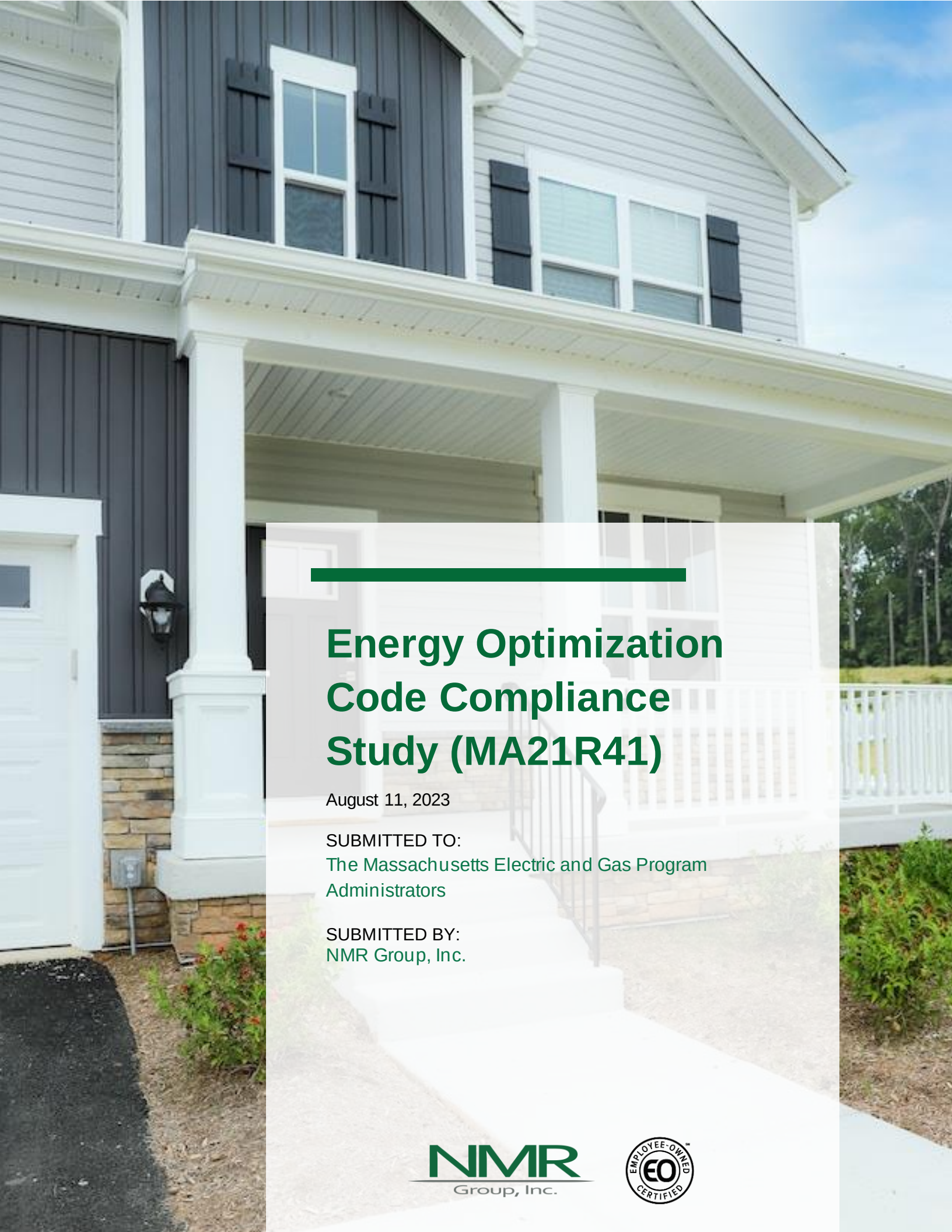


Energy Optimization Code Compliance Study (MA21R41)

August 11, 2023

SUBMITTED TO:
The Massachusetts Electric and Gas Program Administrators

SUBMITTED BY:
NMR Group, Inc.

NMR Group, Inc.

Residential New Construction Energy Optimization Code Compliance Study

This study used advanced energy modeling (NREL's BEopt tool) to identify combinations of measures (*packages*) that can be used to cost-effectively comply with the 10th edition Massachusetts Building Code, including the new base, stretch, and specialized-opt-in versions of the code taking effect in 2023 and 2024. The modeling tool looks for packages *optimized* for various criteria of interest, such as reducing construction or long-term costs. The study shows how optimization can benefit even minimally code-compliant homes, and shows that optimized designs can ease the transition to meeting these newer code versions.

Design: a prototype home with a specific type of HVAC system. The study included six designs: four single-family (SF) and two multifamily (MF).

Package: a combination of energy-related measures (insulation, HVAC efficiency, etc.) that together yield an optimized version of a given design.

Methods

1. In BEopt, build SF and MF energy models with different types of mechanical systems.

Single-Family	Multifamily
• Air-source heat pump (ASHP) • Furnace with central AC (CAC) • Ground-source heat pump (GSHP) • Mini-split heat pump (MSHP)	• Furnace with central AC (CAC) • Mini-split heat pump (MSHP)

2. In BEopt, test hundreds of measure combinations for each design.

3. Review results to select an *unoptimized*, *minimally code compliant* reference home.

4. Review results to select 5 *optimized but minimally code complaint packages*, each optimally designed for a different goal. These represent reasonable packages for builders to consider if their goal is just meeting code. There are higher performance packages possible, but this study focused on code compliance. All-electric high performance packages will be discussed in a complementary report.

Outputs of Optimization Modeling

For each code version (base, stretch, and specialized) and design (ASHP, furnace/CAC, etc.), the study identified the following minimally code-compliant packages:

Reference Package

Unoptimized home, approximately code compliant. Optimized packages are compared to this package.

Construction Cost Package

Optimized for the lowest initial cost for energy-related measures among the tested measure combinations, including materials and labor.

First Year Cost Package

Optimized for lowest costs to buyer in 1st year of ownership (includes 20% down payment, mortgage payments, mortgage interest tax deduction, and utility bills).

Ownership Cost Package

Optimized to prioritize long-term benefits to the homebuyer, balancing upfront construction and long-term costs over a 30-year mortgage.

Site Savings Package

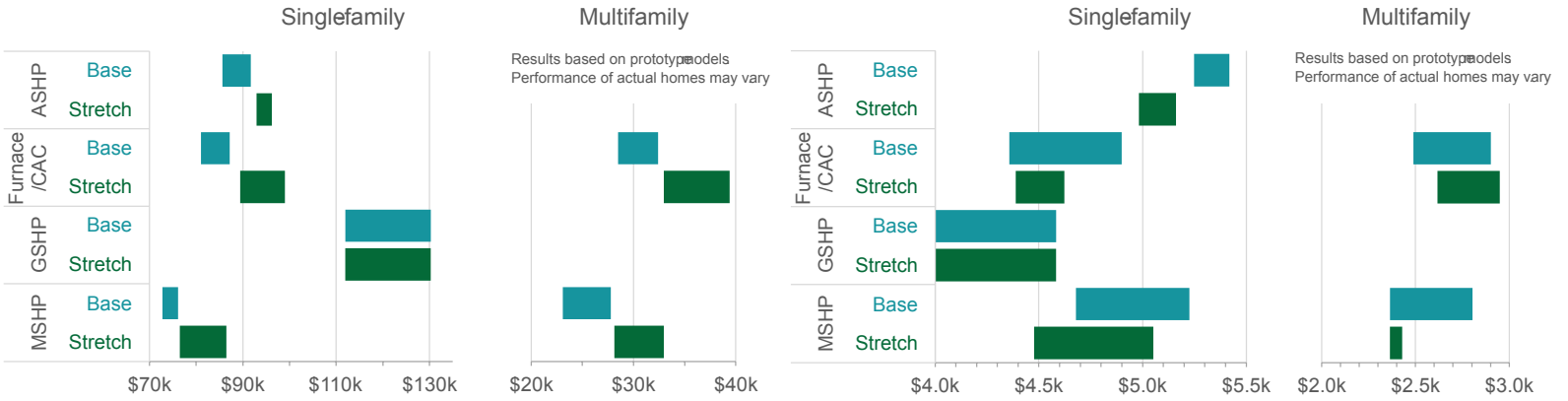
Optimized for max *site* energy savings (savings at the meter) *among the options tested in this study*; just meets code - there are other packages possible that save more energy.

Source Savings Package

Optimized for max *source* energy savings (savings for energy suppliers rather than at the meter); same caveats as Site Savings; just meets code - there are other packages possible that save more energy.

Key Findings

Optimized stretch code packages have similar construction & long-term operating costs as their base count counterparts. The following charts show the range of performance of the optimized packages identified in the study, comparing optimized base code (blue) and stretch code (green) packages. The first shows the estimated per-unit construction costs for energy-related measures included in the optimized packages, and the second shows estimated long-term annual operating costs (annual costs across a 30-year period) for those packages (per unit). Overlap in the blue and green bars indicates comparable outcomes for base and stretch code packages.



Guidance based on optimization modeling

- ☑ Use heat pumps to access a bigger selection of optimized packages that comply with code.
- ☑ Tighten the building shell to reduce air infiltration.
- ☑ Use 24-inch on-center spacing for wall framing.
- ☑ Use continuous insulation (R-5, R-10, or R-15).
- ☑ Reduce heating and cooling loads with high-efficiency energy recovery ventilation.
- ☑ Spray foam is not necessary to comply with code — even stretch.
- ☑ Double-pane windows (0.29 U-factor) are sufficient to comply with code — even stretch.
- ☑ Induction cook tops are more efficient than gas but cost slightly more to purchase and operate.
- ☑ Water heaters are challenging to electrify cost-effectively.
- ☑ Ground-source heat pumps are the best choice for those focused on long term costs, and mini-splits for those focused on short-term costs or multifamily buildings.

★ Recommendation 1:

Encourage integrated design and reduce barriers to the use of optimization modeling in the residential sector, to help market actors and occupants benefit from the reduced construction cost and energy consumption of optimized designs.

★ Recommendation 2:

Emphasize the benefits of continuous insulation, infiltration reduction, and high-efficiency recovery ventilation in outreach materials and program offerings such as the Code Compliance Support Initiative.

Study Limitations

- The study relies on prototypes, economic assumptions, and modeling; the actual performance and costs of a real home will vary from the estimates shown.
- Market volatility (e.g., supply chain issues and inflation) adds uncertainty to the study's assumptions.
- Construction costs only include energy-related measures (e.g., insulation and wall framing); they do not include other construction costs, like foundation excavation.
- Costs exclude Mass Save and federal tax incentives. Subject to availability and eligibility, incentives may be available to reduce costs further via these offerings.
- The study does not address certain requirements of the specialized code (e.g., solar panels, Passive House requirements, and electrification wiring).

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Glossary

Term	Definition
ACH50	Air Changes per Hour with a 50-Pascal pressure gradient
AERC	Annualized Energy-Related Costs, i.e., utility bills, mortgage, and replacement costs
AFUE	Annual Fuel Utilization Efficiency; higher is better
ASHP	Air-Source Heat Pump; a ducted fixed refrigerant flow heat pump
BEopt	NREL's Building energy optimization modeling tool (more info available here)
BTU	British Thermal Unit; a unit of energy. 1,000,000 BTU = 293 kWh
BTUh	British Thermal Units per Hour; a rate of energy consumption
CAC	Central Air Conditioner
CFA	Conditioned Floor Area
CFM25	Cubic Feet per Minute with a 25 Pascal pressure gradient
CO_2e	Carbon dioxide equivalent, a measure of greenhouse gas emissions
COP	Coefficient of Performance; a measure of equipment efficiency, usually heating; higher is better
DHW	Domestic Hot Water
EF	Energy Factor (including CEF, IMEF, MEF and UEF) measures equipment efficiency; higher is better
EO	Energy Optimization; an approach to efficiency that maximizes savings benefits relative to costs
ERI	Energy Rating Index; summarizes a home's overall efficiency; lower is better
ERV	Energy Recovery Ventilation; higher performance option to an HRV
FGB	Fiberglass Batt; a pad of loosely felted glass fibers that traps air
DOER	Massachusetts Department of Energy Resources
GSHP	Ground-Source Heat Pump
HERS	Home Energy Rating System; summarizes a home's efficiency; lower is better
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilation provides fresh air to a home while reducing energy lost in exhausted air
HSPF2	Heating Season Performance Factor (v. 2); a measure of electric heating efficiency; higher is better
HVAC	Heating, Ventilation and Air Conditioning
IECC	International Energy Conservation Code
kWh	Kilowatt-Hour; a unit of energy typically used for electricity. 1 kWh = 3,412 BTU
MSHP	Mini or Multi-Split Heat Pump; usually ductless and often variable refrigerant flow
Mixed-fuel	A home with combustion-powered equipment e.g., furnace, boiler, water heater, dryer and/or stove
NREL	National Renewable Energy Laboratory
NREMDB	NREL's National Residential Efficiency Measures Database, which provides measure costs
PAs	Massachusetts Gas and Electric Program Administrators
PV	Photovoltaics, also known as solar panels
R-value	Measure of a material's resistance to the flow of heat, higher is better
RNC	Residential New Construction
SEER2	Seasonal Energy Efficiency Ratio (v. 2); a measure of cooling system efficiency; higher is better
SHGC	Solar Heat Gain Coefficient; a measure of how much infrared light passes through a window
SRE	Sensible Recovery Efficiency; heat exchanged between fresh air and exhaust ventilation flows
TDL	Total Duct Leakage; lower is better
U-factor	Measure of heat flow through a material, lower is better, inverse of R-value
UCB	Unconditioned Basement

ES

Executive Summary

The MA21R41 RNC Energy Optimization Code Compliance study uses energy modeling to identify combinations of measures (*packages*) that can be used to cost-effectively comply with the tenth edition Massachusetts building code, including the new *base*, *stretch*, and *specialized* versions of the code. The modeling tool looks for packages *optimized* for various criteria of interest, such as reducing construction or long-term operating costs. This study takes a fuel-neutral approach to the modeling and includes homes using various combinations of electric and natural gas measures. A second phase of this study that focuses on high-performance all-electric packages will be discussed in a complementary report.

This report is a follow-up to the Residential New Construction Energy Optimization Cost Study (20R23).[1] It focuses on single-family and low-rise multifamily home packages that comply with the new code requirements that will take effect in 2024; the results also comply with the less stringent interim code. Table 1 provides a high-level summary of the new code requirements.

Table 1: New Construction Code Compliance Criteria Summary

Building Code	Effective Date	Path	Fuel(s)	Maximum ERI
Interim Stretch	*January 1, 2023*	*ERI*	*Mixed-fuel*	*52*
			All-electric	*55*
Specialized	July 1, 2023	ERI	Mixed-fuel	42†
			All-electric	45†
Base	January 1, 2024 (planned)	Prescriptive	–	‡
		ERI	Mixed-fuel	52
			All-electric	55
Stretch	July 1, 2024	ERI	Mixed-fuel	42
			All-electric	45

† Specialized code requires other provisions outlined in Section 5, including solar panels for some homes and Passive House compliance for large multifamily buildings.

‡ Prescriptive path mandates certain features in lieu of an ERI. Changes from the previous code include:

Attics	***Walls***	***Windows***	***Slabs***	***Lighting***
R-60	*0.045 U / R-20+5 / R-30*	*0.40 SHGC*	*4 feet of R-10*	*100% LEDs*

[1] https://ma-eeac.org/wp-content/uploads/MA20R23-RNC-EO-Final-Report-10222021.pdf

METHODOLOGY

BEopt optimization modeling. The study employs NREL's BEopt modeling tool to identify optimal combinations of energy-efficient measures (*packages*).[2] BEopt simulates construction costs, ownership costs, and energy savings associated with a given set of economic parameters and measure combinations such as insulation levels and HVAC systems. Appendix A describes the modeling inputs in more detail.

A preliminary sensitivity analysis indicated that rebates from the Massachusetts RNC program have limited impact on model results. Consequently, the study excludes those and other efficiency-related incentives, which could potentially reduce costs from those shown in this report. The study does, however, include federal income tax deductions for mortgage interest.

Core model prototypes. The study used BEopt to test six core prototype *designs*, including a single-family colonial home and a 26-unit, three-story multifamily building. Four colonial designs were modeled with different heating and cooling systems: air-source heat pump (ASHP), furnace with central AC (CAC), ground-source heat pump (GSHP), and mini-split (MSHP) systems. The multifamily building was modeled in two versions: furnace/CAC and MSHP.

Code-compliant packages. NMR isolated six packages (a code-compliant reference and five optimized versions) for each flavor of the new code from the hundreds assessed for each core design. The packages presented in the report provide options for builders to construct *minimally code-compliant* homes that meet various goals e.g., use a specific type of HVAC system, reduce construction costs, or even prioritize long-term operational costs.

The packages are optimized, but *do not represent the most efficient packages possible* – they represent **packages that are approximately code compliant**. Packages were considered code-compliant if they satisfied the code's prescriptive requirements (for base code) or had ERI values at or no more than four points lower than the ERI values described in Table 1.

For each code version (base, stretch, and specialized) and design (ASHP, furnace/CAC, etc.), the study identified the following minimally code-compliant packages (2.1 provides more detail):

- **Reference Package**: an unoptimized home that is approximately code compliant.
- **Construction Cost Package**: optimized for the lowest initial cost of energy-related measures among the tested measure combinations, including materials and labor.
- **First Year Cost Package**: optimized for lowest costs to the buyer in the first year of ownership (includes 20% down payment, mortgage payments, mortgage interest tax deduction, and electric and/or natural gas utility bills).
- **Ownership Cost Package**: optimized for long-term benefits to the homebuyer, balancing upfront construction cost with long-term ownership and operating costs.
- **Site Savings Package**: optimized for maximum site energy savings (savings at the meter) among the options tested in this study. This still just meets code ; there are other packages that save more energy.
- **Source Savings Package**: optimized for maximum source energy savings (savings for energy suppliers rather than at the meter); has the same caveats as Site Savings.

[2] https://www.nrel.gov/buildings/beopt.html

Table 2 provides a high-level summary of the costs and economic factors that the modeling tool considers when selecting each of the five different optimization packages (more detail in 2.1.2).

Table 2: Summary of Factors Included in Optimized Package Selection

	Const. Cost	First Year Cost	Ownership Cost	Site Savings	Source Savings
Time frame	0 years	1 year	30 years	30 years	30 years
Construction cost	✓	✓	✓	–	–
Down payment	–	✓	✓	–	–
Mortgage	–	✓	✓	–	–
Utility bills	–	✓	✓	*Consumption*	*Consumption*
Replacement	–	–	✓	–	–
Energy savings	–	*Utility bills*	*Utility bills*	✓	✓
PA rebates	–	–	–	–	–
Federal eff. incentives	–	–	–	–	–
Property taxes	–	–	–	–	–

Italicized entries are indirectly accounted for by the related factor listed.

Notes to readers:

- The report does not need to be read cover-to-cover. Readers are encouraged to skip to a code-specific section of interest and further focus on an HVAC subsection, or one featuring multiple HVAC systems optimized for the same metric e.g., low ownership cost. For guidance in selecting a package for a specific project see 1.4 Choosing a Package. In addition, Appendix C lets users sort through the details of the packages considered in the study.
- The achievable source energy savings for optimized code compliant construction versus an unoptimized furnace/CAC reference are significant (up to 37% in base code and 20% in stretch or specialized codes), but these results are constrained by a focus on code compliance. The study's second phase will remove this restriction and include higher performance all-electric homes.
- Lastly, the report relies on energy modeling of generic buildings. The modeling also incorporates economic assumptions that cannot match the wide variety of specific circumstances under which a home might be built (e.g., local fuel or labor costs). The results of this report should not be used to predict the costs of any specific home.

KEY FINDINGS

- **Use heat pumps to access a bigger selection of optimized packages that comply with code.** Furnace/CAC homes require specific upgrades to satisfy code requirements (e.g., R408; 3.2.1), so there are fewer optimized furnace/CAC packages that comply with code. Heat pump homes already comply with R408, so the tool found more code-compliant heat pump packages.
- **Tighten the building shell to reduce air infiltration.** Reducing air infiltration is highly cost-effective: Nearly three fourths of optimized packages feature extremely low air leakage (less than 1 ACH50), including 97% of stretch code packages and 50% of base code packages.
- **Use 24-inch on-center spacing for wall framing.** All optimized packages use 24-inch on-center spacing instead of the typical 16-inch spacing. Placing studs 24 inches apart saves money on lumber, reduces thermal bridging, and increases the space available for insulation.
- **Use continuous insulation.** Almost every optimized package (95%) includes continuous wall insulation (R-5, 10, or 15). Most (55%) feature R-15, but even the R-5 in 28% of packages provides value. For example, the prescriptive path permits R-20 cavity insulation with R-5 continuous, but without continuous insulation, cavity insulation must be increased to R-30.
- **Reduce heating and cooling loads with high-efficiency energy recovery ventilation.** Stretch code requires at least 65% sensible recovery efficiency (SRE), and half of optimized base code packages upgrade from exhaust-only to recovery ventilation. Four out of five packages with recovery ventilation favor high-efficiency ventilation rated for 85% SRE.
- **Spray foam insulation is not necessary to comply with code – even stretch code.** Only six packages include spray foam insulation, all of which were optimized specifically for energy savings rather than short or long-term cost-effectiveness. However, the sealing effects of closed-cell spray foam may help builders meet the infiltration targets of optimized homes.
- **Double-pane windows (0.29 U-factor) are sufficient to comply with code – even stretch code.** When allowed to select between good, better, and best options (0.29 U-factor, 0.22, and 0.18), the tool never selected the 0.22 windows and only selected the 0.18 windows (triple-pane) in 15% of packages, all of which are maximum energy savings options.
- **Induction cook tops are more efficient than gas but cost slightly more to purchase and operate,** so gas cooking equipment was selected in 95% of packages. Despite the price premium, induction units may be appealing for those looking to electrify, as a recent study (MA21R44) found that their owners were more satisfied than gas stove owners.
- **Water heaters are challenging to electrify cost-effectively.** Given this study's focus on code compliance rather than high performance, the tool could select between storage water heaters (electric resistance or gas) and gas tankless models: Eighty percent of optimized packages feature gas units, two-fifths of which are tankless.
- **Ground-source heat pumps are the best choice for those focused on long term costs, and mini-splits for those focused on the short term or multifamily.** If a GSHP is not possible, furnace/CAC packages are usually the next best alternative in base code, and MSHP in stretch code. However, mini-splits are a better option than furnace/CAC in nearly every multifamily optimization scenario.

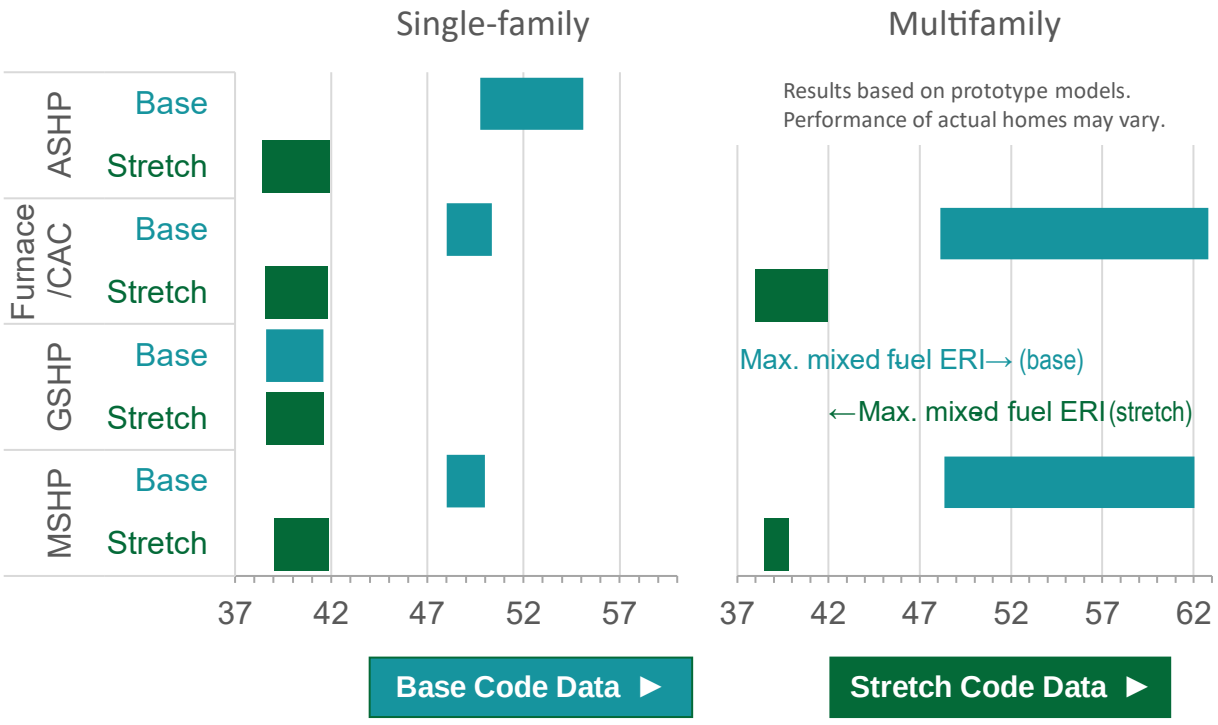
Comparison of optimized packages. The following subsections describe the *optimized, code-compliant packages examined in the study.* The charts contrast the range of performance for these base code (shown in blue) and stretch/specialized code (green) packages. The summaries compare *overall performance (ERI)*, *construction costs*, *long-term annual ownership costs*, *first year ownership costs*, and *energy savings*. The results show *code compliant prototypes*; real world results will vary. High-performance all-electric homes will be described in a separate report.

Performance Summary (ERI)

The range in performance of minimally code-compliant base and stretch code versions of most home designs is similar across many key metrics (utility bills, construction costs, etc.), but there is substantial difference between base and stretch code packages in terms of energy savings and Energy Rating Index (Figure 1). This is reasonable since stretch code places a cap on the maximum permissible rating of 42 for mixed-fuel homes, and the ERI is itself based on energy savings.[3] Any of the selected, optimized base code packages with ERIs higher than the mixed-fuel maximum of 52 comply via the prescriptive path, and many packages with lower ratings can comply via either path. All the stretch code packages also comply with the base code requirements.

The *Energy Rating Index (ERI)* is closely related to the HERS rating. Both summarize a home's net energy consumption, and **lower ratings are better**.

Figure 1: Range of Energy Rating Index Values for Optimized Packages
by Design and Code



[3] The permissible ERI increases by three points for all-electric homes (55 base, 45 stretch), but no packages in this phase benefit from it due to the presence of gas cooking and/or hot water.

Construction Costs

Apartments and single-family homes with MSHPs are cheaper to construct than counterparts with other mechanical systems, in base and stretch code communities. Using optimized packages, the average incremental cost to move from base code compliance to stretch code compliance is also lowest for MSHP homes – approximately $5,000 for multifamily and $5,700 for single-family.

