH50
Mechanical Ventilation	2013, ERV, 83%	2013, ERV, 83%	2013, ERV, 83%	2013, ERV, 83%	2013, ERV, 83%	2013, ERV, 83%
Electric Baseboard	100% Efficiency	100% Efficiency	100% Efficiency	100% Efficiency	100% Efficiency	100% Efficiency
Air-source Heat Pump	SEER 26, 10 HSPF, Ducted	SEER 26, 10 HSPF, Ducted	SEER 26, 10 HSPF, Ducted	SEER 26, 10 HSPF, Ducted	SEER 26, 10 HSPF, Ducted	SEER 26, 10 HSPF, Ducted
Ducts	In Finished Space	In Finished Space	In Finished Space	In Finished Space	In Finished Space	In Finished Space
Cooling Set Point	77 F Programmable	77 F Programmable	77 F Programmable	77 F Programmable	77 F Programmable	77 F Programmable
Heating Set Point	68 F Programmable	68 F Programmable	68 F Programmable	68 F Programmable	68 F Programmable	68 F Programmable
Water Heater	HPWH, 50 gal 3.61 EF	HPWH, 50 gal 3.61 EF	HPWH, 50 gal 3.61 EF	HPWH, 50 gal 3.61 EF	HPWH, 50 gal 3.61 EF	HPWH, 50 gal 3.61 EF
Lighting	100% LED	100% LED	100% LED	100% LED	100% LED	100% LED
Refrigerator	449 kWh	449 kWh	449 kWh	449 kWh	449 kWh	449 kWh
Cooking Range	Electric, Induction	Electric, Induction	Electric, Induction	Electric, Induction	Electric, Induction	Electric, Induction
Dishwasher	254 Rated kWh	254 Rated kWh	254 Rated kWh	254 Rated kWh	254 Rated kWh	254 Rated kWh
Clothes Washer	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR	ENERGY STAR
Clothes Dryer	Electric, Premium	Electric, Premium	Electric, Premium	Electric, Premium	Electric, Premium	Electric, Premium

Table 17. WUFI scenario inputs.

Scenario	SFD - Conditioned	SFD - Unconditioned	Townhouse	Large SFD	6-unit Multifamily	4-story Multifamily
BeOpt Output Used:	Optimal #2	Iter2,pt4	Iter3,pt8	Optimal #1	User-defined	Building: Iter 3, Pt 5
Wood Stud	R-30 (2x6 cell+2poly)	R-45 (2x6 cell+4.5poly)	R-30 (2x6 cell+2"poly)	R-30 (2x6 cell+2"poly)	R-30 (2x6 cell+2"poly)	R-33 (2x6 cell+2.5"poly)
Wall Sheathing	OSB	OSB	OSB	OSB	OSB	OSB
Unfinished Attic	R-60 (16.5" Cellulose)	R-60 (16.5" Cellulose)	R-60 (16.5" Cellulose)	R-60 (16.5" Cellulose)	R-60 (16.5" Cellulose)	None
Finished Roof	R-60 (16.5" Cellulose)	R-60 (16.5" Cellulose)	R-60 (16.5" Cellulose)	None	None	R-60 (16.5" Cellulose)
Finished Basement	R-21 (ICF)	None	R-21 (ICF)	R-18.5 (ICF)	None	None
Unfinished Basement (Framed Floor)	None	R-45 (2x10_empty+7.5"poly)	R-30 (2x10_empty+5"poly)	R-30 (2x10_empty+5"poly)	None	R-39 (2x10_empty+6"poly)
Slab	R-21 (5"EPS)	None	R-21 (5"EPS)	R-16 (4"EPS)	R-16 (4"EPS)	None
Window-To-Wall (WWR)	11%	11%	10%	10%	12%	20%
Windows	U-0.14, SHGC-0.5	S - U-0.14, SHGC-0.5, E/W/N - U-0.14, SHGC-0.3	U-0.14, SHGC-0.5,	U-0.14, SHGC-0.5	U-0.14, SHGC-0.3	SWE - U-0.14, SHGC-0.2, N, NW, NE - U-0.14, SHGC-0.3
Interior Shading	None	None	None	None	None	None
Air Leakage	0.6 ACH50	0.6 ACH50	0.6 ACH50	0.6 ACH50	0.6 ACH50	0.42 ACH50
Mechanical Ventilation	ERV Balanced, 83%	ERV Balanced, 83%	ERV Balanced, 83%	ERV Balanced, 83%	ERV Balanced, 83%	ERV Balanced, 83%
Air-source Heat Pump	HSPF 10, SEER 26	HSPF 10, SEER 26	HSPF 10, SEER 26	HSPF 10, SEER 26	HSPF 10, SEER 26	HSPF 10, SEER 26
PHIUS+ Recirculation Cooling COP	6.08	6.08	6.08	6.08	6.08	6.08
PHIUS+ Cooling Set Point	77F	77F	77F	77F	77F	77F
PHIUS+ Heating Set Point	68F	68F	68F	68F	68F	68F
Water Heater	HPWH EF 3.61	HPWH EF 3.61	HPWH EF 3.61	HPWH EF 3.61	HPWH EF 3.61	HPWH EF 3.61
Lighting	100% LED	100% LED	100% LED	100% LED	100% LED	100% LED
PHIUS+ Lighting kWh/yr	RESNET 80%	RESNET 80%	RESNET 80%	2803	3198	65095
Refrigerator	449 kWh/yr	449 kWh/yr	449 kWh/yr	449 kWh/yr	449 kWh/yr	449 kWh/yr
Cooking Range	.2 kWh/use	.2 kWh/use	.2 kWh/use	.2 kWh/use	.2 kWh/use	.2 kWh/use
Dishwasher	260 Rated kWh/yr	260 Rated kWh/yr	260 Rated kWh/yr	260 Rated kWh/yr	260 Rated kWh/yr	260 Rated kWh/yr
Clothes Washer	116 kWh/yr	116 kWh/yr	116 kWh/yr	116 kWh/yr	116 kWh/yr	116 kWh/yr
Clothes Dryer	Condensing 3.93 CEF	Condensing 3.93 CEF	Condensing 3.93 CEF	Condensing 3.93 CEF	Condensing 3.93 CEF	Condensing 3.93 CEF
PHIUS+ Hot Water Usage	6.6 gal/Person/day	6.6 gal/Person/day	6.6 gal/Person/day	6.6 gal/Person/day	6.6 gal/Person/day	6.6 gal/Person/day
Site Renewal Energy	4 kW	4 kW	5 kW	6 kW	4 kW	50 kW

Table 18. PHIUS+ Space Conditioning Criteria for Worchester, MA

Criteria	Target	SFD - Conditioned	SFD - Unconditioned	Townhouse	Large SFD	6-unit Multifamily	4-story Multifamily
Heating Demand (kBtu/ft²-yr)	6.2	5.66	6.15	6.08	5.66	5.1	1.73
Cooling Demand (kBtu/ft²-yr)	1.9	1.51	1.89	0.73	0.63	1.28	1.87
Heating Peak (Btu/h-ft²)	4.6	3.66	4.44	3.47	3.42	3.9	2.39
Cooling Peak (Btu/h-ft²)	3.8	1.11	1.59	0.82	0.77	1.29	1.36
Source Energy (kWh/person)	3840	2411	1370	3749	3748	3485	3766

Step 6: Impact of New Industry Standards and Software Updates

RESNET released a requirement for approved software to update HERS calculations from an existing standard, "ANSI/RESNET/ICC 301-2014: Standard for the Calculation and Labeling of the Energy Performance of Low-Rise Residential Buildings using an Energy Rating Index" to new standard "ANSI/RESNET/ICC 301-2019:Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index" by July 1st 2021. In addition, the software also incorporated a new standard ANSI/RESNET/ACCA 310-2020: Standard for Grading the Installation of HVAC Systems".

These standard changes had a significant impact on the calculation of the HERS Index. To ensure that the new stretch code target scenario recommendations are relevant for the industry going forward, the project was paused to research and analyze the impact of these changes on stretch code homes.

All scenarios were moved from the previous versions of REM/Rate and Ekotrope to the newly released versions of the software and the HERS Index calculations compared. Below is a summary of the results.

	HERS Index Deltas (301-2019 minus 301-2014)		**Ekotrope Index minus REM/Rate Index**	
Scenario	**REM/Rate**	**Ekotrope**	**301-2014**	**301-2019**
SFD Small Electric	0	-3	5	2
SFD Small Gas	4	0	-1	-5
SFD Large Electric	0	-3	6	3
SFD Large Gas	5	1	0	-4
Townhouse Electric (1) Gas DHW	4	-5	9	0
Townhouse Electric (2) All Electric	4	-3	6	-1
Townhouse Gas	7	0	4	-3
6-unit Electric	-3	-3	7	7
6-unit Gas	4	0	3	-1
4-Story Electric	1	3	3	5
4-Story Gas	1	-2	-2	-5

Based on the above results, all baseline and target scenarios needed to be reconfigured to hit a more appropriate target under the new calculation standards.