Construction costs are limited to labor and materials of energy-related measures that may vary among packages e.g., windows. These are listed in A.3 and A.4. ***Costs exclude energy-efficiency incentives.***

Figure 2: Range of Energy-Related Construction Costs for Optimized Packages
by Design and Code

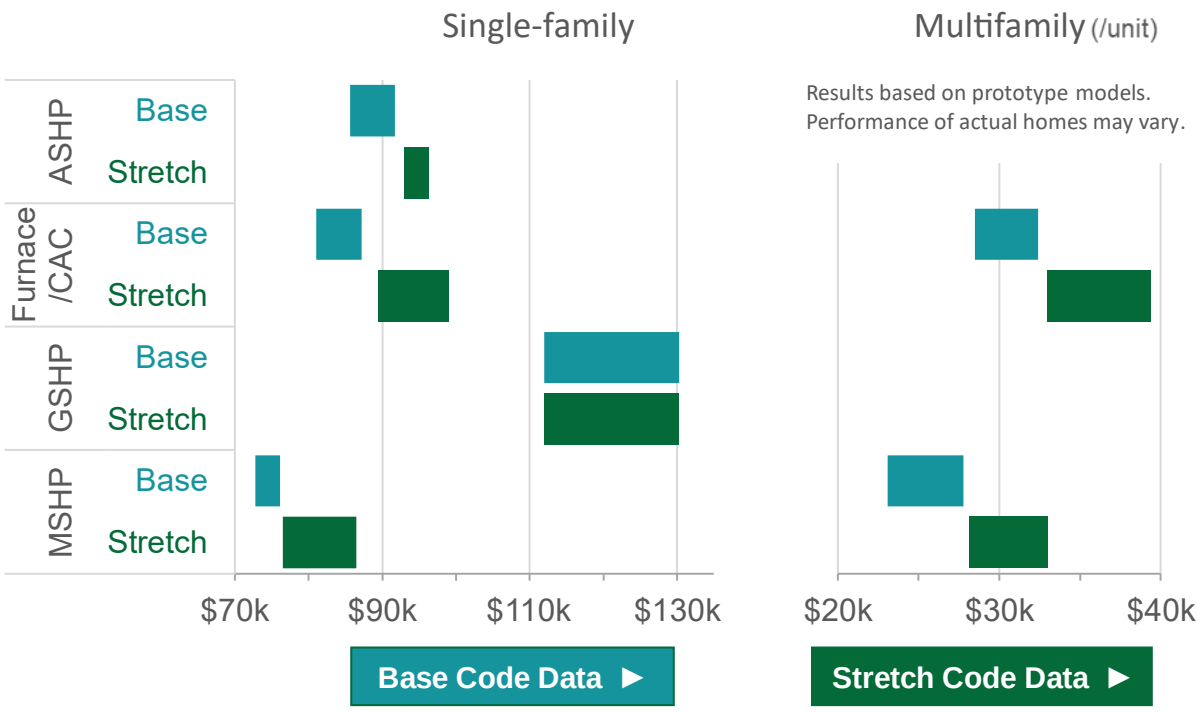


Table 3 presents incremental energy-related construction costs for stretch code packages, ranging from $4,000 to $12,000 more than their base code counterparts. GSHP packages are frequently identical across code versions, hence the $0 incremental cost.

Table 3: Incremental Costs from Base Code to Stretch Code, per Unit

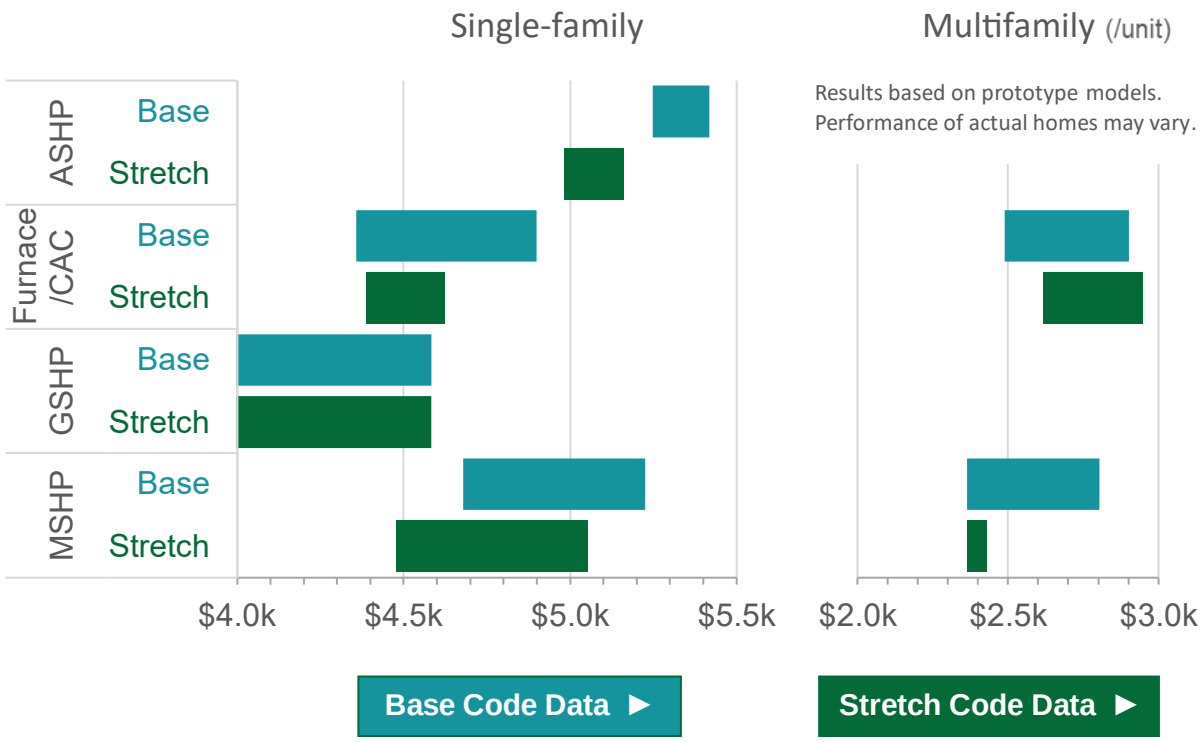
	Design	Source Energy Savings	Site Energy Savings	Construction Cost	First Year Cost	Annual Ownership Cost
SF	Furnace/CAC	$11.8k	$11.8k	$8.3k	$8.4k	$6.4k
SF	ASHP	$4.5k	$4.5k	$7.3k	$7.1k	$7.1k
SF	GSHP	$0.0k	$0.0k	$0.0k	$0.0k	$0.0k
SF	MSHP	$12.5k	$3.4k	$3.7k	$3.2k	$5.9k
MF	Furnace/CAC	$9.6k	$10.2k	$6.2k	$6.0k	$5.4k
MF	MSHP	$5.2k	$5.9k	$5.2k	$5.1k	$3.6k

Long-Term Annual Ownership Costs

There are stretch code packages with long-term ownership costs that are similar to or lower than that of base code packages for every design (Figure 3). GSHP and homes offer the lowest ownership cost among single-family designs. Unlike single-family MSHP packages, multifamily MSHP packages generally have lower operating costs than those of furnace/CAC packages.

Ownership cost balances the additional mortgage expense from the incremental costs of energy-efficiency upgrades with the resulting lower utility bills. ***Costs exclude energy-efficiency incentives.***

Figure 3: Range of Annual Ownership Costs for Optimized Packages
by Design and Code

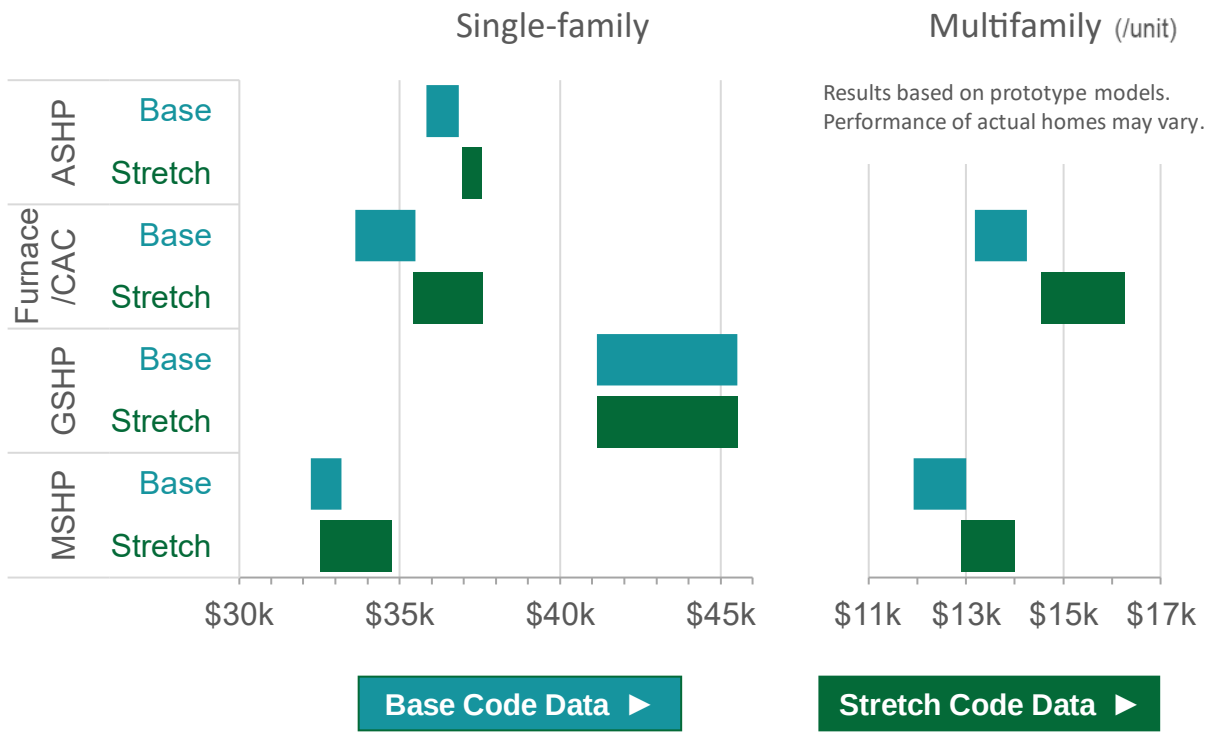


First Year Ownership Costs

Mini-split heat pump packages offer the lowest first-year ownership costs for both single-family and multifamily homes (Figure 4). The range of first year costs for optimized stretch code packages often falls a bit higher than that of base code packages. However, as shown in the earlier Figure 3, there is considerable overlap in the range of *long-term* ownership costs for optimized base and stretch code packages of a given design. Ultimately, when choosing among optimized packages, first year costs could be a bit higher for stretch code homes, but in the long-run, ownership costs appear to be comparable or lower for those homes.

First year ownership costs include a 20% down payment, monthly mortgage payments and utility bills. ***Costs exclude energy-efficiency incentives.***

Figure 4: Range of First Year Costs for Optimized Packages
by Design and Code

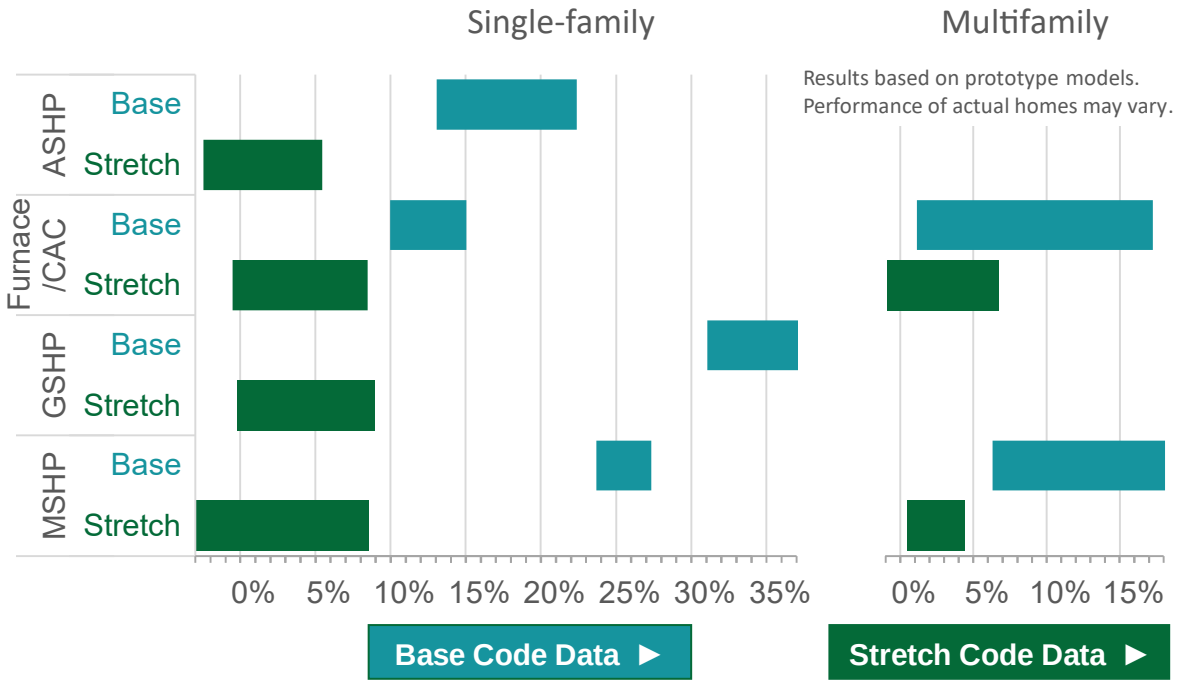


Source Energy Savings

The impacts of optimization. Figure 5 presents the estimated range of source energy savings available by building an optimized package rather than unoptimized. It shows the savings an *optimized base code* home could yield relative to an *unoptimized* base code home, and the savings an *optimized stretch code* home can have relative to an *unoptimized* stretch code home. The savings are shown relative to an unoptimized version of the home *with the same HVAC equipment.*

Source energy is provided by an energy supplier and distributed by utility companies. In contrast to site energy which is typically reported on bills it accounts for energy losses from generating electricity and distributing gas or electricity.

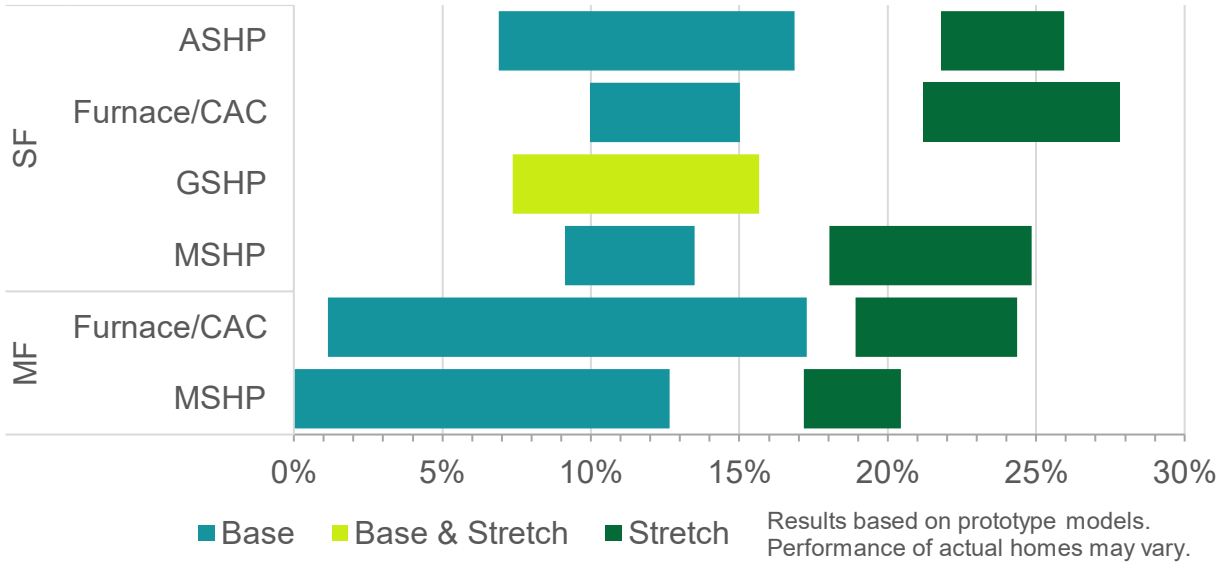
Figure 5: Range of Code-Relative Source Savings for Optimized Packages
by Design and Code



Some optimized stretch code packages (typically construction cost or lowest first year cost) result in slightly negative source savings relative to an unoptimized stretch code reference package, but they still save considerable amounts of energy relative to base code (Figure 6). Recall that this phase of the study is focused on minimal code compliance. Greater savings are possible for most designs, and the second phase of this study will explore high-performance all-electric packages.

Stretch code offers substantial savings. Figure 6 shows estimated savings for optimized base and stretch code packages relative to *unoptimized* versions that comply with *base code*. It highlights the substantial source energy savings of optimized stretch code homes versus unoptimized base code homes. For example, optimized single-family, base code MSHP packages save 9–14% of source energy compared to an unoptimized MSHP home. In contrast, optimized stretch code packages reduce source energy consumption by 18–25% from the same unoptimized base code reference.

Figure 6: Range of Base Code-Relative Source Savings by Design



KEY LIMITATIONS AND SOURCES OF UNCERTAINTY

The study relies on prototype homes, economic assumptions, and modeling. As described in more detail below, the study relied on various assumptions that are reasonable but inherently imperfect. The actual performance and costs of a real home will vary from the estimates shown.

The reported costs do not include all construction-related costs. They only cover building components directly impacting energy efficiency such as exterior wall framing and insulation, not foundation excavation or utility connections, etc. (2.1.2). Some subtler efficiency-related costs—like wider window trim to account for thicker continuous wall insulation—are not explicitly included in the analysis. The costs of a HERS rater, which would be necessary for any stretch code or ERI/HERS path home, are also not included. Final construction costs of any given home will differ.

Multiple factors contribute to uncertainty in construction costs. Supply chain disruptions and high inflation have increased construction costs.[4] In contrast, signs of a possible economic slowdown may lower demand and relieve pressure on prices. Additionally, the construction costs in this study are estimates for a prototypical home using prices collected via separate research efforts, though they have been adjusted for regional and temporal variations. Similarly, the model also takes into account mechanical system replacement costs at the end of the measure's effective useful life, the software is unable to consider factors such as whether there might be more efficient or cheaper versions of these systems available at that future date.

Varying energy prices contribute to uncertainty in model outputs. Recent shocks to energy prices result in discrepancies with the model results. Long-term projections by the EIA are consistent with this study's assumptions, except that after the run-up in rates related to the conflict

[4] As of May 2023, the latest Consumer Price Index (April 2023) had increased 2.2% since the Economic & Energy Distribution Parameters (A.1) were set in Sept. 2022. Multiplying costs in this study by 1.022 may yield more accurate estimates of contemporary costs, but the relative rankings of packages should be stable. In a sensitivity analysis performed for this study, non-construction costs were shown to be insensitive to minor labor/material cost fluctuations.

in Ukraine, the long-term escalation rate for electricity is expected to be lower than modeled.[5] Consequently, even though both gas and electric rates have increased in the short term, electrification should be more attractive than is presented in this report.

Program rebates and other incentives such as the 45L federal tax credit are not included in this analysis. Many optimized homes in this study may be eligible for these incentives, but as outlined in Methodology (and 2.2.1 PA Rebates and Other Incentives), the PAs and EEAC consultants decided that RNC program rebates (based on performance relative to a typical new home) should be excluded from the optimization process. This was influenced by the recognition that, although program participation is high, not all homes participate, and when they do, rebates are often treated as after-the-fact reductions in cost. This decision is consistent with both the Department of Energy Resources/PSD's work to develop the new code,[6] and the recent study commissioned by the Home Builders and Remodelers Association of Massachusetts.[7] Both apply incentives to the modeling output, rather than factoring it into energy model.

Several provisions of the specialized code are not accounted for in this study, such as solar panels, Passive House requirements and wiring for electrification (discussed in Section 5). Consequently, the optimized specialized and stretch code packages in this study are equivalent.

This study intentionally excluded solar panels from the energy models, to simplify the analysis and comply with Department of Public Utilities guidance. This is most significant for mixed-fuel packages in specialized code communities (Section 5). However, the Phase 2 examination of cost-effective electrification will likely incorporate solar panels and battery storage.

Based on MA20R23, HPWHs and propane systems were omitted from this study. While efficient, HPWHs' high incremental cost prevented them from showing up in lower-performing packages in that study. However, they will be featured in the phase two electrification follow-up. MA20R23 also reviewed propane costs; given that heat pump systems compare favorably to natural gas systems, the higher cost of propane should make those systems less cost competitive.

This report does not account for the potential introduction of a clean heat standard. The proposed standard is discussed in reports stemming from the July 2022 climate bill,[8, 9] released after this study began. The Executive Office of Environmental Affairs' report states that, "The clean heat standard will be used to reduce greenhouse gas emissions from building heat, with a focus on encouraging electrification and energy efficiency" (p. 57). The economics of homes heated with fossil-fuels would be less favorable under the standard than is reported here.

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[5] U.S. Energy Information Administration (2023). Annual Energy Outlook. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2023&region=1-1&cases=ref2023&start=2021&end=2050&f=A&linechart=~ref2023-d020623a.6-3-AEO2023.1-1~ref2023-d020623a.5-3-AEO2023.1-1&map=ref2023-d020623a.4-3-AEO2023.1-1&ctype=linechart&sourcekey=0 (Accessed May 2023)

[6] PSD (2020). Stretch Energy Code Development Support Documentation. https://www.mass.gov/lists/stretch-energy-code-development-support-documentation#residential-analysis-documents- (Accessed Sept. 2022)

[7] Boston Globe (July 4). As Mass. Towns Adopt New Climate-Friendly Buildings Codes, Builders Push Back. https://www.bostonglobe.com/2023/07/04/business/mass-towns-adopt-new-climate-friendly-building-codes-homebuilders-push-back/ (Accessed July 2023)

[8] MA Commission on Clean Heat (Nov. 2022). Massachusetts Commission Clean Heat: Final Report. https://www.mass.gov/doc/massachusetts-commission-on-clean-heat-final-report-november-30-2022/download (Accessed Mar. 2023)

[9] Massachusetts Executive Office of Environmental Affairs (Dec. 2022). Clean Energy and Climate Plan for 2050. https://malegislature.gov/Bills/192/SD3441 (Accessed May 2023)

RECOMMENDATIONS AND CONSIDERATIONS

Recommendation 1. Encourage integrated design and reduce barriers to the use of optimization modeling in the residential sector. Both this and the previous optimization study have shown the potential for builders, homeowners, program administrators and other emissions reduction advocates to benefit from the reduced construction cost and energy consumption of optimized designs. Although few energy modeling tools are as powerful as BEopt, Ekotrope recently introduced an add-on called Scenario Modeling which facilitates exploration of measure alterations that may be used to improve a building plan. Working with Ekotrope to make these tools more accessible to builders or increasing awareness of the analogous "Batch File Modifications" tool in REM/Rate could increase the adoption of more cost-effective and impactful design choices.

Recommendation 2. Emphasize the benefits of continuous insulation, infiltration reduction, and high SRE recovery ventilation in outreach materials and program offerings such as the Code Compliance Support Initiative. These measures are closely coupled and necessary to meet the new requirements in the tenth edition of the Massachusetts building code. In particular, the very low infiltration rates of most multifamily packages (0.43 ACH50, included in half of base code packages and every stretch code package) will be required by the specialized code, which has already been adopted in 18 municipalities. While there are approximately two dozen completed multifamily Passive House projects in Massachusetts and twice as many under construction, many employed earlier versions of the standard.[10,11] As such, knowledge of the practices necessary to achieve these low infiltration rates is not very widespread, and market actors would benefit from efforts to disperse this information.

Consideration 1. Consider allowing small (<12,000 ft^2) mid-rise multifamily buildings in stretch and specialized code communities to participate in the PAs' *residential* new construction program. The tenth edition building code allows for those buildings to follow the residential code rather than commercial code.[12] Program administrators may wish to compare the alignment of residential and commercial incentives for such structures and consider whether this presents an opportunity to better serve a key segment of the market.

Consideration 2. Given the potential represented by ground-source heat pumps, consider enhanced efforts to accelerate the adoption of this technology. These efforts might include special programs to manage the large upfront costs of these systems or additional advocacy and support, including for less-common techniques such as direct-exchange heat pumps, which may increase the number of sites where GSHPs are viable. Note that in addition to the high efficiency and large energy savings of this technology in general, it also has less impact on peak demand than ASHPs and MSHPs. This is due to reduced reliance on supplementary resistance heating because GSHPs interact with the nearly constant, moderate temperatures of the high heat capacity subsoil rather than the weather-driven, low heat capacity atmosphere.

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[10] PASSIVEhouse Massachusetts (2023). Projects. https://phmass.org/projects/ (Accessed July 2023)
[11] phius alliance (2023). Certified projected database. https://www.phius.org/certified-project-database?&status=46,25&project_type=28&building_function=27,36,93&location=Massachusetts (Accessed July 2023)
[12] Massachusetts Department of Energy Resources (Dec. 2022) 2023 Technical Guidance: Massachusetts Stretch Energy Codes. https://www.mass.gov/doc/draft-2023-technical-guidance-for-the-stretch-energy-code-and-specialized-code/download (Accessed Mar. 2023)

Consideration 3. Note that MSHP packages in this study have higher costs relative to other HVAC systems than in 20R23. This is primarily due to two slight methodological differences: 1) the study's approach to addressing the International Residential Code's requirements for the conditioning of occupiable space (R402.2.1) was revised,[13] and 2) the unit costs were updated from the web-scraped results employed in 20R23 to regressions of installation costs from recent Massachusetts Clean Energy Center heat pump rebate program data.[14] The second phase of this study will provide additional insight on the costs of higher-performance all-electric homes.

[13] In this study the costs of supplementary head units and compressors were baked into the model inputs, whereas in 20R23 the model outputs were adjusted manually.
[14] MassCEC (2021).Clean Heating and Cooling Project Databases. https://www.masscec.com/public-records-requests (Accessed Oct. 2022)

Section 1 Introduction and Background

This report presents results from the first phase of the residential new construction (RNC) Energy Optimization (EO) Code Compliance and Electrification Modeling study for the Massachusetts Program Administrators (PAs) and the Energy Efficiency Advisory Council (EEAC). This is a follow-up study to the Residential New Construction Energy Optimization Cost Study (20R23).[15] This phase of the study focuses on using optimization modeling in support of the PAs' code compliance efforts under the recently issued tenth edition of the Massachusetts building code. A second phase of the study will focus on optimization modeling of all-electric new homes in Massachusetts and those results will be discussed in a complementary report to follow.

1.1 Goals

The study phase has two primary goals using EO modeling: 1) provide analysis of the upfront and long-term costs plus energy consumption for residential new construction to inform municipal deliberations regarding adoption of the three flavors of the tenth edition building code (base, stretch, and specialized), also potentially informing other local energy-related ordinances and 2) offer general guidance and specific examples of how builders can cost-effectively comply with the new codes.

1.2 Study Background

PSD worked with the Department of Energy Resources (DOER) to model a variety of residential scenarios to support development of the updated building code, with initial results generated in 2020.[16] These scenarios include different home designs and assumptions compared to this study and its 2021 predecessor funded by the Massachusetts PAs, 20R23. For example, the homes in this study and 20R23 are based on a weighted sample of base and stretch code homes from the earlier 19X02 Residential New Construction Baseline/Compliance Study.[17] However, the team reviewed the PSD findings and models, and accounted for some of these differences (such as window costs) when developing the inputs for this study.

More recently, a study commissioned by the Home Builders and Remodelers Association of Massachusetts was published in summer of 2023, near the finalizing of this report.[18] It also incorporates different assumptions, and a distinctly different approach to calculating costs and compliance from this study or DOER/PSDs. Consequently, the incremental costs of specialized compliance in that study are two to three times that for single-family construction cost optimized packages in this report (Table 3).

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[15] https://ma-eeac.org/wp-content/uploads/MA20R23-RNC-EO-Final-Report-10222021.pdf

[16] PSD (2020). Stretch Energy Code Development Support Documentation. https://www.mass.gov/lists/stretch-energy-code-development-support-documentation#residential-analysis-documents- (Accessed Sept. 2022)

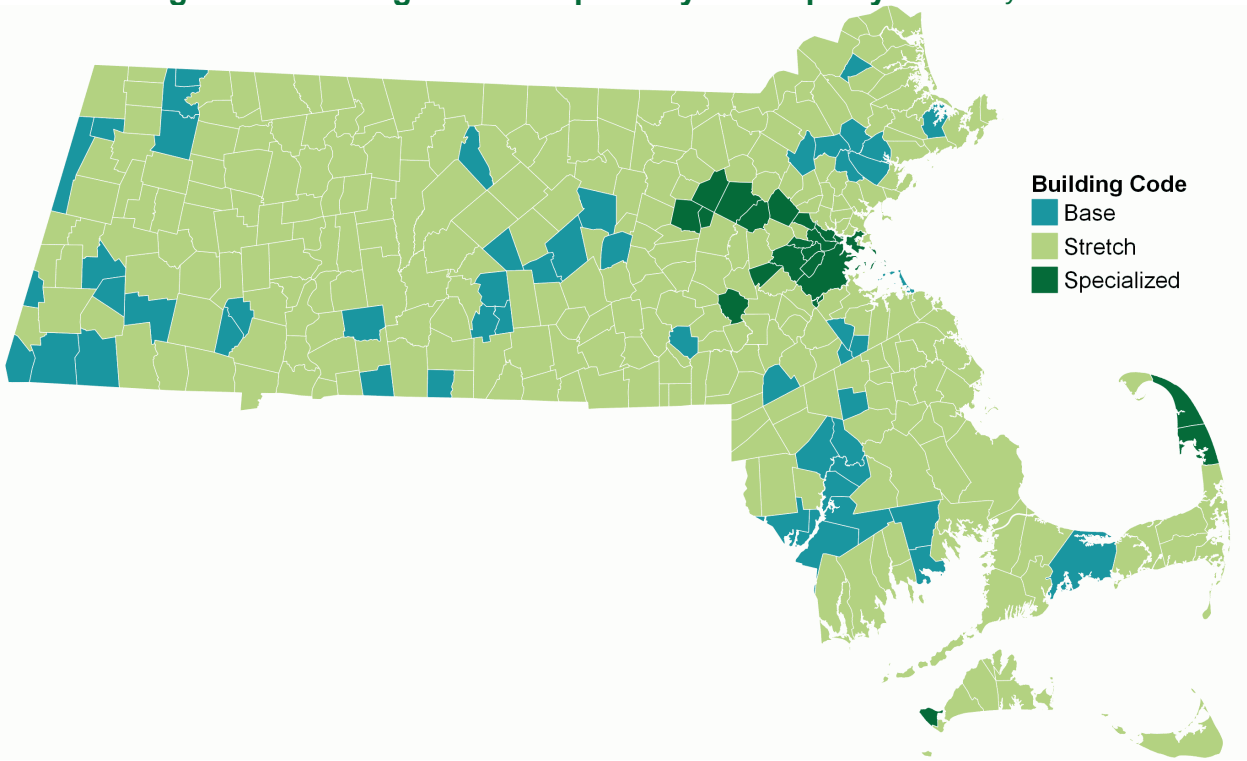
[17] https://ma-eeac.org/wp-content/uploads/MA19X02-B-RNCBL_ResBaselineOverallReport_Final_2020.04.01_v2.pdf

[18] Bakhshi, P. et al. (June 2023). Public Policy for Net Zero Homes and Affordability. https://hbrama.com/wp-content/uploads/2023/05/Public-Policy-for-Net-Zero-Homes-and-Affordability-Final-6-14-23.pdf (Accessed July 2023)

The 20R23 report explored cost-effective improvements to the typical new home constructed under the late stages of the ninth edition Massachusetts building code, as well as the cost of achieving additional energy savings using readily available technologies. In contrast, this report explores building code compliance. This shift in focus results from the purely prospective nature of the study, rather than the blend of prospective and retrospective of 20R23.

Finally, the tenth edition building code represents a significant departure from the previous edition. In particular, the new specialized code adds numerous requirements to promote the construction of net-zero ready buildings. This code is proving to be quite popular, quickly surpassing base code. It has already been adopted by the eighteen dark green communities in Figure 7, and covers nearly one fifth of the state's population (18%). Although base code (blue) is still used in 51 communities, these represent only 9% of the population. The remaining 283 cities and towns with 73% of the Commonwealth's population had previously adopted stretch code.

Figure 7: Building Code Adoption by Municipality as of July 2023[19]



1.2.1 Base Code

The new base code is close to the International Energy Conservation Code (IECC) 2021 reference code, with amendments to the ERI path and prescriptive path requirements. ERI path thresholds depend on the equipment in a home. An all-electric home may comply with a rating of 55 or less, whereas a mixed-fuel home must not exceed 52. The prescriptive path introduces an R-5 continuous wall insulation requirement, and a 0.40 SHGC maximum for windows. Ceiling insulation is increased from R-49 to R-60, and slab insulation depth is increased from two feet to four. Finally, the additional efficiency options for combustion equipment have been removed.

[19] Massachusetts Department of Energy Resources (July 2023). Massachusetts Building Energy Code Adoption by Municipality. https://www.mass.gov/doc/building-energy-code-adoption-by-municipality/download (Accessed July 2023)

1.2.2 Stretch Code

The stretch code introduces a new mechanical ventilation recovery requirement, simplifies the HERS rating credits available for efficient equipment, and significantly lowers the permissible ratings. After an 18-month transition period, the maximum permissible ratings will have decreased from 55 under the ninth edition to 42 (mixed-fuel) or 45 (all electric) in the tenth edition.

1.2.3 Specialized Code

This new code option has already been adopted by 17 communities across the Commonwealth,[20] and it is intended as a net-zero ready option for communities at the vanguard of meeting Massachusetts' climate goals. It builds upon stretch code with an amended version of the IECC reference code's Appendix RC and includes a variety of provisions and compliance options. Some notable requirements include:

- Passive House compliance for large (>12,000 ft^2) multifamily buildings.
- Mandatory solar panels for mixed-fuel buildings.
- Installation of 240 Volt circuits to support future electrification of combustion equipment including space heating, water heating, cooking, and clothes dryers.

1.3 Report Organization

This report is not intended to be read cover to cover. Notably, Section 3 and Section 4 are broken out by code, HVAC and optimization type so that the reader may jump immediately to the material that interests them.

The main body of this report is organized into the following sections:

- Section 2 Methodology Overview: an outline of the modeling and analysis undertaken in this study, including key terms used in the report.
- Section 3 Base Code Compliant Packages: a description of the reference and select optimized packages that minimally comply with the Massachusetts base code.
- Section 4 Stretch Code Compliant Packages: a description of the reference and select optimized packages that minimally comply with the Massachusetts stretch code.
- Section 5 Specialized Code Compliant Packages: a description of optimized packages that minimally comply with the new specialized code, and their limitations.
- Appendix A Model Inputs

[20] Massachusetts Department of Energy Resources (May 25, 2023). Massachusetts Building Energy Code Adoption by Municipality. https://www.mass.gov/doc/building-energy-code-adoption-by-municipality/download

- Model Inputs: the economic and energy-related inputs used in modeling.
- Appendix B Additional Details: additional analysis results.
- Appendix C Package Composition an overview of measure options across packages.

1.4 Choosing a Package of Interest

To zero in on a package of interest, answer the following questions until you reach a line with a blue hyperlink. Click the link to learn about the performance of those packages. Details about the options in a package are in Appendix C. Note: If you do not have access to natural gas, consider heat pumps and B.3 Electrification Impacts rather than propane, given the availability of cost-effective electric systems.

Question: ***Which code are you building for or interested in? Base, stretch, or specialized?***

Base Code

Question: ***What is your primary concern?***

- Construction Cost; labor and materials of energy-related measures e.g., windows
- First Year Cost; 20% down payment, monthly mortgage payments and utility bills
- Ownership Cost; balances additional mortgage from upgrades with lower utility bills
- Site Energy Savings; energy consumption reported on utility bills
- Source Energy Savings; includes power generation and distribution losses

- A specific technology:
  - SF ASHP; single-family home with ducted air-source heat pump
  - SF Furnace/CAC; single-family home with furnace and central air conditioner
  - SF GSHP; single-family home with ducted ground-source heat pump
  - SF MSHP; single-family home with ductless mini-split heat pump
  - MF Furnace/CAC; multifamily home with furnace and central air conditioner
  - MF MSHP; multifamily home with ductless mini-split heat pump

Stretch Code

Question: What is your primary concern?

- Construction Cost; labor and materials of energy-related measures e.g., windows
- First Year Cost; 20% down payment, monthly mortgage payments and utility bills
- Ownership Cost; balances additional mortgage from upgrades with lower utility bills
- Site Energy Savings; energy consumption reported on utility bills
- Source Energy Savings; includes power generation and distribution losses

- A specific technology:
  - SF ASHP; single-family home with ducted air-source heat pump
  - SF Furnace/CAC; single-family home with furnace and central air conditioner
  - SF GSHP; single-family home with ducted ground-source heat pump
  - SF MSHP; single-family home with ductless mini-split heat pump
  - MF Furnace/CAC; multifamily home with furnace and central air conditioner
  - MF MSHP; home with ductless mini-split heat pump

Specialized Code

Use the stretch code results above and consult Section 5 for caveats.

Section 2 Methodology Overview

The team used NREL's BEopt software to model hundreds of variations for each of six core building *designs*. The modeling tool tests different combinations of measure-level enhancements to a core building design, and these are evaluated to identify measure *packages* that are optimized to best meet various criteria of interest.

2.1 TERMINOLOGY

Design. A *design* refers to a specific combination of home style (*e.g.*, single-family Colonial) and HVAC equipment type (*e.g.*, furnace/CAC). Table 4 describes the six designs examined in this study, which include four single-family and two multifamily homes.

Table 4: Code Compliance (Phase I) Designs

Report	ASHP	Furnace/CAC	GSHP	MSHP
Single-family	Colonial	Colonial	Colonial	Colonial
Multifamily	–	3-story, 26-units	–	3-story, 26-units

The HVAC types listed in the columns of Table 4 are:

- ASHP; air-source heat pump, ducted
- Furnace/CAC; natural gas furnace and central air conditioner
- GSHP; ground-source heat pump, ducted
- MSHP; mini-split heat pump, ductless

Package. A *package* refers to a combination of measures (insulation, HVAC efficiency, etc.) for a given design which were selected to optimize the building's performance for a specific metric.

2.1.1 Optimization Types

Descriptions of the different approaches to defining the "best" package are outlined below, with a summary presented in Table 5.

R. The **Reference Package** is an unoptimized home that is approximately code compliant. The various optimized packages described below are compared to this reference package. Additional details can be found in the Reference Packages subsections Base Code Compliant Packages (3.2) and Stretch Code Compliant Packages (4.2).

0. The **Construction Cost Package** has the lowest initial cost for efficiency-related measures among the tested measure combinations. See Construction for details.

1. The **First Year Cost Package** represents the lowest costs to the buyer in the first year of ownership. It has the lowest sum of the following: 20% down payment, first year mortgage payments, first year mortgage interest tax deduction, and first year utility bills. This package may be easier to understand than the Ownership Cost Package, which looks at a 30-year period and considers a wider variety of long-term economic variables.[21]

[21] The first year cost metric does not include end-of-life replacement costs. Consequently, unlike ownership cost, it does not assume like-for-like replacement. This omission allows for future electrification, improvements in technology

2. The **Ownership Cost Package** prioritizes benefits to the homebuyer by balancing upfront construction and long-term ownership costs. It includes all the energy-efficiency upgrades and equipment replacements that exceed their initial upfront costs with utility bill savings over the life of a 30-year mortgage. One can view this metric through two lenses:
    a. The lowest ownership cost package which just satisfies a particular code. This form is featured in Section 3 and Section 4.
    b. The minimum ownership cost possible within the parameters of this study i.e., the bottom of the optimization curves of Figure 9 through Figure 14. These packages are described in Appendix B.2.
3. The **Site Savings Package** achieves the maximum site energy savings possible when choosing between the measure-level model inputs used in this study. It prioritizes energy savings at the utility meter, regardless of upfront or operational costs, and would be of most interest to the eco-minded owner. Readers should note that the Site Savings package does *not* represent the most energy savings technologically possible in a new home. It represents only the maximum savings achievable among the tested combinations of options included in this study, which just meet the specified building code.
4. The **Source Savings Package** is similar to the Site Savings Package – and in fact often refers to the same combination of measures – but it maximizes energy savings for energy suppliers rather than utility meter dollar savings. This is because electricity generation from non-renewable resources is typically less efficient than burning the same fuel directly in the home. However, this distinction diminishes as the grid becomes greener.

Table 5: Summary of Factors Included in Optimized Package Selection

	Const. Cost	First Year Cost	Ownership Cost	Site Savings	Source Savings
Time frame	0 years	1 year	30 years	30 years	30 years
Construction cost	✓	✓	✓	–	–
Down payment	–	✓	✓	–	–
Mortgage	–	✓	✓	–	–
Utility bills	–	✓	✓	*Energy*	*Energy*
Replacement	–	–	✓	–	–
Energy savings	–	*Utility bills*	*Utility bills*	✓	✓
PA rebates	–	–	–	–	–
Federal eff. incentives	–	–	–	–	–
Property taxes	–	–	–	–	–

Italicized entries are indirectly accounted for by the related factor listed.

or changes in inflation-adjusted equipment pricing. The first year cost package also differs from other optimizations because the selection process allows the second-best combination of measures to be chosen If the combination with the lowest total first year cost is identical to that of another package. This only occurs if the difference in first year costs between the first and second place combinations is $100 or less per unit, but creates greater variety.

2.1.2 Design and Package Shorthand

The study and accompanying datasets use the following coding system to reference specific home designs and optimized packages, where major aspects of the package are represented by a single letter or number. This encoding (**Error! Reference source not found.**) is slightly different to the one employed in the *Residential New Construction Energy Optimization Cost Study* (20R23). In particular, the codes for optimization levels have changed; only Ownership Cost and Site Savings remain the same.[22] For example, "DCMW.B1" refers to a stud-construction Colonial with a mini-split heat pump HVAC system in a base code community, optimized for the lowest total first year cost.

Table 6: Design and Package Naming Convention Key

Walls	Home Style	HVAC	Location	Code	Optimization Focus
D: Stud	C: Colonial†	A: ASHP†	W: Worcester	B: Base	R. Reference (None)
2: Double stud†,‡	3: 3-story MF	F: Furnace		S: Stretch	0. Construction Cost
		G: GSHP†		Z=Specialized	1. First Year Cost
		M: MSHP			2. Ownership Cost
					3. Site Savings
					4. Source Savings
					GO. Global Minimum Ownership Cost

† Single-family only. ‡ Phase II only.

All homes in this study are modeled in Worcester, unlike the 20R23 study, which also modeled homes in Boston and Cape Cod. Results from that study indicate that the home designs were highly similar across locations, except for heating and cooling equipment capacity. For brevity, this report focuses on stud-construction, colonial designs in the Worcester climate for single-family homes, along with multifamily low-rise construction.

[22] The payback period packages of the previous study, which attempted to maximize energy savings with little to no increase in energy cost, have no direct analog in this study. However, they are most closely related to first year cost.

2.2 COSTS INCLUDED IN ANALYSIS

Construction costs included in this analysis are limited to the labor and materials costs of *energy-related measures* that could vary between packages which are listed in A.3 and A.4, see also Appendix B.1. Other aspects of the home which are not considered include:

- Land preparation, excavation, or pouring a foundation
- Partition walls (i.e., interior walls that separate rooms in conditioned space)
- Utility hook-ups (e.g., gas line connections)[23] or in-home distribution systems, such as wiring or plumbing[24]
- Fit and finish such as roofing, siding, flooring, cabinetry, etc.
- Lighting, since all designs include 100% LEDs to meet code lighting efficacy requirements
- Non-cooking appliances, which were held constant at baseline efficiencies
- HERS rater costs

Many costs employed in this analysis come from NREL's NREMDB, while others are from 20R23 or were gathered specifically for this study. All are adjusted to reflect the Massachusetts market and represent estimated prices for October 2022.

Material costs of energy-efficiency related materials and supplies. Costs vary by measure type and efficiency. For example, a high-efficiency furnace is more expensive than a low-efficiency furnace. Similarly, installing a furnace requires ductwork that is not required for MSHPs.

Labor costs associated with the construction and incorporation of energy-efficiency measures. Costs vary by measure and option since some selections are more labor intensive than others. For example, more time is required to spray the twenty-two inches of insulation that may be required for an R-60 ceiling versus nineteen for R-49. Similarly, installing a furnace requires labor for ductwork that is not required for MSHPs.

Utility bills represent the cost of the metered electricity and gas, including variable and fixed costs (consumption and service fees, respectively). The price of electricity and gas is the most recent average available from the EIA at the time of modeling, with rate escalation rates of 0.4% for electricity and 0.0% for natural gas.

The **mortgage** in this study is a standard 30-year arrangement, with a fixed interest rate of 6.2%. Per the discussion of construction costs above, BEopt does not cover the total construction cost of the home, nor does it estimate the sale price of the home. Rather, the mortgage costs in this report are limited to the efficiency-related aspects of the home.

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[23] In the 20R23 study, PAs estimated typical costs to bring gas to a single-family home (Eversource estimated $2,850; Berkshire Gas estimated $5,400). These can be treated as add-on costs and have been adjusted for inflation; they were not included in models. PAs said these costs are not passed to homeowners if connection length is ≤100 feet.

[24] Perfectly capturing these costs is outside the scope of this study. Electric cooking, for example, might require additional wiring and electrical costs but would also displace gas piping. 20R23 found that prevailing wages for MA plumbers and electricians are comparable based on BLS data, meaning that labor for additional wiring may be offset by reduced pipe-laying. Also 20R23 showed that 200 Amp service common in new homes is typically sufficient for electrification. However, panels or interconnects may be required to prevent the EVs from charging during peak loads.

Ownership cost is another name for the annualized energy-related costs (AERC) of a home. This is a holistic metric that helps people better assess long-term costs. It balances the initial incremental costs of installing energy-efficiency upgrades with the lower utility bills resulting from increased energy efficiency. AERC is a metric provided by BEopt which includes the net present value of the mortgage, mortgage interest tax deduction,[25] utility bills, and projected replacement costs over the duration of the analysis period (30 years).

Replacement costs represent the costs to replace features of a home at the end of their effective life, particularly heating, cooling, and hot water equipment. These assume like-for-like replacement, with adjustments for inflation. For example, the effective life of a MSHP in the NREMDB is 15 years. This means that the ownership cost (AERC) for a home with MSHPs includes the present value of two heat pump system purchases. The first is part of the home construction, and the second at the end of the first MSHP's expected useful life in 15 years. The software is unable to consider factors such as whether there might be more efficient or cheaper versions of these systems available at that future date.

2.2.1 PA Rebates and Other Incentives Excluded from Analysis

This study does not include rebates from the Mass Save RNC program or other incentives, such as those which may be available through the Inflation Reduction Act of 2022.[26] However, it does include federal income tax deductions for mortgage interest.[25] Ultimately, the PAs and EEAC consultants decided to exclude incentives from modeling, considering the following factors:

- The small but predictable impact incentives have relative to other parameters.
- The recognition that although program participation is high, not all homes participate.
- The impression that rebates are often treated as after-the-fact reductions in cost.
- The program may periodically revise its eligibility requirements and incentive amounts.
- The difficulty of accurately including some incentives in the model.

This decision is consistent with both DOER/PSD's work to develop the new code,[27] and a recent study commissioned by the Home Builders and Remodelers Association of Massachusetts.[28]

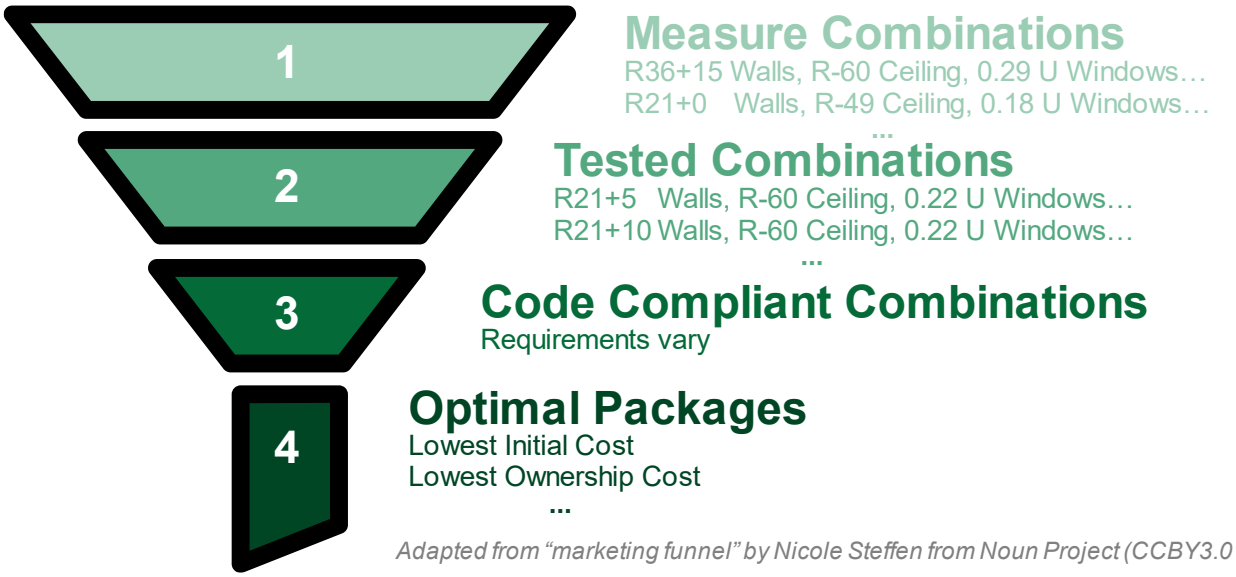
A preliminary sensitivity analysis to see how adjusting model inputs affects optimization outcomes revealed that incentives typically have only a small impact, although this varies by optimization type and metric. For instance, when including program incentives, optimization modeling yielded packages with decreased ownership costs as expected, but it did so uniformly across packages. Similarly, efficiency-related construction costs and utility bills in the new packages only changed by negative one to one percent. On the other hand, the composition of some packages optimized for cost rather than energy was altered, resulting in a slight increase in source energy savings.

[25] Since BEopt only models energy-related features, the deduction rarely exceeds $3,000, and typically around $1,400.
[26] Like the revised 45L, Tax Credits for Zero Energy Ready Homes.
[27] PSD (2020). Stretch Energy Code Development Support Documentation. https://www.mass.gov/lists/stretch-energy-code-development-support-documentation#residential-analysis-documents- (Accessed Sept. 2022)
[28] Bakhshi, P. et al. (June 2023). Public Policy for Net Zero Homes and Affordability. https://hbrama.com/wp-content/uploads/2023/05/Public-Policy-for-Net-Zero-Homes-and-Affordability-Final-6-14-23.pdf (Accessed July 2023)

2.3 Optimized Package Selection

The packages featured in this report are the result of a multi-step filtering process summarized in Figure 8, and explained at greater length below.

Figure 8: Package Selection Process



Adapted from "marketing funnel" by Nicole Steffen from Noun Project (CCBY3.0

Package Selection Step 1.
There are far more efficiency options for most measures than it is possible to examine in this study. For example, furnaces are available in a wide variety of rated efficiency values: 80 AFUE, 90 AFUE, 92 AFUE, 95 AFUE, 98.5 AFUE and more. Therefore, the study uses a narrower set of possibilities for each measure (e.g., 95 and 98.5 AFUE furnaces). These are informed by the 19X02 Single-Family Residential Baseline study, NMR's professional expertise, and input from the PAs and EEAC Consultants. Nevertheless, millions of measure combinations are possible using the options listed in Building Shell Measure Options (A.3) and Equipment Options (A.4).

Package Selection Step 2. BEopt begins modeling many different measure combinations (grey points in Figure 9), and in the process learns which measure options are more or less likely to yield desirable results. The software begins to favor better-performing measure options when testing future combinations and chooses those which have previously fared poorly less often. However, these options are not eliminated entirely. It is possible that synergistic effects from later changes to other measures result in better performance from previously unfavorable options. For example, an ERV is not likely to be a useful addition to a home with a high infiltration rate, but if the building's air leakage is reduced, then an ERV may become a viable option compared to bathroom exhaust fans.

Package Selection Step 3. NMR reviewed the tested packages in BEopt's output to select those that complied with the base, stretch and specialized codes.[29] In addition, to meet the goals for Phase I of this study – i.e., the selection of minimally compliant home designs – the team set a minimum ERI-threshold to avoid potentially selecting any optimized packages that far outperformed code (a lower ERI indicates better performance). These stretch and specialized minimum ERI thresholds are based on the distribution of ERI scores for all tested combinations; the minimum value for the base code is informed by section R406.5 of the building code. The maximum ERI thresholds for stretch code are not the higher interim ratings thresholds permissible from January 2023 through June 2024,[30] but instead the final requirements once the tenth edition of the Massachusetts building code fully goes into effect in July 2024.

Table 7: Code Compliance (Phase I) Home Energy Rating Criteria

	Minimum (Best Performing)	Maximum (Worst Performing)
Base Code	48	N/A – Prescriptive path 52 mixed-fuel, ERI path 55 all-electric, ERI path
Stretch & Specialized Codes	38	42 mixed-fuel 45 all-electric

Package Selection Step 4. The selected package for a given optimization is chosen by sorting and filtering the packages resulting from the previous step. For example, the lowest initial cost ASHP single-family stretch code home is selected from the list of stretch code compliant single-family homes by sorting the list from lowest initial cost to highest. The first ASHP home on the list is then designated the optimal Construction Cost package (for single-family homes using ASHPs that minimally comply with stretch code; DCAW.S0).[31]

2.4 MODELS

The figures below show all tested combinations (small grey points) modeled for each of the six designs in this study. Clusters of optimized packages (large green points) inside the dotted rectangles represent the minimally code compliant packages for either the base or stretch/specialized codes (see Section 5 for details about the specialized code). Clicking on a rectangle will take you to the corresponding section of report (i.e., clicking on the base code box of the single-family GSHP figure will take you to the section comparing geothermal base code packages (3.3.4). The lowest

☛ Click a shaded box in the figures below to jump to a discussion of those packages

[29] The 10th edition building code explored in this study calls for HERS Index ratings (lower values represent better performance) to specify home performance levels. However, BEopt only supplies Energy Rating Index (ERI) scores. Fortunately, ERI is closely related to the HERS index. In fact, the IECC that the MA building code is derived from uses ERI, and the previous version of the MA stretch code treated ERI and HERS index as interchangeable.
[30] The interim values are the same as the new base code: 52 mixed-fuel, 55 all-electric, 58 all-electric with photovoltaics.
[31] The ERI threshold and final package selection steps happen concurrently. Thus, if there is no tested combination which exceeds the minimum ERI, this requirement is ignored and only step 4 is applied.

point of the curves in each figure, the Global Minimum Ownership Cost (GO), are collected and discussed in Appendix B.2.