Step 7: Update Scenario Baselines

With the updates defined in Step 6, it was found that a baseline HERS score of 55 was no longer relevant to the considered scenarios of this task. Therefore, the baseline building options were adjusted to produce a HERS score of 52 for each scenario across the ratings software.

For developing the new HERS 52 baselines, an additional modeling run in BEopt was not performed due to the software not considering the new implemented standards as discussed in Step 6. In the revised optimization runs, BEopt scenarios ranged from ERIs of 67 to 32. From these data sets for each building type, there were dozens of configurations that were in the range of 50 – 53 ERI that were assessed to influence REM/Rate modeling to reach a HERS 52 baseline.

Multiple iterations of modeling in REM/Rate were performed by adjusting the existing HERS 55 baselines, based on optimized BEopt configurations, until a target of HERS 52 was reached for each building type. Once these new baselines were selected, the configuration was remodeled in BEopt to generate measure costs so that new incremental costs could be calculated.

The following adjustments shown in Table 19 through Table 23 were made to each building type to reach HERS 52 from the original HERS 55 baselines.

Table 19. Small Single Family Home Baseline Adjustments.

Option	HERS 55	HERS 52
Wall Sheathing	DOER_OSB	DOER_OSB
Unfinished Attic	DOER_Ceiling R-49 Cellulose, Vented	MA_Ceiling R-49 Cellulose, Vented
Finished Roof	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10
Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt	None
Finished Basement	None	DOER_Ceiling R-30 Fiberglass Batt
Windows	DOER_U-0.28, 0.29 SHGC	MA_U-0.18, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_3 ACH50
Mechanical Ventilation	DOER_2013, Exhaust	MA_2013, HRV, 75%
Central Air Conditioner	DOER_SEER 14.2	DOER_SEER 14.2
Furnace	DOER_Gas, 95% AFUE	DOER_Gas, 95% AFUE
Ducts	DOER_4 CFM25 per 100ft2, R-6	DOER_2 CFM25 per 100ft2, R-6
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF
Lighting	DOER_75% LED	DOER_100% LED
Refrigerator	DOER_633 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_Standard	DOER_Energy Star
Clothes Dryer	DOER_Gas	DOER_Gas, Premium

Table 20. Large Family Single Home Baseline Adjustments.

Option	HERS 55	HERS 52
Wall Sheathing	DOER_OSB	DOER_OSB
Unfinished Attic	DOER_Ceiling R-49 Cellulose, Vented	MA_Ceiling R-49 Cellulose, Vented
Finished Roof	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10
Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt	DOER_Ceiling R-30 Fiberglass Batt
Interzonal Floor	R-30 Fiberglass Batt	MA_R-30 Fiberglass Batt
Windows	DOER_U-0.28, 0.29 SHGC	MA_U-0.25, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_3 ACH50
Mechanical Ventilation	DOER_2013, Exhaust	MA_2013, HRV, 75%
Central Air Conditioner	DOER_SEER 13	DOER_SEER 14.2
Furnace	DOER_Gas, 92% AFUE	DOER_Gas, 98% AFUE
Ducts	DOER_4 CFM25 per 100ft2, R-6	DOER_2 CFM25 per 100ft2, R-6
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF
Lighting	DOER_75% LED	DOER_100% LED
Refrigerator	DOER_633 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_Standard	DOER_Energy Star
Clothes Dryer	DOER_Electric, Standard	DOER_Gas, Premium

Table 21. Townhouse Baseline Adjustments.