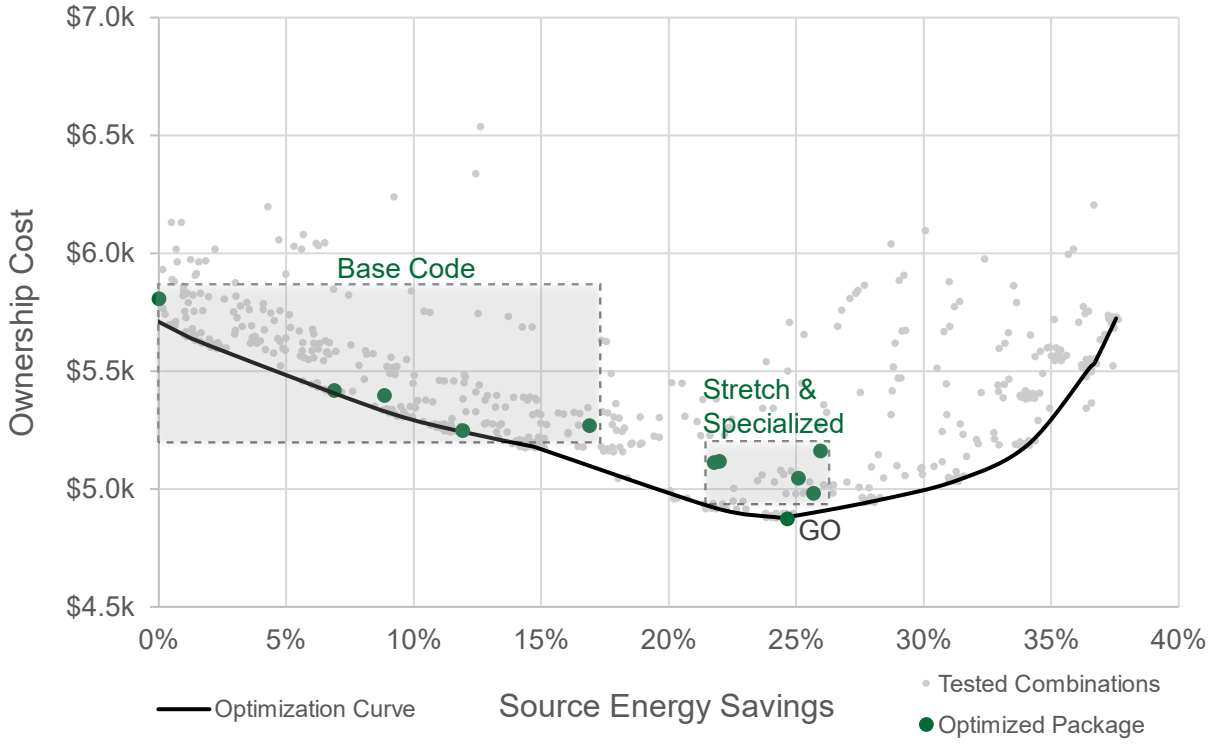
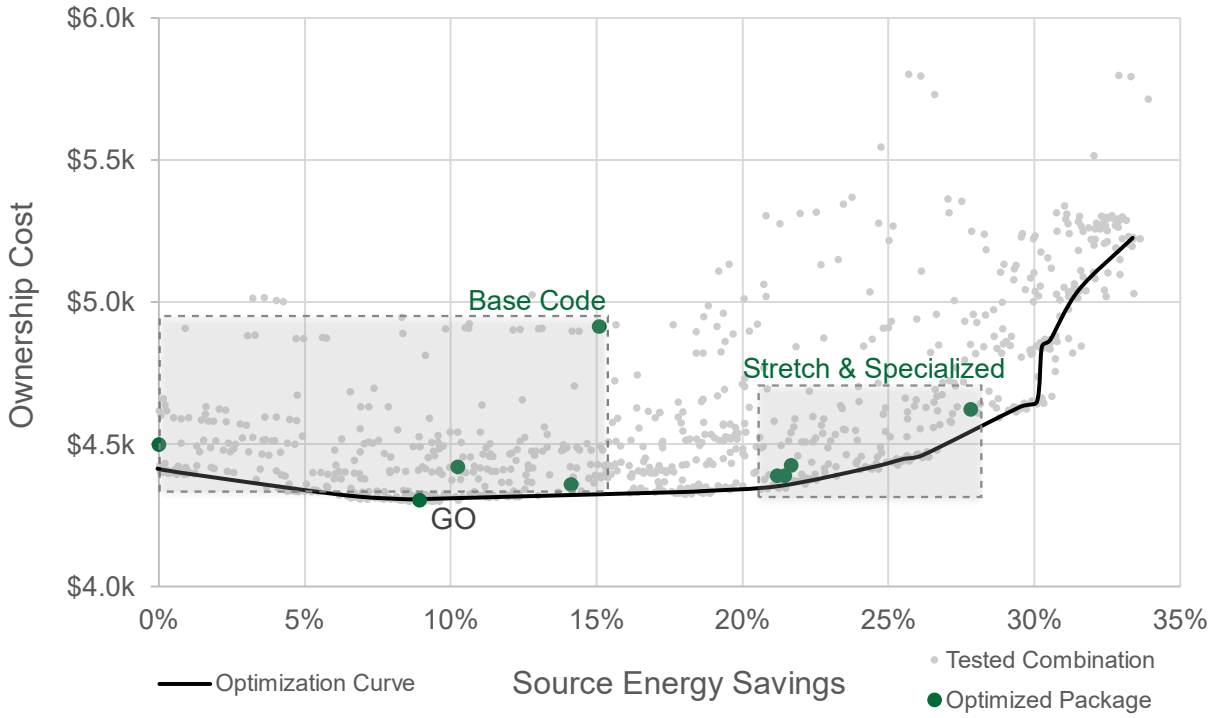


Figure 9: Single-Family ASHP Optimization

The crooked shape of the optimization curve in Figure 10 and others that follow is a byproduct of the multi-dimensional data produced by the modeling process. Given the study's focus on code compliance, BEopt optimized for ERI rather than source energy savings in its exploration of measure options. As a result, the ownership cost–source energy savings slice of the data may not have a smooth contour.

Figure 10: Single-Family Furnace/CAC Optimization



Due to the overwhelming efficiency of ground-source heat pumps, the base code and stretch packages are identical for this design in Figure 11. Therefore, the clickable bookmarks have been divided into two adjacent boxes.

Figure 11: Single-Family GSHP Optimization

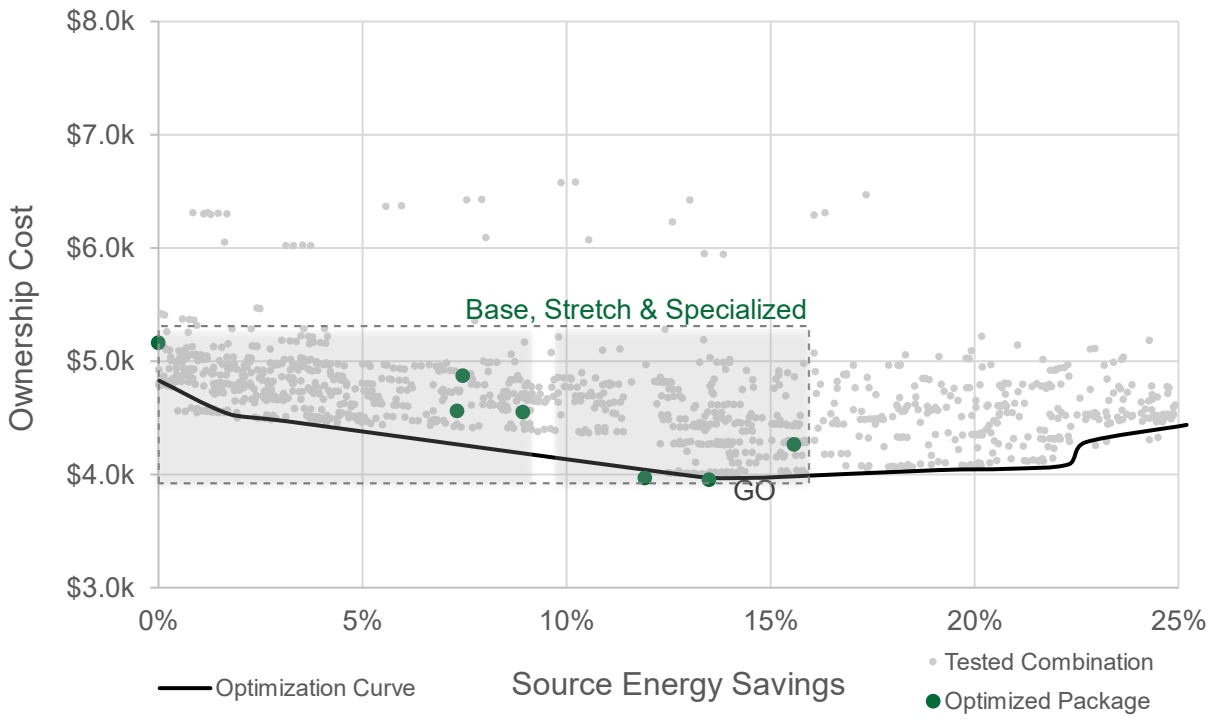


Figure 12: Single-family MSHP Optimization

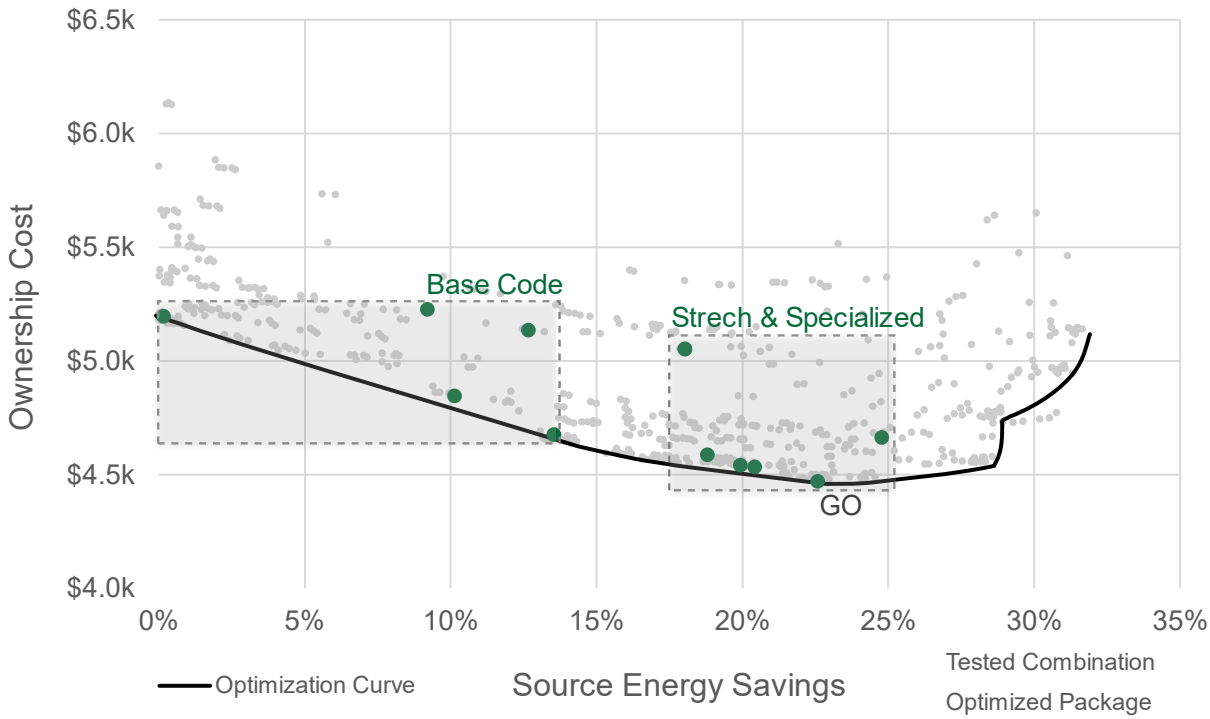


Figure 13: Multifamily Furnace/CAC Optimization

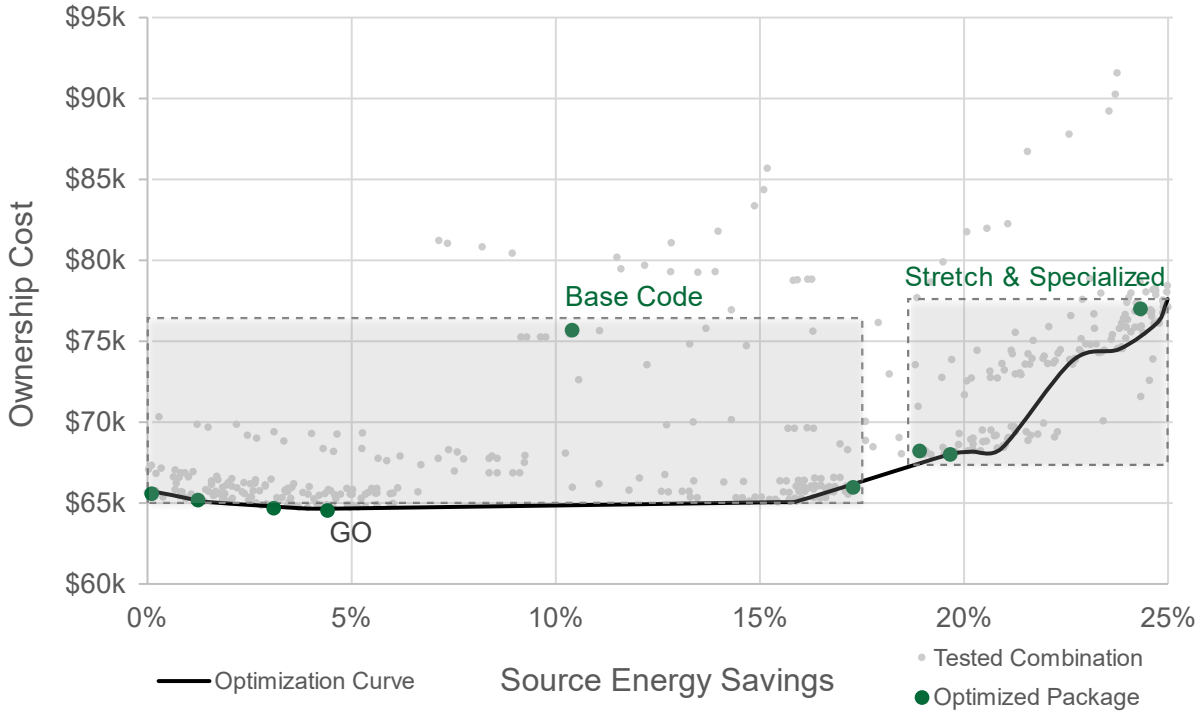
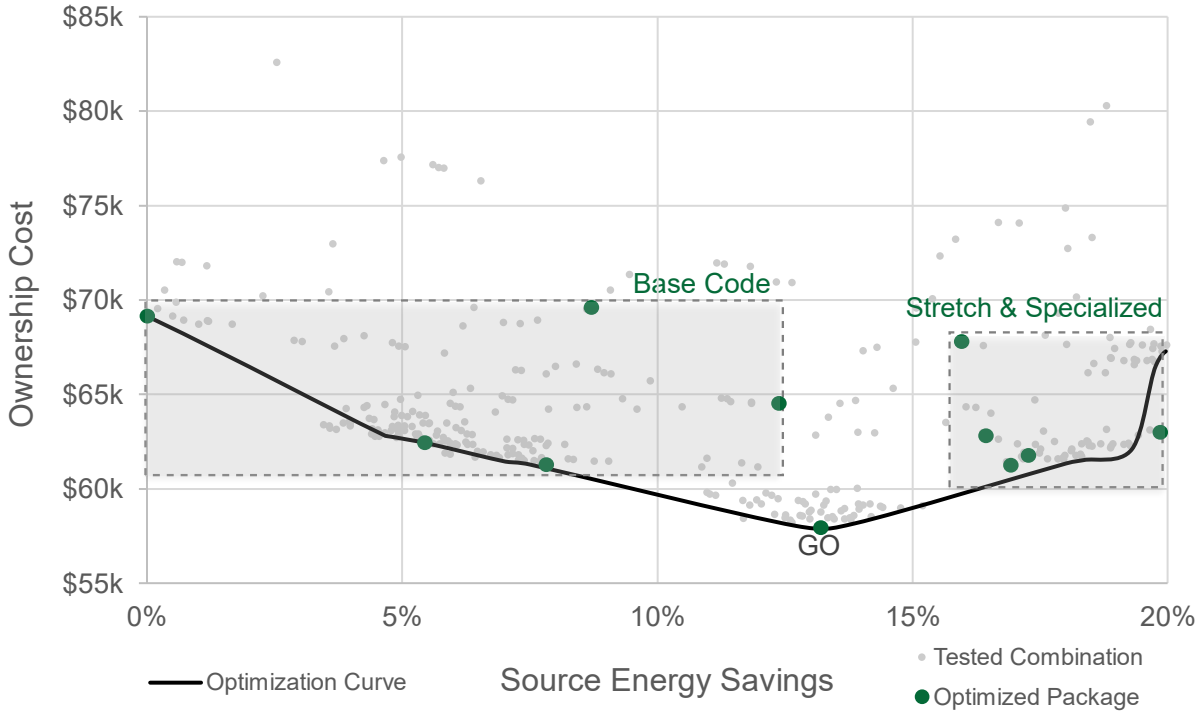


Figure 14: Multifamily MSHP Optimization



Section 3 Base Code Compliant Packages

The following section describes the reference and optimized packages that **minimally comply with the Massachusetts base code**.[32] Packages that comply with the stretch and specialized codes are described in the following sections (Section 4 and Section 5, respectively). A broad overview comparing base and stretch code packages is available in the executive summary's Key Findings.

This section presents the following for minimally base code compliant packages:

- 3.1 Key Features of Optimized Homes
- 3.2 Reference Package Details
- 3.3 Package Comparison by HVAC
- 3.4 Package Comparison by Optimization

How to read this section. Please note that the package comparison subsections (3.3 and 3.4) cover the same material with different emphases. Therefore, readers interested in identifying an optimal construction package do not have to read both. *Readers who want to compare packages with the same basic HVAC type should focus on 3.3; readers who want to compare packages optimized for the same metric but with different HVAC types should focus on 3.4.*[33]

3.1 Key Features of Optimized Homes

By examining the measures commonly selected in packages optimized for compliance with base code, the study identified the following design choices that can result in greater energy and cost savings in new homes.

☑ **Use 2×6×24 inch framing.** Like the 20R23 study, all but two optimized packages employ 24-inch on-center spacing instead of the 16-inch on-center spacing typically seen in the most recent Massachusetts RNC baseline study. Increased spacing reduces the amount of lumber required and associated thermal bridging of the studs. Filling the freed space with additional insulation further increases the home's thermal efficiency.

☑ **Use balanced ventilation in furnace homes.** All optimized single-family furnace/CAC packages, and two multifamily furnace/CAC packages include an ERV, in contrast to the reference home's exhaust-only ventilation system. ERV units exchange heat and humidity between airstreams entering and leaving a home without mixing them. They reduce heating and humidification needs in the winter, then reduce cooling and dehumidification needs in the summer. These ERVs may be sufficient to comply with the new requirements described in section R408 of the building code (3.2.1).

[32] Primarily via the ERI path (R406.5), although many packages also comply via prescriptive path (R401–R404); see B.5 for details. Also note that any stretch code package from Section 4 would satisfy the maximum base code energy rating of 52 for mixed-fuel homes.
[33] Specifically, section 3.3 calls out when a single package satisfies multiple optimization criteria or when the heating equipment is upgraded, while Table 15 in section 3.4 summarizes which design fairs best under different scenarios.

MSHPs are the best technology for multifamily buildings, and for single-family packages focused on the shorter term i.e., construction or first year cost. GSHPs excel at maximizing energy savings and reducing ownership costs. If a ground-source heat pump is not practical, mini-split packages are a good alternative.

Deeply bury HVAC ducts where possible. All but one package for single-family homes with ducted HVAC systems includes deeply buried ducts (R-25),[34] instead of using the R-8 duct insulation in the reference furnace/CAC home. The exception is the GSHP package optimized for deepest source energy savings, which compensated for this by moving HVAC into conditioned space, i.e., insulating the roof rather than the ceiling.

Use continuous wall insulation to increase energy savings and reduce long-term costs. Ninety-three percent of optimized packages include some continuous insulation, and 78% of ownership cost, site and source energy savings packages feature R-15.

Most packages (70%) include gas water heaters due to the pricing of natural gas. However, several site savings and construction cost packages feature electric storage water heaters, which do not require ventilation. Heat pump water heaters, which can be used to comply with R408 (3.2.1), are not featured in this report given its focus on minimal code compliance. However, they will be in the Phase II electrification report.

3.2 Reference Package Details

The reference packages for base code homes comply with the prescriptive requirements for insulation levels, air leakage, duct leakage and efficient lighting. However, as discussed in the next subsection, this is insufficient to comply with the building code for furnace/CAC homes, unless the builder opts for ERI-based compliance (R406.5).[35]

3.2.1 R408 Additional Efficiency Package Options

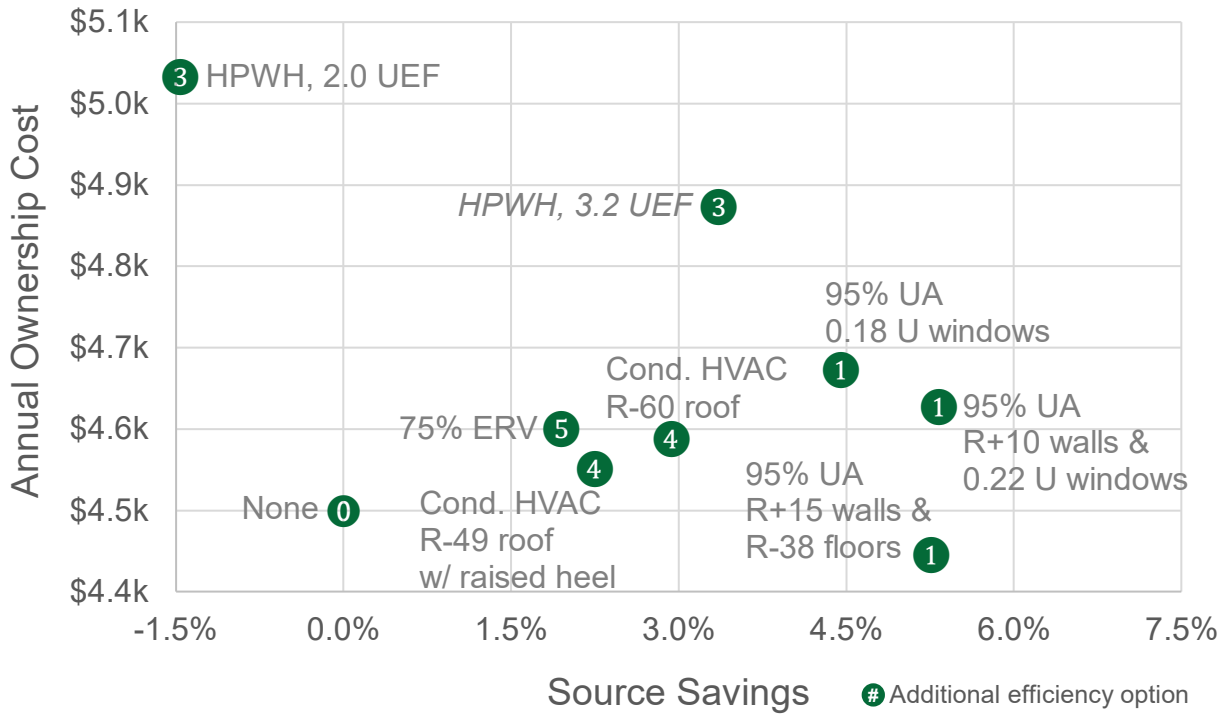
Required add-ons for prescriptive base code. Builders pursuing prescriptive path compliance in base code communities *must include a high-performance measure from section R408*.[36] The menu of options from which builders must select follows (filled circles are plotted in Figure 15):

❶ 5% or greater reduction in building envelope UA (R408.2.**1**)
② 10 HSPF/16 SEER or better ASHP or MSHP (R408.2.**2**.1); approx. 8.5 HSPF2/15.2 SEER2
② 3.5 COP or better GSHP (R408.2.**2**.2)
❸ 2.0 UEF or better heat pump water heater (R408.2.**3**.1)
③ Provide 40% or more of domestic hot water with a solar hot water system (R408.2.**3**.2)[37]
❹ Place all ductwork and air handlers in conditioned space (R408.2.**4**)[34]
❺ 3 ACH50 or less air infiltration (no trade-off), and 75% SRE recovery ventilation (R408.2.**5**)

[34] Multifamily furnace designs are modeled with conditioned ductwork, which is customary for in-unit HVAC. However, some multifamily buildings feature mechanical equipment in unconditioned utility closets on outside walls of apartments.
[35] ERI-path compliance for a base code furnace/CAC home without PV requires a rating less than or equal to 52.
[36] Formerly R407 in the 2018 code version.
[37] This option is not modeled in this study.

Since all heat pump (②) options in this study (A.3) satisfy the above requirements, only furnace/CAC homes require special attention to comply with this provision of base code. Figure 15 below plots the performance and ownership costs of a non-compliant furnace/CAC home (None ❶) and shows how those values vary when the home is configured to include different R408 compliant measure options. As a reminder, heat pump water heaters (❸) are not featured in the code compliance phase of this study. They are listed below for illustrative purposes only. In addition, code only requires a 2.0 UEF HPWH, but these have been displaced by more efficient models of 3.0 UEF or more. Therefore, a common 3.2 UEF model is included for comparison.

Figure 15: R408 Options for a Single-Family Furnace/CAC Prescriptive Path Home



The best R408 option for any given home will vary, as can be seen in the composition of base code compliant packages in the appendix. That said, adding an ERV (❺) may be the simplest way to comply for those who prefer to use a furnace and central air conditioner (details on that design can be found in Section 3.3.2 and Appendix C). However, there is some uncertainty about the viability of this approach. The draft base code published in December 2022 lists section R408.2.5 as an option in R408.2, but does not actually include the R408.2.5 Improved air sealing and efficient ventilation system option from the IECC reference code.[38] Furthermore, MSHPs may be preferable to builders, since this package has lower construction costs than the furnace/CAC package with an ERV, as shown in Table 8. The annual cost for the homeowner of the unoptimized MSHP is 20% higher than a prescriptive furnace/CAC home with ERV, but ownership and construction costs can both be reduced with optimized packages from Section 3.3.4.

[38] Massachusetts State Board of Building Regulations and Standards (Dec. 2022). 780 CMR Tenth Edition.https://www.mass.gov/doc/10th-edition-total-version-1213/download (Accessed May 2023)

Table 8: R408 Option Details for a Prescriptive Path Single-Family Home

R408 Efficiency Option	ERI	Source Energy Savings	Const. Cost	Utilities (1st Yr)	First Year Cost	Annual Ownership Cost
⓿ *Reference, Furnace/CAC without R408*	*58.7*	*0.0%*	*$82.8k*	*$3.4k*	*$34.0k*	*$4.5k*
❶ 95% UA, R+10 walls, 0.22 U windows	55.8	5.3%	$89.7k	$3.3k	$35.6k	$4.6k
❶ 95% UA, 0.18 U windows	56.4	4.4%	$89.4k	$3.3k	$35.5k	$4.7k
❶ 95% UA, R+15 walls, R-38 floors†	56.0	5.2%	$86.3k	$3.3k	$34.7k	$4.5k
② ASHP, 8.5 HSPF2 / 13.4 SEER2	59.5	6.6%	$88.1k	$4.6k	$36.5k	$6.2k
② GSHP, 4.0 COP / 20.0 EER2	47.6	25.6%	$128.3k	$3.6k	$45.4k	$6.6k
② MSHP, 8.7 HSPF2 / 18.7 SEER2	54.1	16.0%	$74.9k	$4.1k	$32.8k	$5.5k
❸ HPWH, 2.0 UEF (minimum required)	57.7	-1.5%‡	$84.2k	$3.8k	$34.8k	$5.0k
❸ *HPWH, 3.2 UEF (commonly available)*	54.0	3.3%	$85.2k	$3.6k	$34.7k	$4.9k
❹ Conditioned HVAC, R-60 roof	57.6	2.9%	$91.7k	$3.3k	$36.1k	$4.6k
❹ Cond. HVAC, R-49 roof w/ raised heel	58.0	2.2%	$88.9k	$3.4k	$35.5k	$4.6k
❺ 75% ERV	55.0	1.9%	$84.2k	$3.3k	$34.4k	$4.6k

② These correspond to the reference packages DCAW.BR, DCGW.BR and DCMW.BR respectively.
† R-30+5 may be substituted for R-38 floors, as they perform equally well.
‡ Even though both HPWH entries have lower ERI than the reference home, greater reliance on resistive heating by the 2.0 UEF HPWH (81% vs. 60%) results in increased source energy consumption. For example, the 2.0 UEF HPWH only increases the furnace heating load by 400 kBTU/yr, compared to 2,700 kBTU/yr for a 3.2 UEF HPWH.

3.3 Package Comparison by HVAC

Reference and optimized packages: same HVAC design. The reference packages in this section are for *homes of the same design*, permitting the reader to easily assess the benefits of different types of optimization (2.1.1). Energy savings for the optimized packages are presented *relative to a reference home with the same type of HVAC system*. In the first subsection, for example, the reference package and all the optimized packages are single-family colonial homes, each using an ASHP HVAC system (though potentially of different efficiencies).

Note to Readers:
Reference packages in this section have the *same* type of HVAC system as each optimized package.

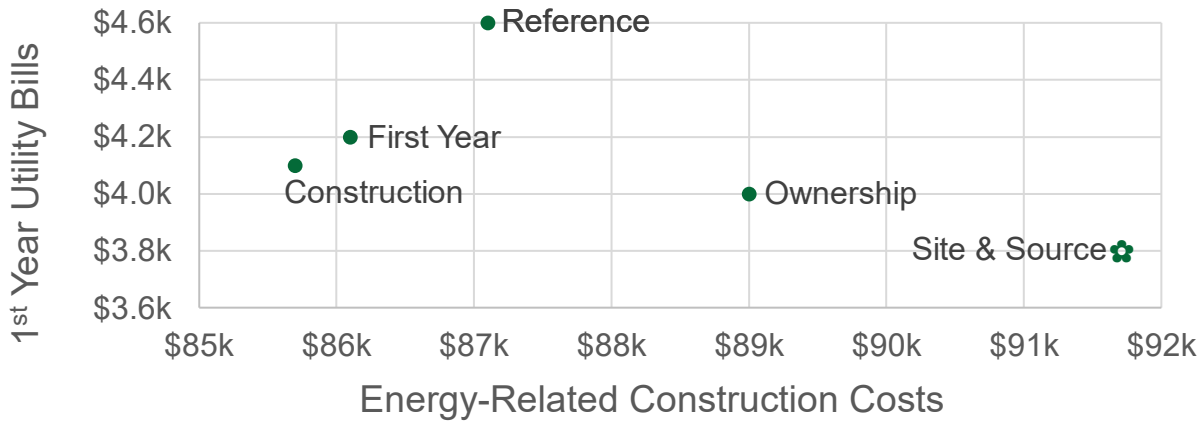
One package may satisfy multiple optimization types. Sometimes a single combination of measures is the best candidate for multiple optimization criteria, e.g., construction and first year cost packages. This is especially common for the site and source energy savings package.[39] In such cases, the table which accompanies each figure will contain identical values, and symbols (✦ or ✿) are used to indicate that these packages are identical.

[39] Although fuel-switching of stoves and water heaters is permitted in the optimization modeling, it is rarely advantageous due to the relative costs of electricity and natural gas. Consequently, BEopt tests these options less often, and frequently there is no all-electric tested combination in the vicinity of the target performance level to select as a distinct site savings package. While these end uses typically only represent a few percent of a home's energy use, readers may consult B.3 for details on adjusting the results of packages in this report to further optimize the site energy savings through electrification of mixed-fuel packages.

3.3.1 SF ASHP

As shown in Figure 16 and Table 9, four unique combinations of measure options were found to satisfy the optimization criteria of this study. All four include deeply buried ducts (ducts buried in attic insulation such that they are effectively insulated to R-25), compared to the R-8 of the reference home. The primary difference between the construction package and the others is it includes a 75% recovery ERV. Otherwise, the primary differences among the various packages are the levels of ceiling insulation (R-49 vs. R-60) and/or continuous wall insulation (R-15 vs. R-5).

Figure 16: Single-Family Base Code ASHP Packages (DCAW.B)



The modest increase in construction costs of the ownership and site/source packages (✿) relative to the construction and first year packages in Table 9 results in three- and six-year payback periods.

Table 9: Single-Family Base Code ASHP Package Details (DCAW.B)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference*	*59.5*	*0.0%*	*$87.1k*	*$4.6k*	*$36.5k*	*$5.8k*	*DCAW.BR*
	Construction	50.7	6.9%	$85.7k	$4.2k	$35.8k	$5.4k	DCAW.B0
	First Year	55.1	6.9%	$86.1k	$4.2k	$35.8k	$5.4k	DCAW.B1
	Ownership	52.4	11.9%	$89.0k	$4.0k	$36.4k	$5.2k	DCAW.B2
	Site✿	49.7	11.9%	$91.7k	$3.8k	$36.9k	$5.3k	DCAW.B3
	Source✿	49.7	11.9%	$91.7k	$3.8k	$36.9k	$5.3k	DCAW.B4

✿✦Packages with identical symbols include the same combination of measure options.

3.3.2 SF Furnace/CAC

As shown in Figure 17, four unique combinations of measure options were found to satisfy the optimization criteria of this study. All three include deeply buried ducts (ducts buried in attic insulation such that they are effectively insulated to R-25), and Passive House levels of air leakage. The primary differences between the site savings/ source savings packages (✿) and the remaining packages are additional continuous wall insulation (R-15 vs. R-5 or none), increased ceiling insulation (R-60 vs. R-49), and electric DHW equipment.

The roughly 7% increase in construction costs of the site/source savings package (✿) relative to the other optimized packages (see Table 10) increases first year utility bills by 12% due to the installation of an electric resistance water heater. However, this package obtains 50% deeper source energy savings compared to the lower-efficiency construction and first year packages (15% vs, 10%). In contrast, the ownership cost package obtains nearly the same level of savings as the site/source energy savings packages, but with lower construction cost and first year utility bills.

Figure 17: Single-Family Base Code Furnace/CAC Packages (DCFW.B)

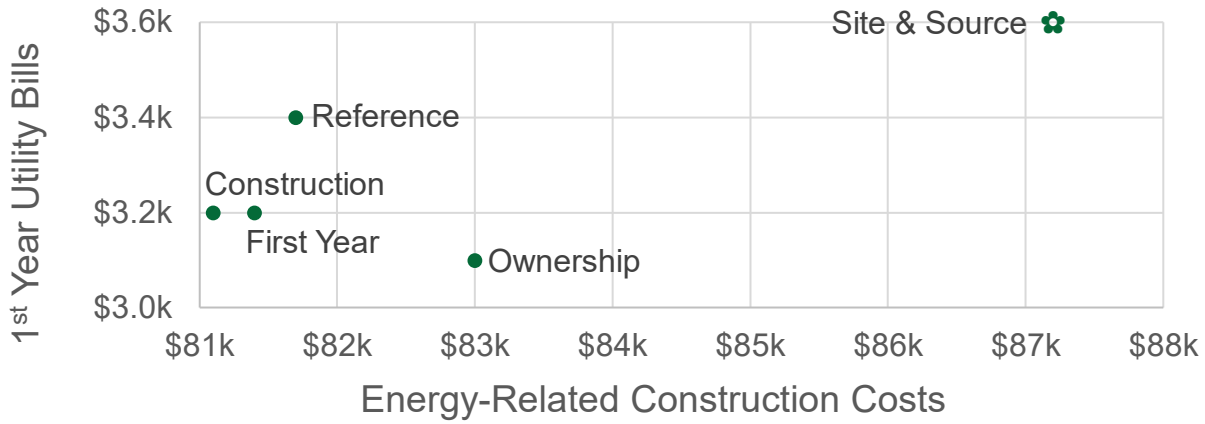


Table 10: Single-Family Base Code Furnace/CAC Package Details (DCFW.B)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference†*	*58.7*	*0.0%*	*$81.7k*	*$3.4k*	*$34.0k*	*$4.5k*	*DCFW.BR*
	Construction	50.4	10.0%	$81.1k	$3.2k	$33.6k	$4.4k	DCFW.B0
	First Year	50.3	10.2%	$81.4k	$3.2k	$33.7k	$4.4k	DCFW.B1
	Ownership	48.4	14.1%	$83.0k	$3.1k	$34.0k	$4.4k	DCFW.B2
	Site✿	48.0	15.0%	$87.2k	$3.6k	$35.5k	$4.9k	DCFW.B3
	Source✿	48.0	15.0%	$87.2k	$3.6k	$35.5k	$4.9k	DCFW.B4

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).

✿✦Packages with identical symbols include the same combination of measure options.

3.3.3 SF GSHP

Unique combinations of measure options satisfy each of the five optimization criteria in Figure 18, yielding five different optimized packages. All of them reduce infiltration to Passive House standards (from 3 to 0.85 ACH50) and include 85% recovery ERVs and additional continuous wall insulation (R-10 or higher vs. the R-5 of the reference home). The source savings package is not an optimal investment compared to the ownership cost package, given that it increases savings by roughly 2 percentage points but has a 14% higher construction cost. However, another perspective is that for only a 2% increase in efficiency-related construction costs, this package reduces the consumption of the reference home by nearly one-sixth.

Figure 18: Single-Family Base Code GSHP Packages (DCGW.B)

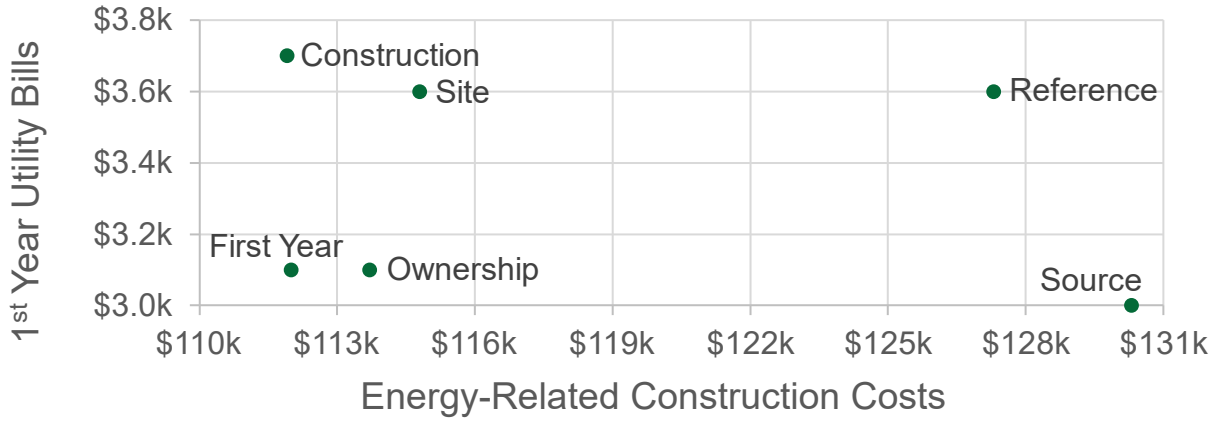


Table 11: Single-Family Base Code GSHP Package Details (DCGW.B)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference*	*47.6*	*0.0%*	*$127.3k*	*$3.6k*	*$45.4k*	*$5.2k*	*DCGW.BR*
	Construction	41.6	7.4%	$111.9k	$3.7k	$41.7k	$4.6k	DCGW.B0
	First Year	39.7	12.0%	$112.0k	$3.1k	$41.1k	$4.0k	DCGW.B1
	Ownership	39.2	13.6%	$113.7k	$3.1k	$41.5k	$4.0k	DCGW.B2
	Site	40.2	9.0%	$114.8k	$3.6k	$42.3k	$4.6k	DCGW.B3
	Source	38.6	15.7%	$130.3k	$3.0k	$45.5k	$4.3k	DCGW.B4

3.3.4 SF MSHP

As shown in Figure 19 and detailed in Table 12, four unique combinations of measure options were found to satisfy the optimization criteria of this study. All optimized packages downgraded the level of ceiling insulation (R-49 vs. the R-60 of the reference home). The distinguishing feature of the ownership/source savings package (✿) relative to other optimized packages was that it favored conventional 16-inch spaced walls over 24-inch spacing. Distinguishing features of the other optimized packages were additional continuous wall insulation (R-15 vs. R-5) and/or electric DHW equipment.

Figure 19: Single-Family Base Code MSHP Packages (DCMW.B)

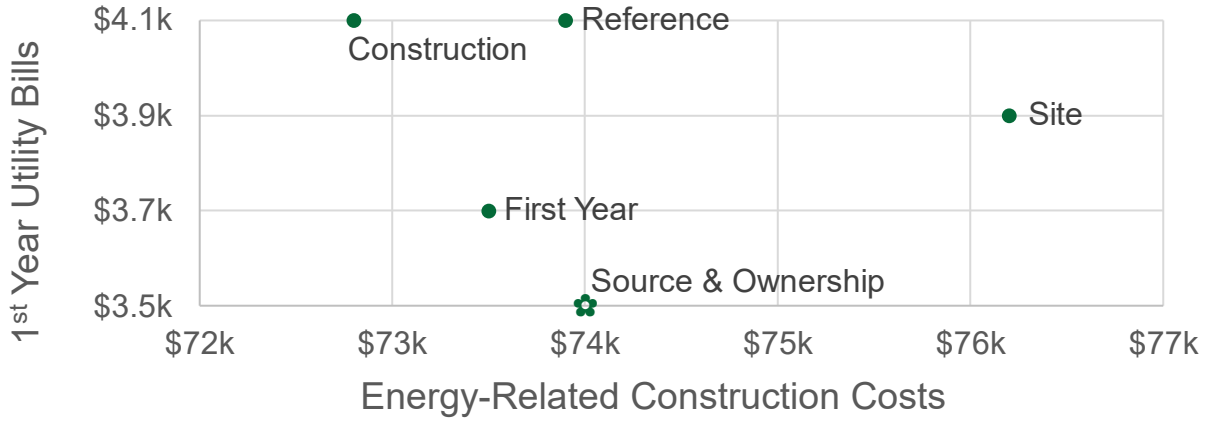


Table 12: Single-Family Base Code MSHP Package Details (DCMW.B)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference*	*54.1*	*0.0%*	*$73.9k*	*$4.1k*	*$32.8k*	*$5.2k*	*DCMW.BR*
	Construction	50.0	9.1%	$72.8k	$4.1k	$32.5k	$5.2k	DCMW.B0
	First Year	49.7	10.1%	$73.5k	$3.7k	$32.3k	$4.8k	DCMW.B1
	Ownership✿	48.0	13.5%	$74.0k	$3.5k	$32.2k	$4.7k	DCMW.B2
	Site	48.2	12.6%	$76.2k	$3.9k	$33.2k	$5.1k	DCMW.B3
	Source✿	48.0	13.5%	$74.0k	$3.5k	$32.2k	$4.7k	DCMW.B4

✿✦Packages with identical symbols include the same combination of measure options.

3.3.5 MF Furnace/CAC

Each of the optimized packages in Figure 20 include a 75% efficient recovery ventilation system. The ownership cost, site savings, and source savings packages upgrade the additional continuous wall insulation (R-15 vs. the R-5 of the reference home and remaining optimized packages). The incremental savings achievable with the site savings package compared to the ownership cost package (seven percentage points) resulting from severely reduced air infiltration and electric DHW equipment likely may not justify the increased upfront costs (Table 13). However, the substantial incremental savings achievable with the source savings package (14 percentage points) likely do justify a minor (2%) increase in the annual ownership cost. It should be noted that the increased utility bills of the latter are a result of water heater fuel-switching, as it uses an electric resistance storage water heater rather than a gas storage model.

Figure 20: Multifamily Base Code Furnace/CAC Packages, Whole Building (D3MF.B)

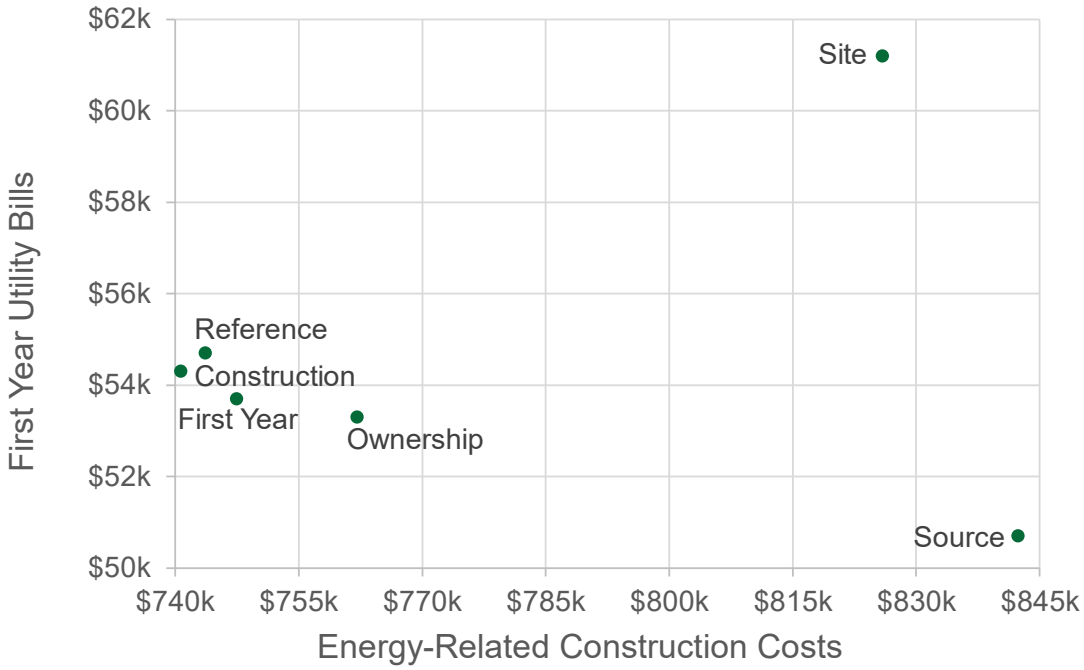


Table 13: MF Base Code Furnace/CAC Package Details, per Building (D3FW.B)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
MF	*Reference†*	*63.0*	*0.0%*	*$743.7k*	*$54.7k*	*$343.8k*	*$65.7k*	*D3FW.BR*
	Construction	62.8	1.1%	$740.7k	$54.3k	$342.8k	$65.3k	D3FW.B0
	First Year	61.5	3.0%	$747.5k	$53.7k	$343.9k	$64.8k	D3FW.B1
	Ownership	48.8	4.3%	$762.1k	$53.3k	$347.1k	$64.7k	D3FW.B2
	Site	52.8	10.4%	$825.9k	$61.2k	$370.6k	$75.4k	D3FW.B3
	Source	48.1	17.3%	$842.4k	$50.7k	$364.2k	$66.0k	D3FW.B4

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).

✿✦Packages with identical symbols include the same combination of measure options.

3.3.6 MF MSHP

As shown in Figure 21, unique combinations of measure options satisfied each of the five optimization criteria of this study, though with no clear trends in terms of associated cost metrics. Some packages tighten the building envelope to Passive House standards and include additional continuous wall insulation (ownership cost, site savings, source savings), while others feature electric water heaters (construction cost and site savings). Due to the electric water heater and lack of significant upgrades, the construction cost package (D3MW.B0) is the only base code package of any design which consumes more source energy than the reference home of the same design.[40] The water heater fuel switching in the construction cost package results in a 6.6% increase in source energy consumption relative to the reference package, but a 9.4% decrease in site energy consumption.

Figure 21: Multifamily Base Code MSHP Packages, per Building (D3MW.B)

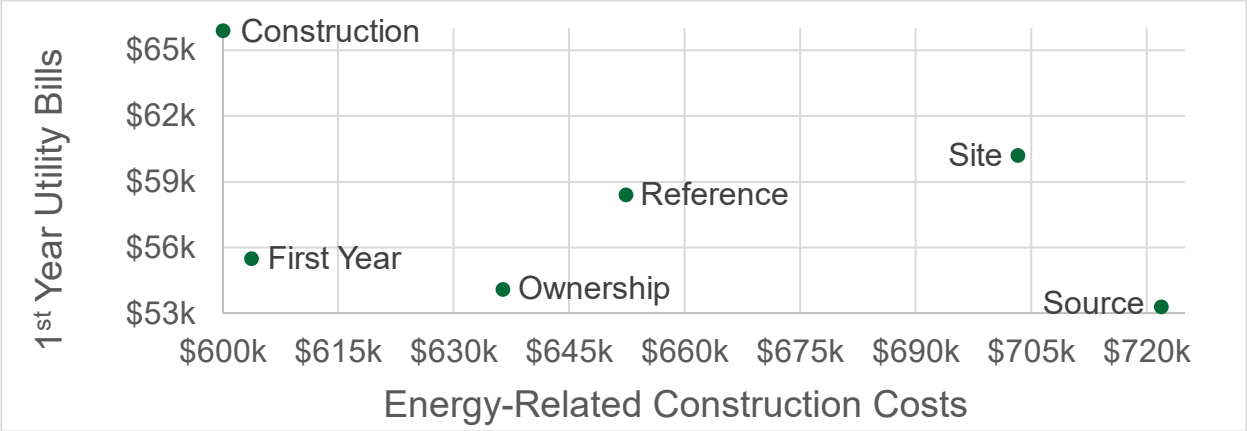


Table 14: MF Base Code MSHP Package Details, per Building (D3MW.B)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
MF	*Reference*	*59.7*	*0.0%*	*$652.4k*	*$58.4k*	*$325.1k*	*$69.1k*	*D3MW.BR*
	Construction	62.0	-0.8%	$599.9k	$65.9k	$319.7k	$72.9k	D3MW.B0
	First Year	57.0	5.4%	$603.7k	$55.5k	$310.2k	$62.6k	D3MW.B1
	Ownership‡	55.2	7.7%	$636.4k	$54.1k	$316.9k	$61.5k	D3MW.B2
	Site	48.9	8.6%	$703.3k	$60.2k	$338.0k	$69.5k	D3MW.B3
	Source	48.4	11.9%	$721.9k	$53.3k	$337.1k	$64.6k	D3MW.B4

‡ See Appendix B.2 for a higher performance alternative.

[40] It does include an R-3 to R-5 hot water pipe insulation upgrade, and 24-inch center upper-story walls. Other packages which include this water heater substitution offset the increase in source energy consumption with additional enhancements, particularly extra continuous wall insulation and/or high performance ERVs.

3.4 PACKAGE COMPARISON BY OPTIMIZATION

Optimized packages: savings compared to furnace reference home. To help readers evaluate the pros and cons of different HVAC technologies, the site and source energy savings shown in this section are *relative to the furnace/CAC reference package,* since this was the most common HVAC type in several recent studies of new homes. In each subsection, we present packages with different HVAC systems which have been optimized for the same metric, e.g., initial construction cost, all of which are compared to the reference home with a furnace and central air conditioning system. As a reminder, savings comparisons in the previous section (Package Comparison by HVAC), were presented relative to a reference home of the same HVAC system type.

Note to Readers:
Reference packages in this section all have furnace/CAC systems.

Table 15 provides a summary of the packages which perform best against the reference furnace/CAC home when optimizing different variables – the packages are ranked by their relative performance on that metric. However, in some cases the rankings are quite tight. For example, the incremental first year cost of the single-family MSHP package (DCMW.B1) is only $500 for more than double the source energy savings.

Table 15: Best Performing Base Code Packages by Optimization Type

	Rank	Source Energy Savings	Site Energy Savings	Efficiency Construction Cost	First Year Cost	Annual Ownership Cost
SF	First	GSHP	GSHP	MSHP	MSHP	GSHP
	Second	MSHP	MSHP	Furnace/CAC	Furnace/CAC	Furnace/CAC
	Third	ASHP	ASHP	ASHP	ASHP	MSHP
	Fourth	Furnace/CAC	Furnace/CAC	GSHP	GSHP	ASHP
MF	First	MSHP	MSHP	MSHP	MSHP	MSHP
	Second	Furnace/CAC	Furnace/CAC	Furnace/CAC	Furnace/CAC	Furnace/CAC

In the subsections that follow, the report provides details about each of the optimized packages, including ERI, source savings, construction cost, and so forth. *Highlighted columns identify the optimization metric being discussed in that section.*

3.4.1 Construction Cost

Construction cost packages minimize the upfront investment in energy-related measures (insulation, HVAC equipment, etc.), and may be of interest to some builders.

Optimized single-family and multifamily MSHP packages have lower construction costs than other HVAC system types (Figure 22). However, they also have higher first-year utility costs and annual ownership costs than both the reference and optimized furnace/CAC packages.

Figure 22 : Base Code Construction Cost Packages, per Unit

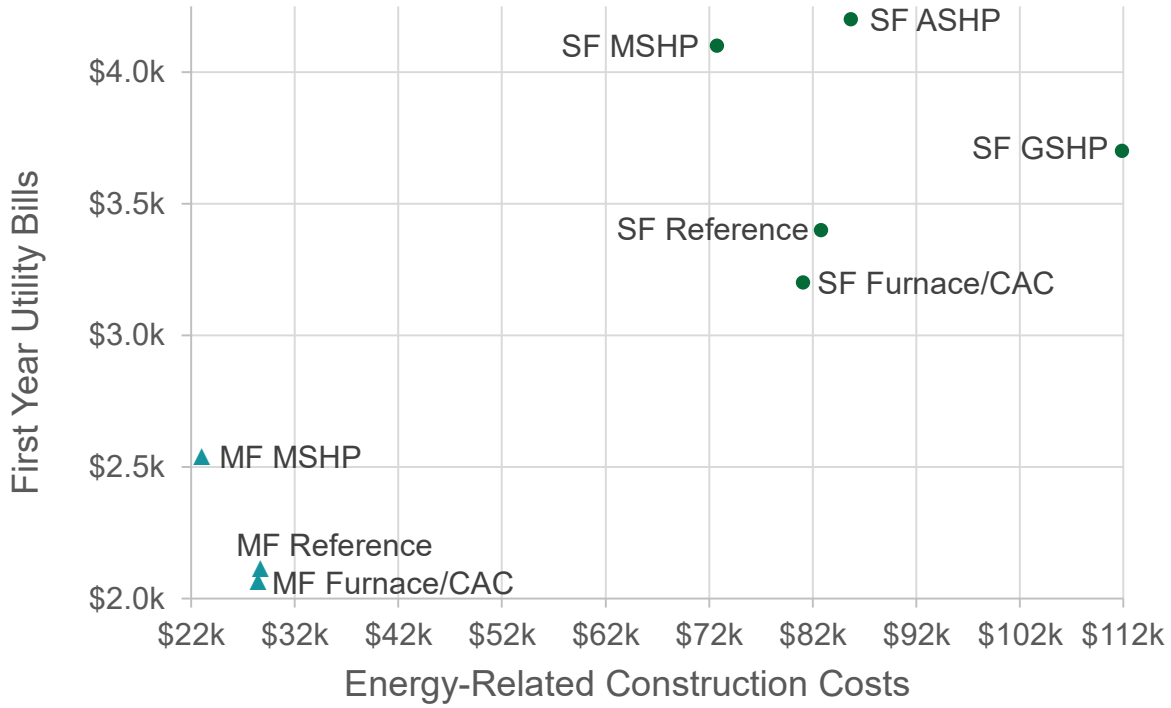


Table 16: Base Code Construction Cost Package Details, per Building

	Design	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*58.7*	*0.0%*	*$81.7k*	*$3.4k*	*$34.0k*	*$4.5k*	*DCFW.BR*
SF	Furnace/CAC	50.4	10.0%	$81.1k	$3.2k	$33.6k	$4.4k	DCFW.B0
SF	ASHP	50.7	14.9%	$85.7k	$4.1k	$35.8k	$5.4k	DCAW.B0
SF	GSHP	41.6	31.1%	$111.9k	$3.7k	$41.7k	$4.6k	DCGW.B0
SF	MSHP	50.0	23.7%	$72.8k	$4.1k	$32.5k	$5.2k	DCMW.B0
MF	*Ref.† Furnace*	*63.0*	*0.0%*	*$743.7k*	*$54.7k*	*$343.8k*	*$65.7k*	*D3FW.BR*
MF	Furnace/CAC	62.8	1.1%	$740.7k	$54.3k	$342.8k	$65.3k	D3FW.B0
MF	MSHP	62.0	6.3%	$599.9k	$65.9k	$319.7k	$72.9k	D3MW.B0

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).