Option	HERS 55	HERS 52
Wall Sheathing	DOER_OSB	DOER_OSB
Unfinished Attic	DOER_Ceiling R-49 Cellulose, Vented	MA_Ceiling R-49 Cellulose, Vented

Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt	DOER_Ceiling R-30 Fiberglass Batt
Windows	DOER_U-0.28, 0.29 SHGC	MA_U-0.28, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_3 ACH50
Mechanical Ventilation	DOER_2013, Exhaust	MA_2013, HRV, 75%
Central Air Conditioner	DOER_SEER 13	DOER_SEER 14.2
Furnace	DOER_Gas, 92% AFUE	DOER_Gas, 95% AFUE
Ducts	DOER_4 CFM25 per 100ft2, R-6	DOER_2 CFM25 per 100ft2, R-6
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF
Lighting	DOER_75% LED	DOER_100% LED
Refrigerator	DOER_633 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_Standard	DOER_Energy Star
Clothes Dryer	DOER_Electric, Standard	DOER_Gas, Premium

Table 22. 6-unit MF Baseline Adjustments.

Option	HERS 55	HERS 52
Wall Sheathing	DOER_OSB	DOER_OSB
Unfinished Attic	DOER_Ceiling R-49 Cellulose, Vented	MA_Ceiling R-49 Cellulose, Vented
Windows	DOER_U-0.28, 0.29 SHGC	MA_U-0.28, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_3 ACH50
Mechanical Ventilation	DOER_2013, Exhaust	DOER_2013, Exhaust
Central Air Conditioner	DOER_SEER 13	DOER_SEER 14.2
Furnace	DOER_Gas, 92% AFUE	DOER_Gas, 95% AFUE
Ducts	DOER_4 CFM25 per 100ft2, R-6	DOER_2 CFM25 per 100ft2, R-6
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF
Lighting	DOER_75% LED	DOER_100% LED
Refrigerator	DOER_633 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_Standard	DOER_Energy Star
Clothes Dryer	DOER_Electric, Standard	DOER_Gas, Premium

Table 23. 4-story MF Baseline Adjustments.

Option	HERS 55	HERS 52
Wall Sheathing	DOER_OSB	DOER_R-5 XPS
Finished Roof	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10
Windows	DOER_U-0.28, 0.29 SHGC	MA_U-0.18, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_2 ACH50
Mechanical Ventilation	DOER_2013, Exhaust	DOER_2013, Exhaust
Central Air Conditioner	DOER_SEER 14.2	DOER_SEER 14.2
Furnace	DOER_Gas, 95% AFUE	DOER_Gas, 98% AFUE
Ducts	DOER_In Finished Space	DOER_In Finished Space
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF
Lighting	DOER_75% LED	DOER_100% LED
Refrigerator	DOER_633 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_Standard	DOER_Energy Star
Clothes Dryer	DOER_Gas	DOER_Gas, Premium

Step 8: HERS 42 Target Scenarios

Similar to Step 7, dozens of BEopt configurations within an ERI range of 39 – 42 were modeled in the revised optimization runs for each building type. From those data sets, optimized configurations were assessed to influence modeling choices in REM/Rate to reach a target of HERS 42 for each scenario. These REM/Rate modeling results were then remodeled in BEopt to generate measure costs so that new incremental costs could be calculated.

Table 24 through Table 28 show the selected building options to reach HERS 42 for both gas and electric heating scenarios compared to the HERS 52 gas heating baseline.

Final REMRate load reports are included in Appendix B and C.

Table 24. Small Single Family HERS 42 Target Scenarios.

Option	HERS 52 Baseline	Gas Heating - HERS 42	Electric Heating - HERS 42
Wood Stud	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Wall Sheathing	DOER_OSB	DOER_R-5 XPS	DOER_OSB
Interzonal Walls	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Unfinished Attic	MA_Ceiling R-49 Cellulose, Vented	DOER_Roof R-38 Open Cell Spray Foam, Unvented	DOER_Roof R-38 Open Cell Spray Foam, Unvented
Finished Roof	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10
Finished Basement	None	Whole Wall R-21 Fiberglass Batt, 2x6, 24 in o.c.	None
Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt	None	DOER_Ceiling R-30 Fiberglass Batt
Windows	MA_U-0.18, 0.29 SHGC	MA_U-0.18, 0.29 SHGC	MA_U-0.28, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_1 ACH50	DOER_2 ACH50
Mechanical Ventilation	MA_2013, HRV, 75%	MA_2013, HRV, 75%	MA_2013, HRV, 75%
Central Air Conditioner	DOER_SEER 14.2	DOER_SEER 16 (2 Stage)	None
Furnace	DOER_Gas, 95% AFUE	DOER_Gas, 98% AFUE	None
Mini-Split Heat Pump	None	None	MA_SEER 20, 12 HSPF, Ductless
Ducts	DOER_2 CFM25 per 100ft2, R-6	DOER_In Finished Space	None
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF	DOER_HPWH, 50 gal
Lighting	DOER_100% LED	DOER_100% LED	DOER_100% LED
Refrigerator	DOER_550 kWh	DOER_550 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas	DOER_Electric, Induction
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_EnergyStar	DOER_EnergyStar	DOER_Energy Star
Clothes Dryer	DOER_Gas, Premium	DOER_Gas, Premium	DOER_Electric, Premium

Table 25. Large Single Family Home HERS 42 Target Scenarios.