SF Construction Cost

All four construction cost optimized designs offer at least 10% source energy savings compared to the reference furnace/CAC. The MSHP package resulted in the lowest initial construction cost of any HVAC type – substantially lower than even the furnace/CAC reference home – but is among the costliest to operate; second only to the related technology of ASHP (Table 16).

The optimized furnace/CAC and GSHP packages both significantly reduce infiltration (0.85 ACH50 i.e., Passive House levels) and include 85% efficient ERVs. The optimized furnace/CAC package offers slightly reduced construction costs and utility bill than the reference version (1% lower construction cost and 5% lower utility bills) for 10% source energy savings, whereas the hefty 31% reduction in energy consumption of the GSHP is paired with a heftier 37% construction cost increase. Nevertheless, the GSHP home offers the second-lowest ownership cost among construction-cost optimized single-family homes—second only to the optimized furnace/CAC package.

The optimized ASHP package does not pan out economically compared to the reference furnace/CAC package by any metric.

MF Construction Cost

Unlike every other base code package in this study, the construction cost base code multifamily mini-split package (D3MW.B0) has *increased* source energy consumption compared to a reference home of the same design (i.e., also with a MSHP system), though it does save energy compared to the furnace/CAC reference. This is discussed in greater detail in the next section (3.3.6).

The two optimized packages differ in their choice of ceiling insulation (continuous vs. not) and storage water heater (electric vs. gas). The MSHP package offers a lower initial construction cost but the electric water heaters in that package contribute to higher first-year utilities (20%) and annual ownership costs (11%).

3.4.2 First Year Cost

These packages minimize initial costs to the buyer, including a 20% down payment, first year mortgage payments, first year mortgage interest tax deduction, and first year utility bills.

First year cost and construction cost packages are frequently similar. They tend to differ in only one or two design choices, such as the level of additional continuous wall insulation or type of water heater. Therefore, similar to 3.4.1 Construction Cost, both single- and multifamily MSHP packages performed best according to this metric (Table 17). The single-family package did, however, have higher first-year utility costs and annual ownership costs than the reference and optimized furnace/CAC packages. As shown in Figure 23, the multifamily package had a higher first-year utility cost than its reference and optimized furnace/CAC packages, but 10% lower annual ownership costs.

Figure 23: Base Code First Year Cost Packages, per Unit

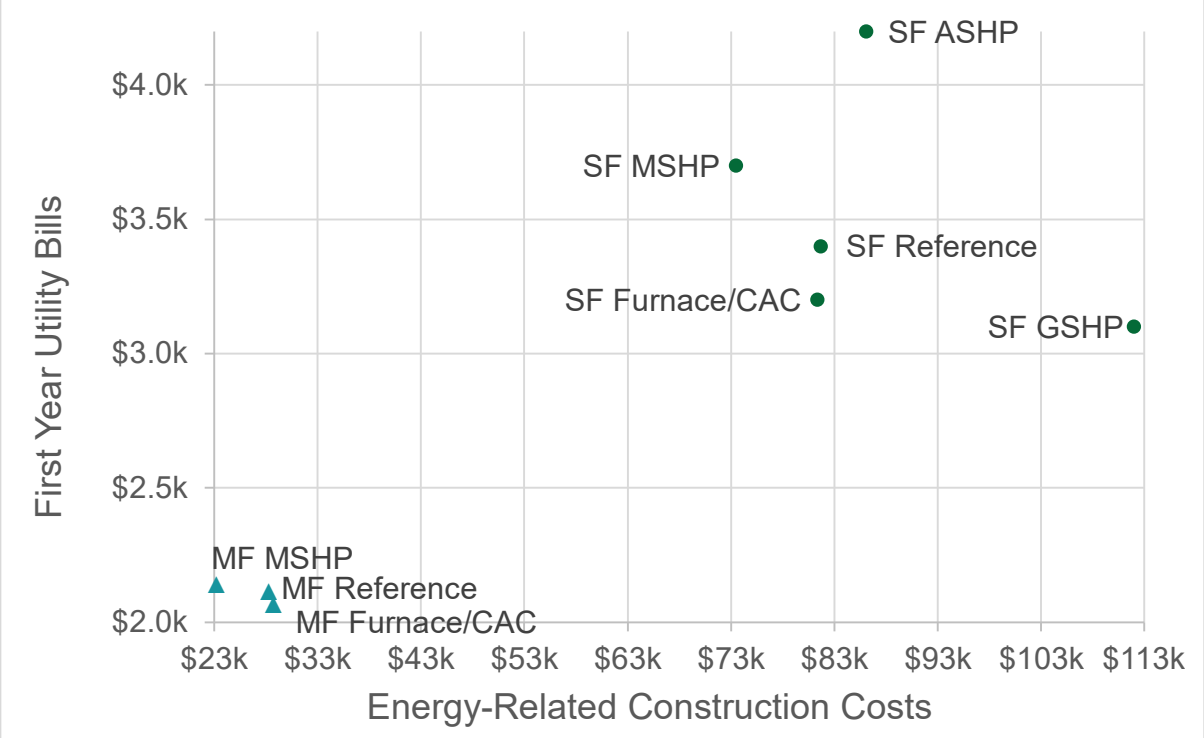


Table 17: Base Code First Year Cost Package Details, per Building

	Design	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*58.7*	*0.0%*	*$81.7k*	*$3.4k*	*$34.0k*	*$4.5k*	*DCFW.BR*
SF	Furnace/CAC	50.3	10.2%	$81.4k	$3.2k	$33.7k	$4.4k	DCFW.B1
SF	ASHP	55.1	13.1%	$86.1k	$4.2k	$35.8k	$5.4k	DCAW.B1
SF	GSHP	39.7	34.5%	$112.0k	$3.1k	$41.1k	$4.0k	DCGW.B1
SF	MSHP	49.7	24.5%	$73.5k	$3.7k	$32.3k	$4.8k	DCMW.B1
MF	*Ref.† Furnace*	*63.0*	*0.0%*	*$743.7k*	*$54.7k*	*$343.8k*	*$65.7k*	*D3FW.BR*
MF	Furnace/CAC	61.5	3.0%	$747.5k	$53.7k	$343.9k	$64.8k	D3FW.B1
MF	MSHP	57.0	12.1%	$603.7k	$55.5k	$310.2k	$62.6k	D3MW.B1

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).

SF First Year Cost

All four first-year cost optimized designs offer 10% or greater source energy savings compared to the reference furnace/CAC package. The MSHP package resulted in the lowest initial first-year cost of any HVAC type, but is among the costliest to operate, second only to the ASHP option (Table 17).

The optimized furnace/CAC and GSHP packages tighten the building envelope to Passive House standards (0.85 ACH50) and include an 85% efficient ERV. Both packages offer lower first year utility bills, 6-10% lower than the reference. However, the furnace/CAC home is marginally less expensive than the reference furnace/CAC package for 10% source energy savings, whereas the hefty 35% reduction in energy consumption of the GSHP is paired with a 21% first-year cost increase. Nevertheless, the GSHP home offers the lowest ownership cost among construction-cost optimized single-family homes.

The optimized ASHP package does not pan out economically compared to the reference furnace/CAC package by any metric.

MF First Year Cost

Both optimized multifamily packages yield source energy savings compared to the reference furnace/CAC building, but the MSHP building offers four times the savings of the furnace/CAC (12% vs. 3%). As with the single-family packages, the optimized MSHP package resulted in the lower first year cost and comparable utility costs, compared to the furnace/CAC package. The primary difference between these packages is the tightness of their building envelope, with the furnace/CAC building tightened to achieve 1.5 ACH50.

3.4.3 Ownership Cost

Ownership cost packages balance construction and replacement costs against long-term utility bill savings. These packages are ideal for buyers of single-family homes who plan to be long-term occupants, or owner-operators of apartment buildings where rent includes utilities. In addition, a list of the Global Minimum Ownership Cost packages which ignore the constraint of only just complying with code are available in Appendix B.2.

As shown in Figure 24, MSHP packages are the lowest construction cost option, but GSHP has the lowest ownership cost among single-family designs (Table 18) despite having the highest initial construction cost.

Figure 24: Base Code Ownership Cost Packages, per Unit

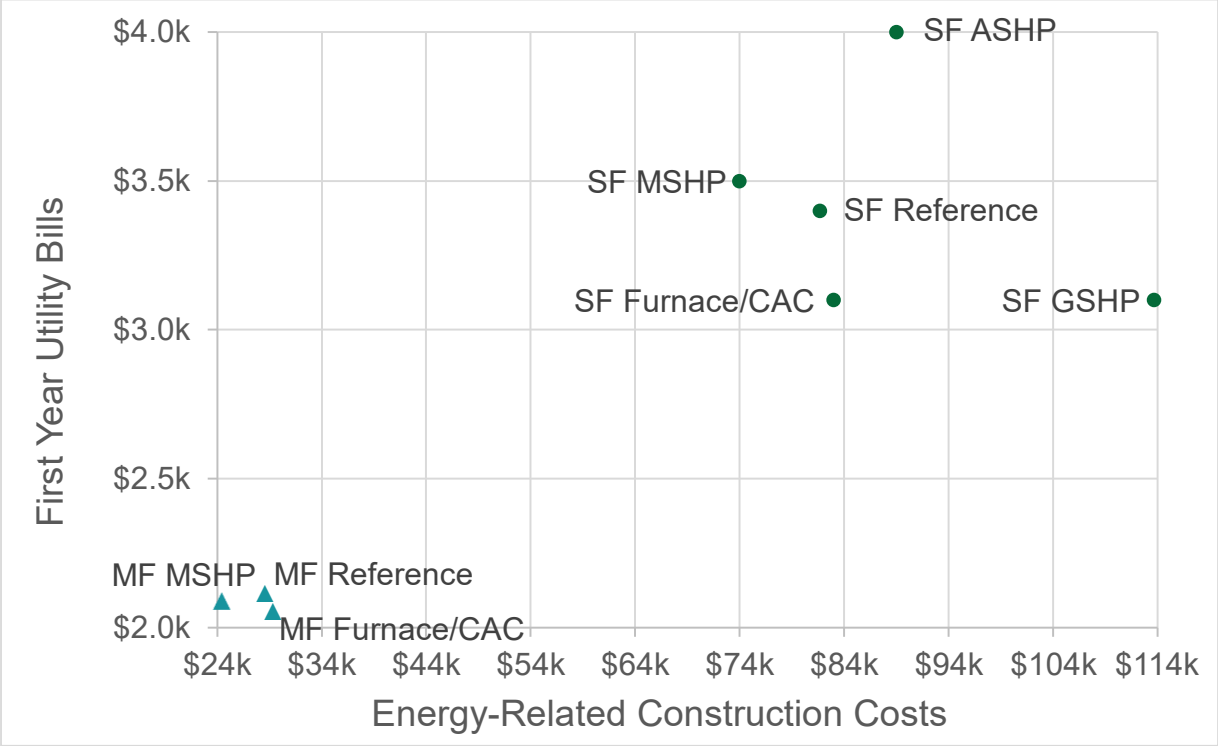


Table 18: Base Code Ownership Cost Package Details, per Building

	Design	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*58.7*	*0.0%*	*$81.7k*	*$3.4k*	*$34.0k*	*$4.5k*	*DCFW.BR*
SF	Furnace/CAC	48.4	14.1%	$83.0k	$3.1k	$34.0k	$4.4k	DCFW.B4
SF	ASHP	52.4	17.8%	$89.0k	$4.0k	$36.4k	$5.2k	DCAW.B4
SF	GSHP	39.2	35.7%	$113.7k	$3.1k	$41.5k	$4.0k	DCGW.B4
SF	MSHP	48.0	27.4%	$74.0k	$3.5k	$32.2k	$4.7k	DCMW.B4
MF	*Ref.† Furnace*	*63.0*	*0.0%*	*$743.7k*	*$54.7k*	*$343.8k*	*$65.7k*	*D3FW.BR*
MF	Furnace/CAC	60.6	4.3%	$762.1k	$53.3k	$347.1k	$64.7k	D3FW.B4
MF	MSHP‡	55.2	14.2%	$636.4k	$54.1k	$316.9k	$61.5k	D3MW.B4

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).
‡ See Appendix B.2 for a higher performance alternative.

SF Ownership Cost

All four single-family packages optimizing for ownership cost offer 14% or greater source energy savings compared to the reference furnace/CAC. Each package with ducted HVAC systems includes deeply buried ducts (R-25). All but one of these packages also include R-15 continuous wall insulation.

The optimized MSHP package offers the lowest initial construction and first year costs of any HVAC package, but higher utility and annual ownership costs than all but the uneconomical ASHP package. In contrast, the GSHP package resulted in the lowest annual ownership cost and double the source energy savings of any other single-family HVAC package, albeit with the highest initial and first year costs.

MF Ownership Cost

Both optimized multifamily packages reduce energy consumption compared to the reference furnace/CAC building, but the MSHP building offers three times the savings of the furnace/CAC (12% vs. 4%). The primary difference between the optimized furnace/CAC and MSHP packages is the tightness of their building envelopes, with the furnace/CAC building tightened to 1.5 ACH50 infiltration, compared to the Passive House standard of 0.43 ACH50 in the MSHP building.

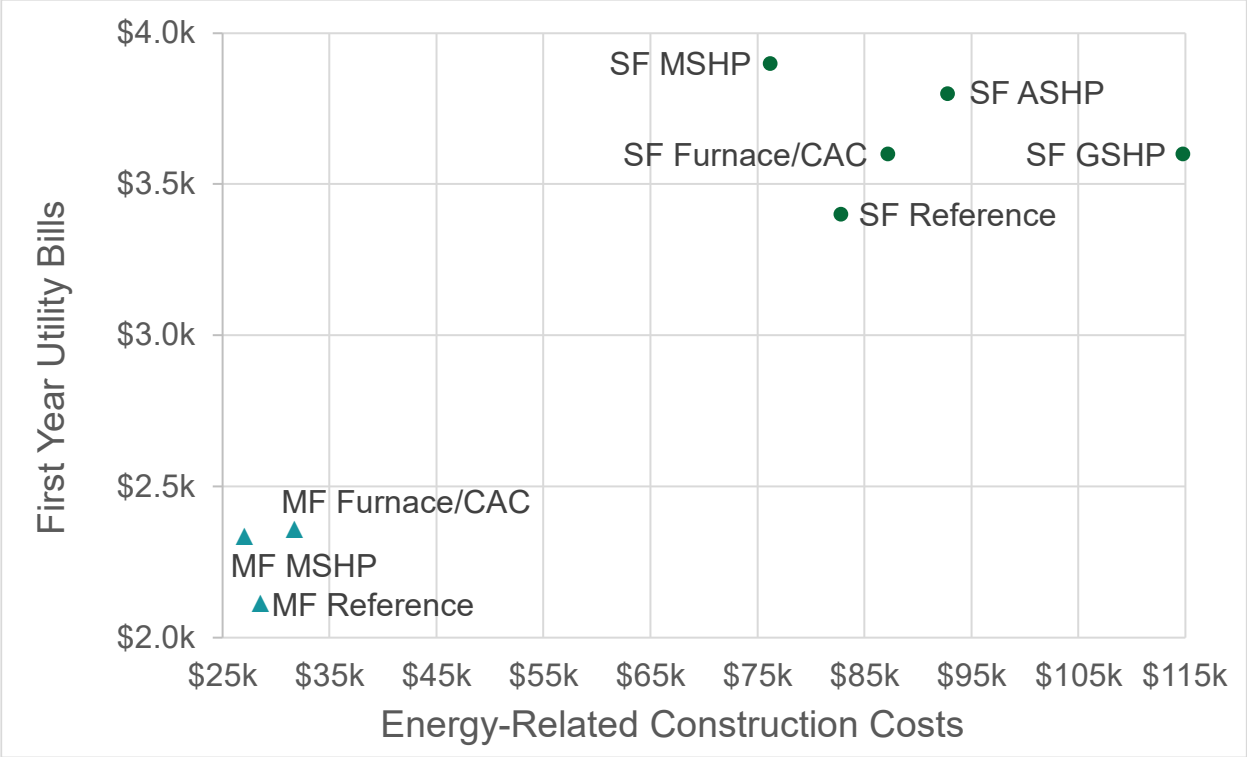
Due to the decreased construction cost of the multifamily mini-split ownership package compared to a furnace/CAC design (less equipment, no ducts), this package has a lower cost of ownership despite a marginally higher utility bill: $3 per month per apartment in the first year (Table 18).

The global minimum ownership cost MSHP package (D3MW.GO) in Appendix B.2 performs better than the package described above by introducing 75% efficient recovery ventilation.

3.4.4 Site Energy Savings

Site savings packages attempt to maximize the site energy savings within the menu of measure options explored in this study (0). They prioritize energy savings at the utility meter, regardless of upfront or operational costs, and would be of most interest to the eco-minded owner. However, as a side-effect of BEopt's modeling process, several options which can increase site savings are frequently excluded from the site savings package since they are typically not cost effective.[41] Consequently, the single-family ASHP and furnace/CAC packages optimized for site savings are identical to those optimized for source savings. Appendix B.3 discusses adjustments from the electrification of cooking and water heating which can be made to fully maximize site savings.

Figure 25: Base Code Site Energy Savings Packages, per Unit



[41] That is, the long-term ownership cost exceeds the utility bill savings.

Table 19: Base Code Site Energy Savings Package Details, per Building

	Design	ERI	Source Energy Savings	Site Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*58.7*	*0.0%*	*0.0%*	*$81.7k*	*$3.4k*	*$34.0k*	*$4.5k*	*DCFW.BR*
SF	Furnace/CAC	48.0	15.0%	28.0%	$87.2k	$3.6k	$35.5k	$4.9k	DCFW.B3
SF	ASHP	49.7	22.4%	43.7%	$91.7k	$3.8k	$36.9k	$5.3k	DCAW.B3
SF	GSHP	40.2	32.3%	56.9%	$114.8k	$3.6k	$42.3k	$4.6k	DCGW.B3
SF	MSHP	48.2	26.6%	53.4%	$76.2k	$3.9k	$33.2k	$5.1k	DCMW.B3
MF	*Ref.† Furnace*	*63.0*	*0.0%*	*0.0%*	*$743.7k*	*$54.7k*	*$343.8k*	*$65.7k*	*D3FW.BR*
MF	Furnace/CAC	52.8	10.4%	30.4%	$825.9k	$61.2k	$370.6k	$75.4k	D3FW.B3
MF	MSHP	48.9	15.1%	37.5%	$703.3k	$60.2k	$338.k	$69.5k	D3MW.B3

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).

SF Site Savings

All four packages offer 28% to 57% reductions in site energy consumption (15% to 32% source) compared to the furnace/CAC reference package. Every optimized package with a ducted HVAC system (ASHP, furnace/CAC, and GSHP) includes R-15 continuous wall insulation. The furnace/CAC and GSHP packages also tighten the building envelope to Passive House standards (0.85 ACH50) and feature an 85% efficient ERV. Consequently, the GSHP package offers the deepest site energy savings of any HVAC package (57%), albeit with the highest initial and first year costs. In contrast, among these different site savings packages, the MSHP offers the lowest initial construction and first year costs but the highest utility cost.

The optimized furnace/CAC package includes an electric water heater, alongside the other aforementioned improvements, to achieve a 28% reduction in site energy consumption and the lowest utility cost of any HVAC package—all with just a 12% increase in construction cost compared to the reference package.

MF Site Savings

Both multifamily packages reduce site consumption by 30% to 40% (10–15% source). The optimized MSHP package saves more source energy than the optimized furnace/CAC and is cheaper by all metrics. Compared to the reference furnace/CAC package, the MSHP package offers lower initial construction and first year costs, but higher utility and annual ownership costs.

There are two primary differences between the optimized furnace/CAC and MSHP packages: 1) the furnace/CAC package includes an ERV with 75% recovery efficiency, while the MSHP package includes one with 85% efficiency, and 2) the optimized MSHP package includes triple-pane windows in place of double-pane. Both packages feature Passive House (0.43 ACH50) infiltration levels, and R-38+24 roofs.

3.4.5 Source Energy Savings

Rather than maximizing utility meter savings (also known as site energy savings), source savings packages maximize savings for energy suppliers. Traditional generation of electricity from non-renewable resources is typically less efficient than burning the same fuel directly in the home, therefore this metric tends to favor combustion appliances more than site savings does. However, the distinction between site and source savings diminishes as the grid becomes more efficient and the electricity supply switches to low-carbon alternatives.

The base code single-family furnace/CAC and ASHP source savings packages are the same as those for site savings discussed in the previous subsection (3.4.4).

Figure 26 : Base Code Source Energy Savings Packages, per Unit

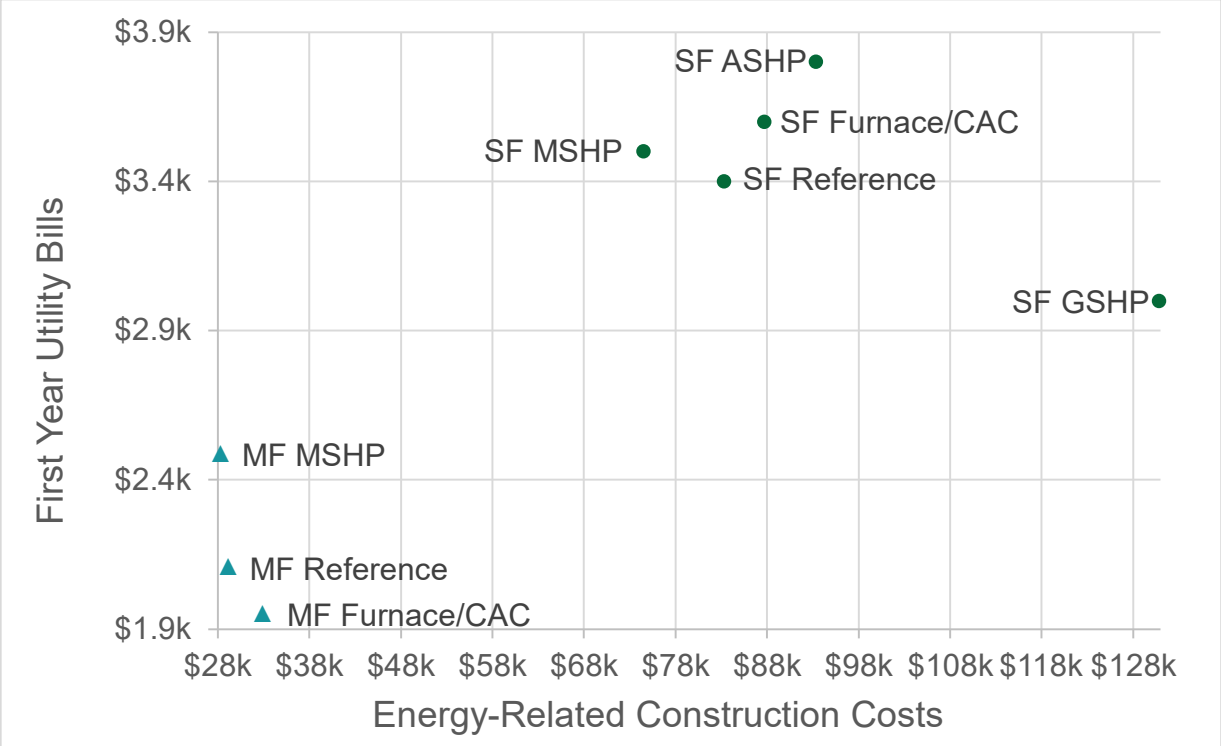


Table 20: Base Code Source Energy Savings Package Details, per Building

	Design	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*58.7*	*0.0%*	*$81.7k*	*$3.4k*	*$34.0k*	*$4.5k*	*DCFW.BR*
SF	Furnace/CAC	48.0	15.0%	$87.2k	$3.6k	$35.5k	$4.9k	DCFW.B4
SF	ASHP	49.7	22.4%	$91.7k	$3.8k	$36.9k	$5.3k	DCAW.B4
SF	GSHP	38.6	37.2%	$130.3k	$3.0k	$45.5k	$4.3k	DCGW.B4
SF	MSHP	48.0	27.4%	$74.0k	$3.5k	$32.2k	$4.7k	DCMW.B4
MF	*Ref.† Furnace*	*63.0*	*0.0%*	*$743.7k*	*$54.7k*	*$343.8k*	*$65.7k*	*D3FW.BR*
MF	Furnace/CAC	48.1	17.3%	$842.4k	$50.7k	$364.2k	$66.0k	D3FW.B4
MF	MSHP	48.4	18.1%	$721.9k	$53.3k	$337.1k	$64.6k	D3MW.B4

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).

SF Source Savings

Three differences between the source savings optimized GSHP package and the site savings package result in an additional five percentage points of source savings: 1) reverting from an electric storage water heater to the default gas storage system, 2) upgrading to a more efficient heat pump and 3) insulating the roof with spray foam rather than the ceiling with blown-in cellulose or fiberglass.

The source savings optimized MSHP package results in an additional 1% source savings compared to the site savings package. It reverts from an electric storage water heater to the default gas storage system.

MF Source Savings

The multifamily furnace/CAC source savings package increases source savings by 7% compared to the site savings package. This is achieved with two modifications: 1) including an electric storage water heater rather than a gas storage system and 2) upgrading from double-pane to triple-pane windows.

The multifamily mini-split source savings package increases source savings by 3% compared to the site savings package. This is achieved with two modifications: 1) using a tankless gas water heater in lieu of an electric storage water heater and 2) upgrading to a higher efficiency heat pump.

Section 4 Stretch Code Compliant Packages

The following section describes the reference and optimized packages that **minimally comply with the Massachusetts stretch code**.[42] Packages that comply with the base and specialized codes are described in Section 3 and Section 5 respectively. A broad overview comparing base and stretch code packages is available in the executive summary's Key Findings.

This section presents the following for minimally base code compliant packages:

- 4.1 Key Features of Optimized Homes
- 4.2 Reference Package Details
- 4.3 Package Comparison by HVAC
- 4.4 Package Comparison by Optimization

How to read this section. As with Section 3, please note that the package comparison subsections (4.3 and 4.4) cover the same material with different emphases. Therefore, readers interested in identifying an optimal construction package do not have to read both. *Readers who want to compare packages with the same basic HVAC type should focus on 4.3; readers who want to compare packages optimized for the same metric but with different HVAC types should focus on 4.4.*[43]

[42] See Appendix B.4 for guidance on bringing homes which are slightly out of compliance up to code.
[43] Specifically, section 4.3 calls out when a single package satisfies multiple optimization criteria or when the heating equipment is upgraded, while Table 28 in section 4.4 summarizes which design fairs best under different scenarios.

4.1 KEY FEATURES OF OPTIMIZED HOMES

By examining the measures commonly selected in packages optimized for compliance with stretch code, the study identified the following design choices that can result in greater energy and cost savings in new homes.

- **Use mechanical ventilation with higher recovery efficiency ratings.** While stretch-code only requires 65% sensible recovery efficiency, all optimized single-family packages and the energy savings optimized multifamily packages upgrade to 85% from the default of 75% recovery efficiency (A.4.1).
- **Improve building envelopes to Passive House standards.** All but one stretch-code optimized package reduced air leakage to the relevant Passive House standard (0.85 ACH50 for SF, 0.43 for MF). The exception is the construction cost MSHP package (DCMW.S0), which incorporates an intermediate level of infiltration: 1.5 ACH50.
- **Take advantage of the energy savings from a thermal break.** Two thirds of optimized packages include R-15 continuous wall insulation, spanning every design and optimization type in this study.
- **Spray foam is not necessary to comply with stretch code.** Very few optimized packages include any spray foam, specifically multifamily site and source energy savings walls, and the roof of the single-family GSHP roof reference and source energy packages.
- **Standard double-pane windows (0.29 U-factor) are sufficient to comply with code.** The only instances of triple-pane (0.18 U-factor) windows are single-family and multifamily furnace/CAC or MSHP packages optimized for source energy savings.
- **MSHPs are the best technology for multifamily buildings, and for single-family packages focused on the shorter term** i.e., construction or first year cost. GSHPs are best for maximizing energy savings and reducing ownership cost. If a ground-source heat pump is not practical for a given site, MSHPs are typically the second-best option for these optimization types.
- **In furnace homes, choose tankless water heaters instead of storage tanks.** Every optimized furnace/CAC package includes a tankless water heater (0.95 UEF) instead of the default storage option (0.67 UEF). Optimized heat pump packages were more varied in selecting between storage, tankless, and electric resistance water heaters.

4.2 REFERENCE PACKAGE DETAILS

As a performance-based code, the stretch code does not provide a specific list of measure-level values that could be used to construct reference home designs for this study. Nevertheless, it is necessary to compare the optimized stretch code packages to something to gauge their relative performance.[44] Therefore, the study developed proxy reference packages for the stretch code

[44] The default output from BEopt compares stretch code packages to the same reference as base code homes, which overstates savings, incremental costs, etc.

models. The proxy reference package for each design (DCAW, DCFW, etc.) is the stretch code compliant combination (Figure 8) with the highest ERI (only just compliant), and the fewest changes from the base code reference package. A summary of the most substantive differences between these stretch code and base code reference packages are provided in Table 21.

Table 21: Comparison of *Base Code* and Stretch Code Reference Packages

	Design	UCB	Walls	Win.	Attic	ACH50	Ducts	Ventilation	DHW†
SF	*Base Code*	*R-30*	*R-21+05*	*0.29 U*	*R-60 ceil.*	*3.00*	*R-8*	*Exhaust only*	*0.67 UEF*
SF	Furnace/CAC‡	R-38	R-21+10	–	–	0.85	R-25	85% ERV	0.95 UEF
SF	ASHP	R-38	R-21+15	0.22 U	R-49 ceil.	0.85	R-25	85% ERV	–
SF	GSHP	–	R-21+05	–	R-60 roof	0.85	–	75% ERV	–
SF	MSHP	R-38	R-21+05	–	–	1.50	–	75% ERV	–
MF	*Base Code*	*R-30*	*R-21+05*	*0.29 U*	*R-49 roof*	*3.00*	*Cond.*	*Exhaust only*	*0.67 UEF*
MF	Furnace/CAC	R-38	R-21+15	–	–	0.43	–	75% ERV	0.95 UEF
MF	MSHP	R-38	R-21+15	–	–	0.43	–	85% ERV	0.95 UEF

† Measure-level values not mandated by stretch code but included in minimally compliant reference packages.
‡ Includes a 98.5 rather than 95 AFUE furnace. All furnace/CAC references include a 13,4 SEER2 (14 SEER) CAC.

4.3 Package Comparison by HVAC

Reference packages in this section are for homes of the same design, permitting the reader to easily assess the benefits of different types of optimization (2.1.1). Energy savings for the optimized packages are thus relative to a reference home with the same type of HVAC system. In the first subsection, for example, the reference and optimized packages are single-family colonial homes with ASHP HVAC systems.

Note to readers:
Reference packages in this section have the *same* type of HVAC system as each optimized package.

One package may satisfy multiple optimization types. Sometimes a single combination of measures is the best candidate for multiple optimization criteria e.g.; the construction and first year cost packages might be the same. This is especially common for the site and source energy savings package.[45] In such cases, the table which accompanies each figure will contain identical values, and symbols (✦ or ✿) are used to confirm that these packages are identical.

[45] Although fuel-switching of stoves and water heaters is permitted in the optimization modeling, it is rarely advantageous due to the relative costs of electricity and natural gas. Consequently, BEopt tests these options less often, and frequently there is no all-electric tested combination in the vicinity of the target performance level to select as a distinct site savings package. While these end uses typically only represent a few percent of a home's energy use, readers may consult B.3 for details on adjusting the results of packages in this report to further optimize the site energy savings through electrification of mixed-fuel packages.

4.3.1 SF ASHP

As shown in Figure 27, four unique combinations of measure options satisfied the optimization criteria of this study. Most measure options in optimized packages were shared with the reference furnace/CAC package, including infiltration level (0.85 ACH50), mechanical ventilation (85% recovery), windows (0.29 U), wall framing and cavity insulation (2×6×24 with R-21), and duct insulation (R-25 via burying in attic insulation). As a result, cost metrics for the optimized ASHP packages do not diverge much from the reference package in Table 22. However, the construction and first year cost packages consume about 2% more source energy than the reference home.

The primary difference between packages is the R-10 continuous wall insulation used in the reference furnace/CAC package and the optimized packages. The initial construction cost and site/source savings packages (✿) used less continuous wall insulation (R-5), while the first year and ownership cost packages added more (R-15). The optimized first year cost package also maintained the reference R-49 ceiling insulation, and reverted to a gas storage water heater, but switched to electric cooking. Finally, the site and source energy savings packages (✿) include a higher efficiency heat pump.

Figure 27: Single-Family Stretch Code ASHP Packages (DCAW.S)

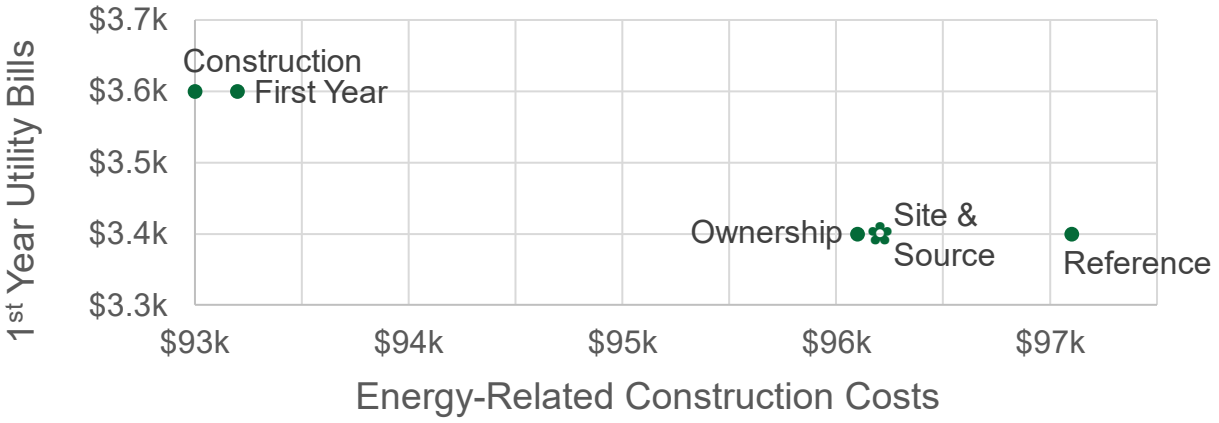


Table 22: Single-Family Stretch Code ASHP Package Details (DCAW.S)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference*	*42.1*	*0.0%*	*$97.1k*	*$3.4k*	*$37.8k*	*$5.1k*	*DCAW.SR*
	Construction	40.4	-2.5%	$93.0k	$3.6k	$36.9k	$5.1k	DCAW.S0
	First Year	41.9	-2.2%	$93.2k	$3.6k	$37.0k	$5.1k	DCAW.S1
	Ownership	38.4	2.6%	$96.1k	$3.4k	$37.5k	$5.0k	DCAW.S2
	Site✿	38.4	3.0%	$96.2k	$3.4k	$37.6k	$5.2k	DCAW.S3
	Source✿	38.4	3.0%	$96.2k	$3.4k	$37.6k	$5.2k	DCAW.S4

✿ Packages with identical symbols include the same combination of measure options.

4.3.2 SF Furnace/CAC

As shown in Figure 28, three unique combinations of measure options satisfied the optimization criteria of this study, however the construction/ownership (✦) and first year cost packages should be ignored in favor of the reference package. Those packages have similar construction and operation costs to the reference, but they use more energy and have a slimmer margin of error to achieve a compliant rating due to a shift from R-60 ceilings to R-49. All the optimized packages share most measure options (0.85 ACH50 air leakage, 85% ERV, etc.) in common with the reference package, but include additional continuous wall insulation (R-15 vs. R-10). In addition, the energy savings packages (✿) include a higher efficiency furnace and air conditioner, plus triple pane windows.

Figure 28: Single-family Stretch Code Furnace/CAC Packages (DCFW.S)

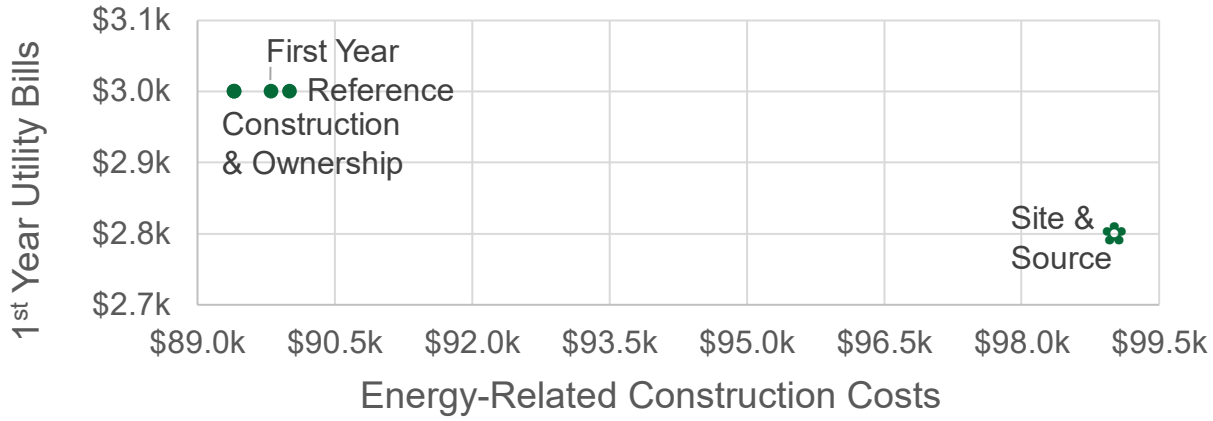


Table 23: Single-family Stretch Code Furnace/CAC Package Details (DCFW.S)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference†*	*41.4*	*0%*	*$90.0k*	*$3.0k*	*$35.6k*	*$4.4k*	*DCFW.SR*
	Construction✦	41.8	-0.6%	$89.4k	$3.0k	$35.4k	$4.4k	DCFW.S0
	First Year	41.7	-0.3%	$89.8k	$3.0k	$35.5k	$4.4k	DCFW.S1
	Ownership✦	41.8	-0.6%	$89.4k	$3.0k	$35.4k	$4.4k	DCFW.S2
	Site✿	38.6	7.9%	$99.0k	$2.8k	$37.6k	$4.6k	DCFW.S3
	Source✿	38.6	7.9%	$99.0k	$2.8k	$37.6k	$4.6k	DCFW.S4

† Package most like prescriptive base code that still complies with stretch/specialized code (4.2).

✿✦Packages with identical symbols include the same combination of measure options.

4.3.3 SF GSHP

Most measure options of the five unique optimized packages in Figure 29 are shared with the reference package including infiltration level (0.85 ACH50), windows (0.29 U), wall framing and cavity insulation (2×6×24 with R-21). All optimized packages include an 85% efficient ERV rather than the 75% recovery efficiency unit of the reference package.

The construction cost and site energy savings yield little to no savings compared to the reference package. However, the first year cost, ownership cost, and source energy savings packages reduce source energy consumption by 5% or more. These packages have comparable utility and annual ownership costs, but their construction costs increase alongside their source savings.

The primary differences between optimized packages are the attic, wall and duct insulation selections, and the choice of water heater. Construction, first year, and ownership cost packages downgraded from the reference R-60 roof insulation to R-49 ceiling insulation. The source savings package includes R-8 duct insulation levels in a sealed attic compared to R-25 of deeply buried ducts in unvented attics of other optimized packages. In addition, the construction cost and site savings packages include electric resistance rather than gas storage water heaters. Lastly, the source savings package also increases the heat pump efficiency.

Figure 29: Single-family Stretch Code GSHP Packages (DCGW.S)

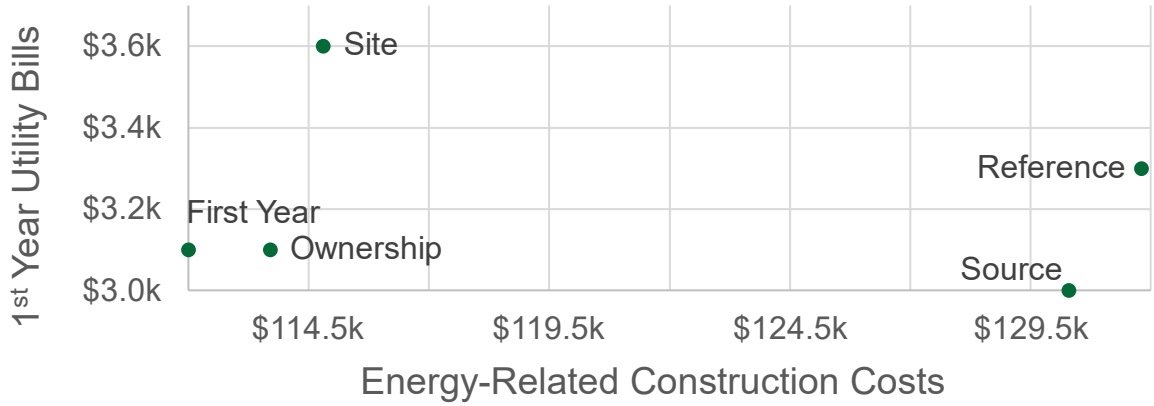


Table 24: Single-family Stretch Code GSHP Package Details (DCGW.S)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference*	*41.6*	*0.0%*	*$131.8k*	*$3.3k*	*$45.4k*	*$4.9k*	*DCGW.SR*
	Construction	41.6	-0.2%	$111.9k	$3.7k	$41.7k	$4.6k	DCGW.S0
	First Year	39.7	4.9%	$112.0k	$3.1k	$41.1k	$4.0k	DCGW.S1
	Ownership	39.2	6.6%	$113.7k	$3.1k	$41.5k	$4.0k	DCGW.S2
	Site	40.2	1.6%	$114.8k	$3.6k	$42.3k	$4.6k	DCGW.S3
	Source	38.6	8.8%	$130.3k	$3.0k	$45.5k	$4.3k	DCGW.S4

4.3.4 SF MSHP

As shown in Figure 30, unique combinations of measure options satisfied each of the five optimization criteria of this study. Relative to other HVAC systems, relatively few measure options in optimized packages are shared with the reference package: 24-inch on-center wall framing with R-21 cavity insulation, and R-49 ceiling insulation.

The primary difference between optimized packages was in the choice of continuous wall insulation and mechanical ventilation. All optimized packages share an 85% efficient ERV in common, in contrast to the 75% recovery efficiency unit of the reference package. The construction and first year cost packages included less (R-5) than the reference (R-10), while the ownership cost, site savings, and source savings packages all included more (R-15). The ducted HVAC packages also include reduced air infiltration (0.85 ACH50).

As shown in Table 25, the optimized packages did not always achieve deeper savings than the reference. In fact, only the ownership cost and source energy savings packages have positive energy savings. These are paired with higher initial construction costs—the source savings package is one of the few in this study to include triple-pane windows—but lower first-year utility and annual ownership costs.

While the construction cost packages trims $200 off the cost of efficiency measures, the resulting 1.4% reduction in energy savings ($49 in first year utilities) is a poor bargain compared to the first year cost package.

Figure 30: Single-family Stretch Code MSHP Packages (DCMW.S)

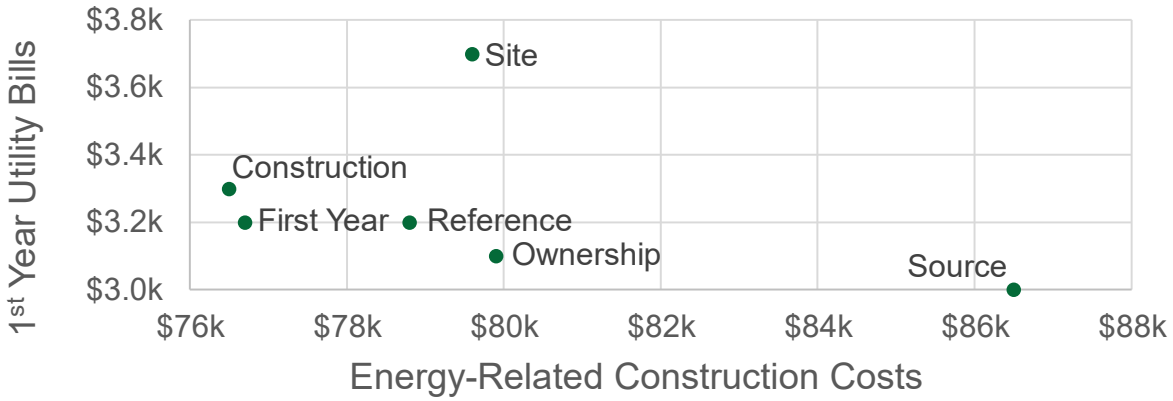


Table 25: Single-family Stretch Code MSHP Package Details (DCMW.S)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Reference*	*41.2*	*0.0%*	*$78.8k*	*$3.2k*	*$32.8k*	*$4.5k*	*DCMW.SR*
	Construction	41.9	-2.0%	$76.5k	$3.3k	$32.6k	$4.6k	DCMW.S0
	First Year	41.1	-0.6%	$76.7k	$3.2k	$32.5k	$4.5k	DCMW.S1
	Ownership	40.0	2.8%	$79.9k	$3.1k	$33.2k	$4.5k	DCMW.S2
	Site	41.9	-3.0%	$79.6k	$3.7k	$33.7k	$5.1k	DCMW.S3
	Source	39.1	5.5%	$86.5k	$3.0k	$34.8k	$4.7k	DCMW.S4

4.3.5 MF Furnace/CAC

Only three combinations of measure options (Figure 31) satisfied the five optimization criteria of this study, The reference/ownership cost (●) and construction cost/first-year cost (✦) are virtually identical except for the use of R-5 hot water pipe insulation in the former and R-3 in the latter.

The site and source energy savings packages (✿) reduce source consumption by nearly 6% accompanied by a 10% higher annual ownership cost. This is due to a 20% increase in construction cost for the following upgrades: R-36+10 spray foam walls (vs. R-21+15), 0.18 U triple-pane windows (versus 0.29 U), R-38+24 roof (vs. R-49), 17.2 SEER2/18 SEER air conditioners (vs. 13.4 SEER2/14 SEER), and 85% efficient ERVs (vs. 75%).

Figure 31: Multifamily Stretch Code Furnace/CAC Packages, per Building (D3FW.S)

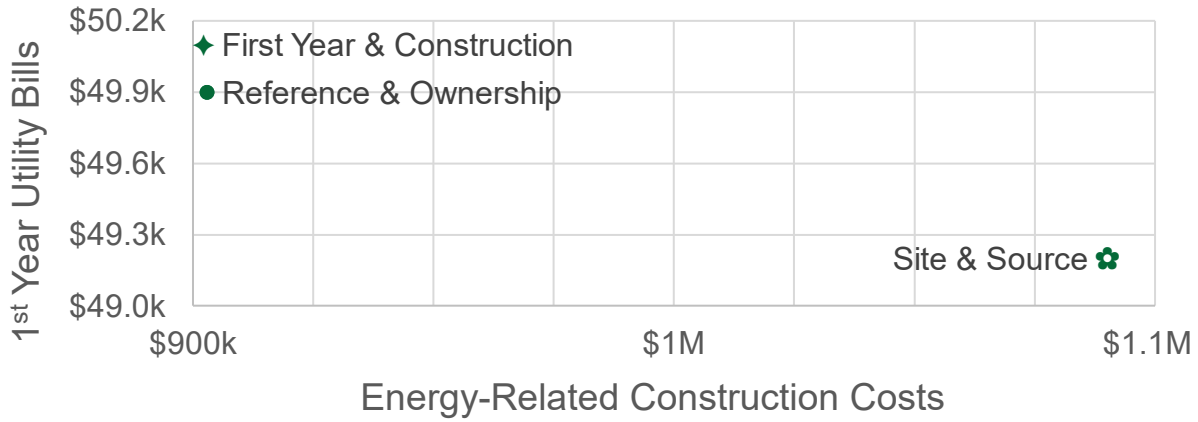


Table 26: MF Stretch Code Furnace/CAC Package Details, per Building (D3FW.S)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
MF	*Reference●*	*42.0*	*0.0%*	*$902.9k*	*$49.9k*	*$378.3k*	*$68.0k*	*D3FW.SR*
	Construction✦	42.0	-0.9%	$902.3k	$50.1k	$378.4k	$68.2k	D3FW.S0
	First Year✦	42.0	-0.9%	$902.3k	$50.1k	$378.4k	$68.2k	D3FW.S1
	Ownership●	42.0	0.0%	$902.9k	$49.9k	$378.3k	$68.0k	D3FW.S2
	Site✿	38.0	5.8%	$1.09M	$49.2k	$422.6k	$76.7k	D3FW.S3
	Source✿	38.0	5.8%	$1.09M	$49.2k	$422.6k	$76.7k	D3FW.S4

✿✦Packages with identical symbols include the same combination of measure options.

4.3.6 MF MSHP

Figure 32 shows the four combinations of measure options which satisfied the optimization criteria of this study, with the site and source energy savings packages being identical (✿). The construction cost, first-year cost, and ownership cost packages all improve on the reference package with 1–2% energy savings, and lower construction/ownership costs. The site and source energy savings packages (✿) achieving deeper (4%) energy savings at a proportionally higher construction cost (5%), while maintaining the lower annual ownership costs of the other optimized packages.

The tankless water heater, Passive House infiltration levels (0.43 ACH50), gas cooking and high efficiency MSHP reference package options are maintained across optimizations. The construction cost package is the only one in this study to omit continuous wall insulation entirely, while the first year cost package decreases it from R-15 to R-5. The first year cost package also downgrades the ERV to 75% efficiency. The site/source savings packages (✿) are among the few to upgrade to triple-pane (0.18 U) windows, and R-36 spray foam walls.

Figure 32: Multifamily Stretch Code MSHP Packages, per Building (D3MW.S)

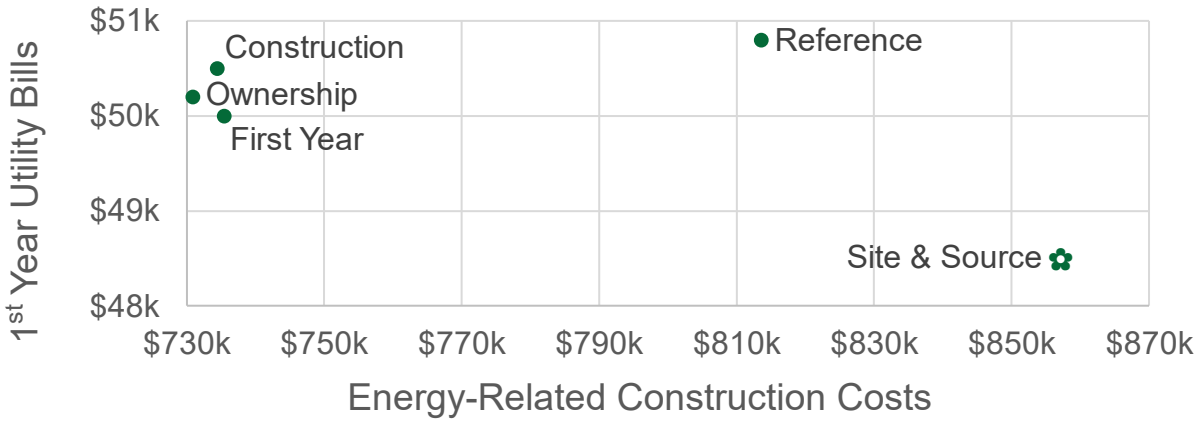


Table 27: MF Stretch Code MSHP Package Details, per Building (D3MW.S)

	Optimization	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
MF	*Reference*	*40.6*	*0.0%*	*$813.6k*	*$50.8k*	*$355.8k*	*$67.8k*	*D3MW.SR*
	Construction	39.9	0.5%	$734.4k	$50.5k	$336.0k	$63.0k	D3MW.S0
	First Year	39.5	1.5%	$735.4k	$50.0k	$335.7k	$61.9k	D3MW.S1
	Ownership	39.6	1.1%	$730.9k	$50.2k	$336.2k	$61.4k	D3MW.S2
	Site✿	38.5	4.4%	$857.2k	$48.5k	$364.2k	$63.1k	D3MW.S3
	Source✿	38.5	4.4%	$857.2k	$48.5k	$364.2k	$63.1k	D3MW.S4

✿ Packages with identical symbols include the same combination of measure options.

4.4 PACKAGE COMPARISON BY OPTIMIZATION

Optimized packages: savings compared to furnace reference home. To help readers evaluate the pros and cons of different HVAC technologies, the energy savings shown in this section are *relative to the furnace/CAC reference package,* since this was the most common HVAC type in several recent studies of new homes. In each subsection, we present packages with different HVAC systems optimized for the same metric e.g., initial construction cost, all of which are compared to the reference home with a furnace and central air conditioning system. As a reminder, savings comparisons in the previous section (4.3), are presented *relative to a reference home of the same HVAC system type*.

Note to readers:
Reference packages in this section all have furnace/CAC systems.

Table 28 provides a summary of the packages which perform best against the reference furnace/CAC home when optimizing different variables, although in some cases the rankings are quite tight. For example, the single-family MSHP annual ownership cost package's annual costs are only $90 more than the ASHP ownership cost package, even though the former saves 50% more site energy.

Table 28: Best Performing Stretch Code Packages by Optimization Type

	Rank	Source Energy Savings	Site Energy Savings	Efficiency Construction Cost	First Year Cost	Annual Ownership Cost
SF	First	GSHP	GSHP	MSHP	MSHP	GSHP
	Second	MSHP	MSHP	Furnace/CAC	Furnace/CAC	Furnace/CAC
	Third	ASHP	ASHP	ASHP	ASHP	MSHP
	Fourth	Furnace/CAC	Furnace/CAC	GSHP	GSHP	ASHP
MF	First	MSHP	MSHP	MSHP	MSHP	MSHP
	Second	Furnace/CAC	Furnace/CAC	Furnace/CAC	Furnace/CAC	Furnace/CAC

In the subsections that follow, the report provides details about each of the optimized packages, including ERI, source savings, construction cost, and so forth. *Highlighted columns identify the optimization metric being discussed in that section.*

4.4.1 Construction Cost

Construction cost packages minimize the investment in efficiency-related measures (insulation, HVAC equipment, etc.), and may be of interest to some builders.