Option	HERS 52 Baseline	Gas Heating - HERS 42	Electric Heating - HERS 42
Wood Stud	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Wall Sheathing	DOER_OSB	DOER_R-5 XPS	DOER_OSB
Interzonal Walls	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Unfinished Attic	MA_Ceiling R-49 Cellulose, Vented	DOER_Roof R-38 Open Cell Spray Foam, Unvented	DOER_Roof R-38 Open Cell Spray Foam, Unvented
Finished Roof	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10
Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt	DOER_Ceiling R-30 Fiberglass Batt	DOER_Ceiling R-30 Fiberglass Batt
Interzonal Floor	MA_R-30 Fiberglass Batt	MA_R-30 Fiberglass Batt	MA_R-30 Fiberglass Batt
Windows	MA_U-0.25, 0.29 SHGC	MA_U-0.18, 0.29 SHGC	MA_U-0.28, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_1.5 ACH50	DOER_1.5 ACH50
Mechanical Ventilation	MA_2013, HRV, 75%	MA_2013, HRV, 75%	MA_2013, HRV, 75%
Central Air Conditioner	DOER_SEER 14.2	DOER_SEER 16 (2 Stage)	None
Furnace	DOER_Gas, 98% AFUE	DOER_Gas, 98% AFUE	None
Mini-Split Heat Pump	None	None	MA_SEER 20, 12 HSPF, Ducted
Ducts	DOER_2 CFM25 per 100ft2, R-6	DOER_In Finished Space	DOER_In Finished Space
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF	DOER_HPWH, 50 gal
Lighting	DOER_100% LED	DOER_100% LED	DOER_100% LED
Refrigerator	DOER_550 kWh	DOER_550 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas	DOER_Electric, Induction
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_EnergyStar	DOER_EnergyStar	DOER_Energy Star
Clothes Dryer	DOER_Gas, Premium	DOER_Gas, Premium	DOER_Electric, Premium

Table 26. Townhouse HERS 42 Target Scenarios.

Option	HERS 52 Baseline	Gas Heating - HERS 42	Electric Heating - HERS 42
Wood Stud	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Wall Sheathing	DOER_OSB	DOER_R-5 XPS	DOER_OSB
Interzonal Walls	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Unfinished Attic	MA_Ceiling R-49 Cellulose, Vented	DOER_Ceiling R-38 Fiberglass, Vented	DOER_Roof R-30 Open Cell Spray Foam, Unvented
Finished Basement	None	Whole Wall R-21 Fiberglass Batt, 2x6, 24 in o.c.	None
Unfinished Basement	DOER_Ceiling R-30 Fiberglass Batt	None	DOER_Whole Wall R-21 Fiberglass Batt, 2x6, 24 in o.c.
Interzonal Floor	MA_R-30 Fiberglass Batt	MA_R-30 Fiberglass Batt	MA_R-30 Fiberglass Batt
Windows	MA_U-0.28, 0.29 SHGC	MA_U-0.18, 0.29 SHGC	MA_U-0.18, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_1.5 ACH50	DOER_2 ACH50
Mechanical Ventilation	MA_2013, HRV, 75%	MA_2013, HRV, 75%	MA_2013, HRV, 75%
Central Air Conditioner	DOER_SEER 14.2	DOER_SEER 16 (2 Stage)	None
Furnace	DOER_Gas, 95% AFUE	DOER_Gas, 98% AFUE	None
Mini-Split Heat Pump	None	None	MA_SEER 20, 12 HSPF, Ducted
Ducts	DOER_2 CFM25 per 100ft2, R-6	DOER_2 CFM25 per 100ft2, R-6	DOER_In Finished Space
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF	DOER_HPWH, 50 gal
Lighting	DOER_100% LED	DOER_100% LED	DOER_100% LED
Refrigerator	DOER_550 kWh	DOER_550 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas	DOER_Electric, Induction
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_EnergyStar	DOER_EnergyStar	DOER_Energy Star
Clothes Dryer	DOER_Gas, Premium	DOER_Gas, Premium	DOER_Electric, Premium

Table 27. 6-unit MF HERS 42 Target Scenarios.

Option	HERS 52 Baseline	Gas Heating - HERS 42	Electric Heating - HERS 42
Wood Stud	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Wall Sheathing	DOER_OSB	DOER_R-5 XPS	DOER_OSB
Unfinished Attic	MA_Ceiling R-49 Cellulose, Vented	DOER_Ceiling R-38 Fiberglass, Vented	DOER_Ceiling R-38 Fiberglass, Vented
Slab	2ft R10 Exterior XPS	2ft R10 Exterior XPS	2ft R10 Exterior XPS
Windows	MA_U-0.28, 0.29 SHGC	MA_U-0.18, 0.29 SHGC	MA_U-0.28, 0.29 SHGC
Air Leakage	DOER_3 ACH50	DOER_1.5 ACH50	DOER_2 ACH50
Mechanical Ventilation	DOER_2013, Exhaust	MA_2013, HRV, 75%	DOER_2013, Exhaust
Central Air Conditioner	DOER_SEER 14.2	DOER_SEER 16 (2 Stage)	None
Furnace	DOER_Gas, 95% AFUE	DOER_Gas, 98% AFUE	None
Mini-Split Heat Pump	None	None	MA_SEER 20, 12 HSPF, Ductless
Ducts	DOER_2 CFM25 per 100ft2, R-6	DOER_In Finished Space	None
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF	DOER_HPWH, 50 gal
Lighting	DOER_100% LED	DOER_100% LED	DOER_100% LED
Refrigerator	DOER_550 kWh	DOER_550 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas	DOER_Electric, Induction
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_EnergyStar	DOER_EnergyStar	DOER_Energy Star
Clothes Dryer	DOER_Gas, Premium	DOER_Gas, Premium	DOER_Electric, Premium

Table 28. 4-story MF HERS 42 Target Scenarios.

Option	HERS 52 Baseline	Gas Heating - HERS 42	Electric Heating - HERS 42
Wood Stud	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.	MA_R-21 Fiberglass Batt, 2x6, 16 in o.c.
Wall Sheathing	DOER_R-5 XPS	DOER_R-5 XPS	DOER_OSB
Finished Roof	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10	DOER_R-30 Fiberglass Batt, 2x10
Interzonal Floor	MA_R-30 Fiberglass Batt	MA_R-30 Fiberglass Batt	MA_R-30 Fiberglass Batt
Windows	MA_U-0.18, 0.29 SHGC	MA_U-0.18, 0.29 SHGC	MA_U-0.28, 0.29 SHGC
Air Leakage	DOER_2 ACH50	DOER_1 ACH50	DOER_1.5 ACH50
Mechanical Ventilation	DOER_2013, Exhaust	MA_2013, HRV, 75%	DOER_2013, Exhaust
Central Air Conditioner	DOER_SEER 14.2	DOER_SEER 16 (2 Stage)	None
Furnace	DOER_Gas, 98% AFUE	DOER_Gas, 98% AFUE	None
Mini-Split Heat Pump	None	None	MA_SEER 20, 12 HSPF, Ductless
Ground Source Heat Pump	None	None	None
Ducts	DOER_In Finished Space	DOER_In Finished Space	None
Water Heater	DOER_Gas Tankless 0.94 EF	DOER_Gas Tankless 0.94 EF	DOER_HPWH, 50 gal
Lighting	DOER_100% LED	DOER_100% LED	DOER_100% LED
Refrigerator	DOER_550 kWh	DOER_550 kWh	DOER_550 kWh
Cooking Range	DOER_Gas	DOER_Gas	DOER_Electric, Induction
Dishwasher	DOER_264 Rated kWh	DOER_264 Rated kWh	DOER_264 Rated kWh
Clothes Washer	DOER_EnergyStar	DOER_EnergyStar	DOER_Energy Star
Clothes Dryer	DOER_Gas, Premium	DOER_Gas, Premium	DOER_Electric, Premium

Appendix A – Passive House WUFI Modeling Reports

Appendix B – HERS 42 REMRate Modeling Reports

Appendix C – MOSS REMRate Modeling Reports

Appendix D – HERS 52 REMRate Modeling Reports