Single-family and multifamily optimized MSHP packages have lower construction costs, than other HVAC system types (Figure 33). The multifamily MSHP package also has comparable first-year utility costs and lower annual ownership costs than both the reference and optimized furnace/CAC packages. However, the single-family MSHP package has slightly higher first-year utility costs ($300) and annual ownership costs ($200) than the furnace/CAC reference package, but these also result in more than double the source energy savings (24% versus 10%).

Figure 33: Stretch Code Construction Cost Packages, per Unit

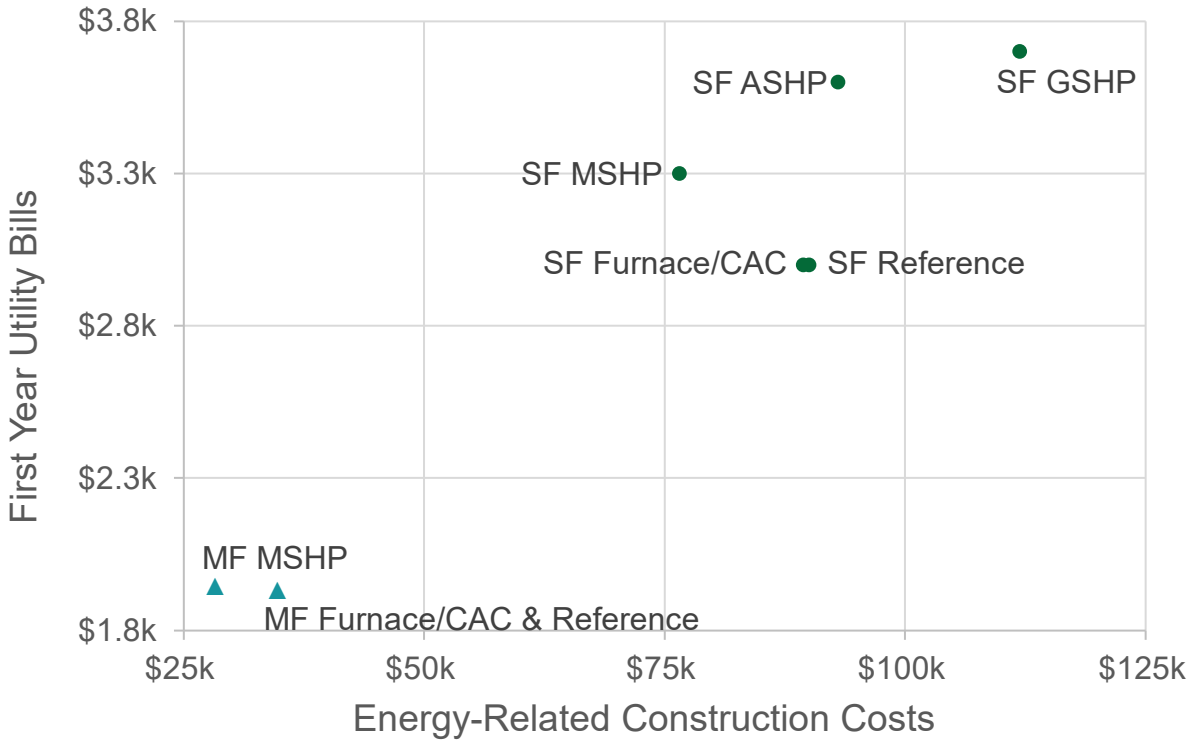


Table 29: Stretch Code Construction Cost Package Details, per Building

	HVAC	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*41.4*	*0.0%*	*$90.0k*	*$3.0k*	*$35.6k*	*$4.4k*	*DCFW.SR*
SF	Furnace/CAC	41.8	-0.6%	$89.4k	$3.0k	$35.4k	$4.4k	DCFW.S0
SF	ASHP	40.4	6.8%	$93.0k	$3.6k	$36.9k	$5.1k	DCAW.S0
SF	GSHP	41.6	12.0%	$111.9k	$3.7k	$41.7k	$4.6k	DCGW.S0
SF	MSHP	41.9	13.0%	$76.5k	$3.3k	$32.6k	$4.6k	DCMW.S0
MF	*Ref.† Furnace*	*42.0*	*0.0%*	*$902.9k*	*$49.9k*	*$378.3k*	*$68.0k*	*D3FW.SR*
MF	Furnace/CAC	42.0	-0.9%	$902.3k	$50.1k	$378.4k	$68.2k	D3FW.S0
MF	MSHP	39.9	3.3%	$734.4k	$50.5k	$336.0k	$63.0k	D3MW.S0

† Package most like prescriptive base code that still complies with stretch/specialized code (4.2).

SF Construction Cost

Only cost optimized heat pump designs offered source energy savings compared to the reference furnace/CAC. The GSHP and MSHP packages yield nearly double the source energy savings of the ASHP package, but the MSHP has a lower construction cost. Every economic metric of the optimized ASHP package is worse than the reference furnace/CAC package, it only surpasses the reference home in energy savings and ERI.

All cost optimized package feature reduced infiltration, with Passive House levels (0.85 ACH50) for all except MSHP, which is instead 1.5 ACH50. The MSHP and ASHP packages also include less continuous wall insulation than the GSHP and furnace/CAC homes (R-5 vs. R-15 and R-10 respectively). Similarly, the MSHP and GSHP packages feature storage water heaters compared to the tankless model of the other packages, as well as modest 75% efficiency recovery ventilation. With these adjustments (infiltration, continuous insulation, water heater, ERV), the MSHP home offers the lowest construction cost and deepest source energy savings, albeit with a 10% higher first-year utility cost and 5% higher annual ownership cost than the furnace/CAC reference home.

MF Construction Cost

Besides the lack of ducts needed in the multifamily MSHP home, which greatly reduces construction costs, the other differences between the furnace/CAC and mini-split packages are the level of continuous wall insulation and the recovery efficiency of the ERV. A stretch code construction cost optimized multifamily mini-split building is the only package in this study without continuous wall insulation. On the other hand, it does include a higher efficiency (85%) ERV. With these changes, the MSHP package offers a substantial 19% lower construction cost and 7% lower annual ownership costs for a marginal increase (1%) in first-year utility costs.

4.4.2 First Year Cost

These packages minimize initial costs to the buyer including a 20% down payment, first year mortgage payments, first year mortgage interest tax deduction, and first year utility bills.

First year cost and construction cost packages are frequently similar. They typically differ in a single design choice, such as level of infiltration or continuous wall insulation. Therefore, similar to 4.4.1 Construction Cost, both single- and multifamily MSHP packages performed best according to this metric (Table 30). The single-family package did, however, have higher first-year utility costs and annual ownership costs than the reference and optimized furnace/CAC packages. As shown in Figure 34, the multifamily package had first-year utility costs comparable to its reference and optimized furnace/CAC packages', but 10% lower annual ownership costs.

Figure 34: Stretch Code First Year Cost Packages, per Unit

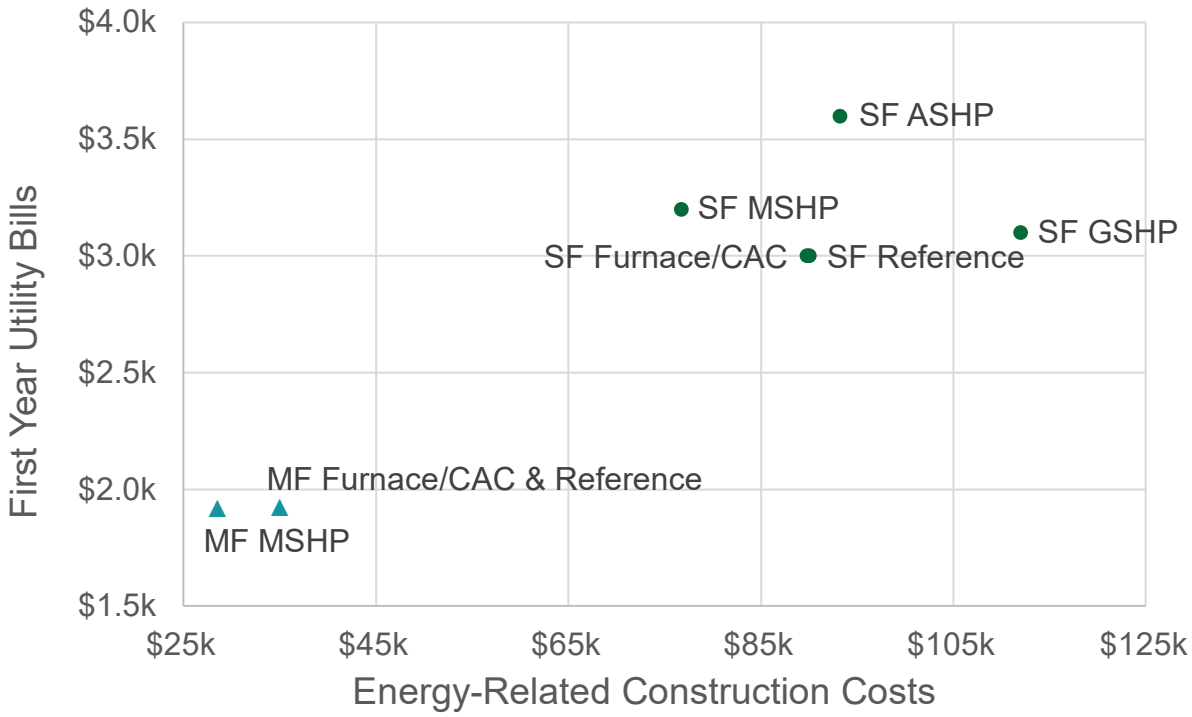


Table 30: Stretch Code First Year Cost Package Details, per Building

	Design	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*41.4*	*0.0%*	*$90.0k*	*$3.0k*	*$35.6k*	*$4.4k*	*DCFW.SR*
SF	Furnace/CAC	41.7	-0.3%	$89.8k	$3.0k	$35.5k	$4.4k	DCFW.S1
SF	ASHP	41.9	7.0%	$93.2k	$3.6k	$37.0k	$5.1k	DCAW.S1
SF	GSHP	39.7	16.4%	$112.0k	$3.1k	$41.1k	$4.0k	DCGW.S1
SF	MSHP	41.1	14.2%	$76.7k	$3.2k	$32.5k	$4.5k	DCMW.S1
MF	*Ref.† Furnace*	*42.0*	*0.0%*	*$902.9k*	*$49.9k*	*$378.3k*	*$68.0k*	*D3FW.SR*
MF	Furnace/CAC	42.0	-0.9%	$902.3k	$50.1k	$378.4k	$68.2k	D3FW.S1
MF	MSHP	39.5	4.2%	$735.4k	$50.k	$335.7k	$61.9k	D3MW.S1

† Package most like prescriptive base code that still complies with stretch/specialized code (4.2).

SF First Year Cost

Only heat pump packages offered energy savings compared to the reference furnace/CAC, with the ASHP offering only half the savings of the others. In fact, energy savings are the only metric this package performs better than the furnace/CAC packages. On the other hand, the MSHP package has the lowest construction cost of any HVAC type, and it is substantially lower than even the reference furnace/CAC package, but costlier to operate than the reference and optimized furnace/CAC homes. The source energy savings of the MSHP package are second only to the GSHP home, which offers the lowest ownership cost among first-year cost optimized single-family homes. However, the extra 1.8% reduction comes with a hefty 46% increase in construction cost, which translates to 26% more in first-year costs.

All cost optimized packages feature significantly reduced infiltration (0.85 ACH50 i.e., Passive House levels), complemented by an 85% efficient ERV. However, they also include R-49 ceilings compared to the R-60 of prescriptive base code or the furnace/CAC reference. The MSHP package only includes R-5 continuous wall insulation, compared to R-10 or R-15 in the other packages.

MF First Year Cost

The first year cost and construction cost packages are identical to each other for both the furnace/CAC and MSHP buildings. See the previous section (MF Construction Cost) for more details.

4.4.3 Ownership Cost

Ownership cost packages balance construction and replacement costs against long-term utility bill reductions. These packages are ideal for buyers of single-family homes who plan to be long-term occupants, or owner-operators of apartment buildings where rent includes utilities. See section 2.1.1 for additional details. In addition, a list of the Global Minimum Ownership Cost packages that ignore the constraint of only just complying with code are available in Appendix B.2.

As shown in Figure 35, MSHP packages are the lowest construction cost option, but

Table 31 reveals that GSHP has the lowest ownership cost among single-family designs despite having the highest initial construction cost.

Figure 35: Stretch Code Ownership Cost Packages, per Unit

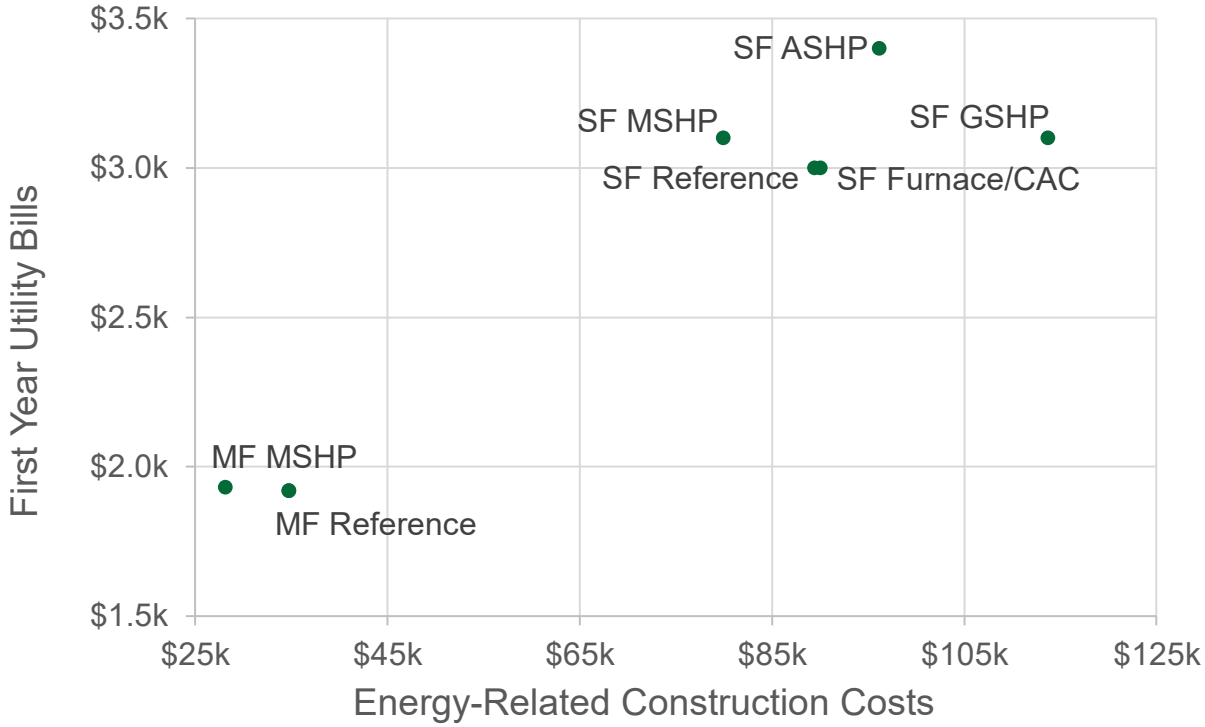


Table 31: Stretch Code Ownership Cost Package Details, per Building

	Design	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*41.4*	*0.0%*	*$90.0k*	*$3.0k*	*$35.6k*	*$4.4k*	*DCFW.SR*
	Furnace/CAC	41.8	-0.6%	$89.4k	$3.0k	$35.4k	$4.4k	DCFW.S2
	ASHP	38.4	11.4%	$96.1k	$3.4k	$37.5k	$5.0k	DCAW.S2
	GSHP	39.2	17.9%	$113.7k	$3.1k	$41.5k	$4.0k	DCGW.S2
	MSHP	40.0	17.0%	$79.9k	$3.1k	$33.2k	$4.5k	DCMW.S2
MF	*Ref.† Furnace*	*42.0*	*0.0%*	*$902.9k*	*$49.9k*	*$378.3k*	*$68.0k*	*D3FW.SR*
	Furnace/CAC	42.0	0.0%	$902.9k	$49.9k	$378.3k	$68.0k	D3FW.S2
	MSHP	39.6	3.8%	$730.9k	$50.2k	$336.2k	$61.4k	D3MW.S2

† Package most like prescriptive base code that still complies with stretch/specialized code (4.2).

SF Ownership Cost

The optimized furnace/CAC package consumes a similar amount of energy as the reference home. The source energy consumption reduction of the GSHP and MSHP packages are double that of the ASHP package, but the GSHP ownership cost is 10% lower than the MSHP. This is the lowest ownership cost of any HVAC type, including the reference furnace/CAC home, albeit with a 26% higher cost for efficiency-related measures.

Nevertheless, there are few differences among the optimized packages. They all include R-15 continuous wall insulation and 85% ERVs coupled with Passive House infiltration levels (.85 ACH50). The ASHP package is the only home to maintain the same R-60 attic insulation as the reference furnace/CAC home; other packages reduced this to R-49. The GSHP and MSHP packages were also downgraded to gas storage water heaters.

The optimized ASHP package does not pan out economically compared to the reference furnace/CAC package by any metric.

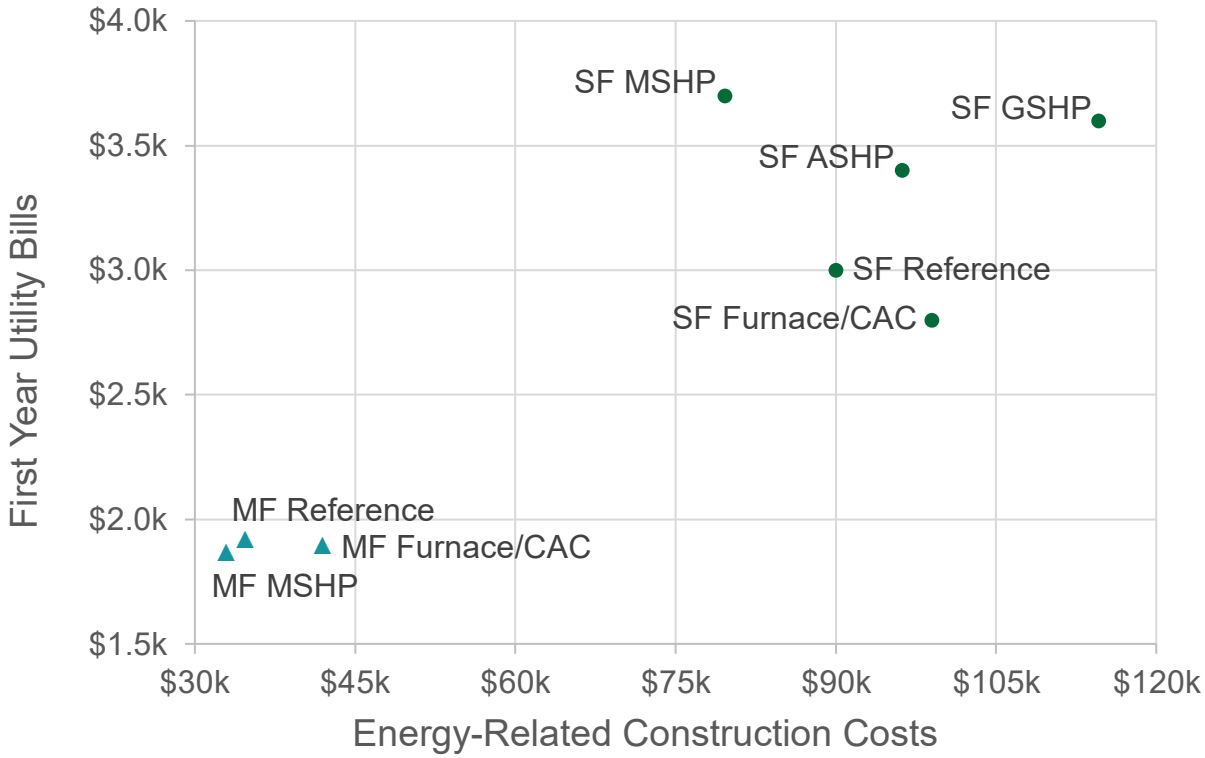
MF Ownership Cost

The optimized and reference furnace/CAC packages are identical, and the MSHP differs only in the ductless heating system. Due to the lack of ducts and higher efficiency, the MSHP package saves more energy, and is cheaper to construct and operate than the furnace/CAC home.

4.4.4 Site Energy Savings

Site savings packages attempt to maximize site energy savings within the menu of measure options explored in this study (0). They prioritize energy savings at the utility meter, regardless of upfront or operational costs, and would be of most interest to the environmentally-minded owner. However, as a side-effect of BEopt's modeling process, several options which can increase site savings are frequently excluded from the site savings package since they are typically not cost effective.[46] Consequently, only the single-family GSHP and multifamily MSHP packages differ from the closely related source savings packages. Appendix B.3 discusses adjustments from the electrification of cooking and water heating that can be made to fully maximize site savings.

Figure 36: Stretch Code Site Energy Savings Packages, per Unit



[46] That is, the long term ownership cost exceeds the utility bill savings.

Table 32: Stretch Code Site Energy Savings Package Details, per Building

	Design	ERI	Source Energy Savings	Site Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*41.4*	*0.0%*	*0.0%*	*$90.0k*	*$3.0k*	*$35.6k*	*$4.4k*	*DCFW.SR*
	Furnace/CAC	38.6	7.9%	8.8%	$99.0k	$2.8k	$37.6k	$4.6k	DCFW.S3
	ASHP	38.4	11.7%	32.9%	$96.2k	$3.4k	$37.6k	$5.2k	DCAW.S3
	GSHP	40.2	13.6%	41.3%	$114.8k	$3.6k	$42.3k	$4.6k	DCGW.S3
	MSHP	41.9	12.1%	40.3%	$79.6k	$3.7k	$33.7k	$5.1k	DCMW.S3
MF	*Ref.† Furnace*	*42.0*	*0.0%*	*0.0%*	*$902.9k*	*$49.9k*	*$378.3k*	*$68.0k*	*D3FW.SR*
	Furnace/CAC	38.0	5.8%	10.5%	$1,091k	$49.2k	$422.6k	$76.7k	D3FW.S3
	MSHP	38.5	7.0%	11.3%	$857.2k	$48.5k	$364.2k	$63.1k	D3MW.S3

† Package most like prescriptive base code that still complies with stretch/specialized code (4.2).

SF Site Energy Savings

The heat pump packages offer more than 30% reductions in site energy use (11–14% source) from the furnace/CAC reference, versus the 9% of the optimized furnace/CAC package. Although the GSHP saves the most site energy, the MSHP achieves 98% of its site energy savings at 60% of the cost.

The furnace/CAC package is one of the few in this study to feature triple-pane windows. Both the GSHP and MSHP packages opt for an electric water heater, and the latter also downgrades from the R-60 attic insulation of other packages to R-49. This change typically has less of an impact than the reduction in continuous wall insulation from R-15 shared by the furnace/CAC, GSHP and MSHP homes to the R-5 included in the ASHP.

MF Site Energy Savings

The multifamily packages reduce site energy consumption by 11% (6-7% source). The MSHP package performs better than the optimized and reference furnace/CAC packages on every metric except ERI, with a rating that is half a point higher than the optimized furnace/CAC.

Both optimized packages feature Passive House (0.43 ACH50) infiltration levels, triple-pane windows and R38+24 roofs. There are two main non-HVAC differences between the optimized multifamily packages: 1) The MSHP package has slightly less more wall insulation with R-15 rather than R-10 and 2) The furnace/CAC package includes an electric convection oven/induction stovetop instead of gas.

4.4.5 Source Energy Savings

Rather than maximizing utility meter savings (also known as site energy savings), source savings packages maximize savings for energy suppliers. Traditional generation of electricity from non-renewable resources is typically less efficient than burning the same fuel directly in the home, therefore this metric tends to favor combustion appliances more than site savings does. However, the distinction between site and source savings diminishes as the grid becomes more efficient and the electricity supply switches to low-carbon alternatives.

The stretch code source savings packages are the same as those for site savings discussed in the previous subsection (4.4.4), except for better performing single-family GSHP and MSHP packages.

Figure 37: Stretch Code Source Energy Savings Packages, per Unit

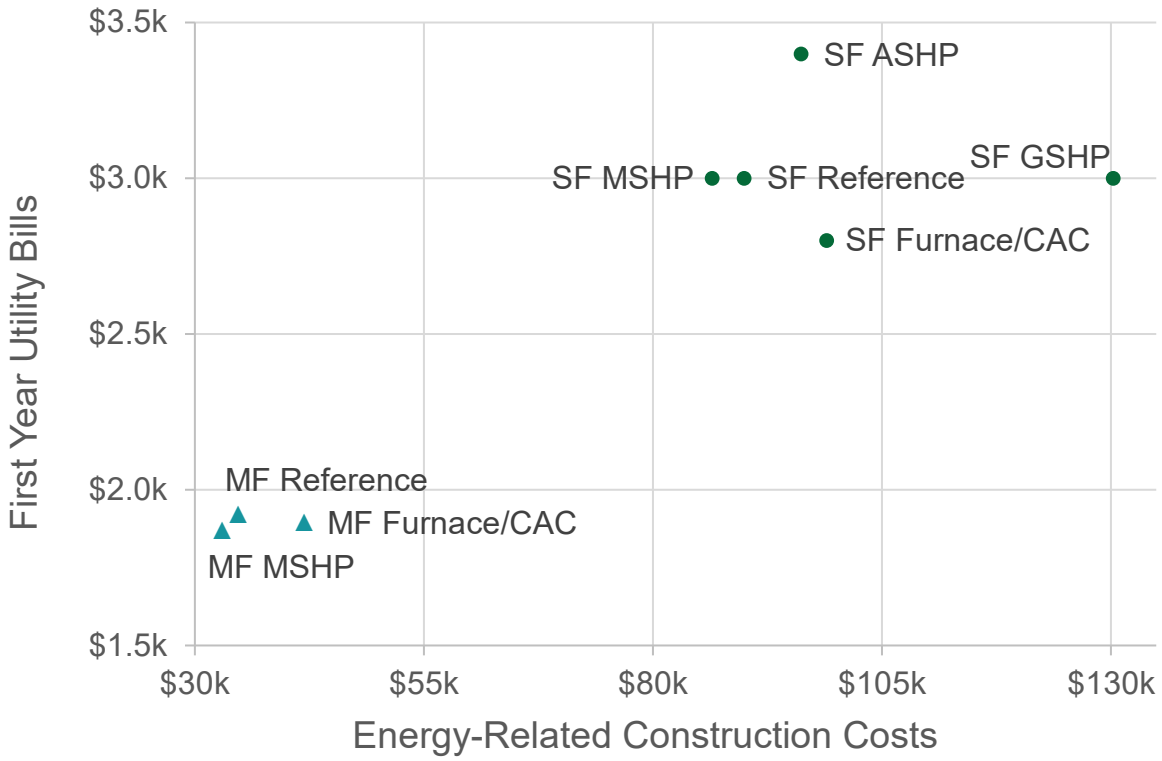


Table 33: Stretch Code Source Energy Savings Package Details, per Building

	Design	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*41.4*	*0.0%*	*$90.0k*	*$3.0k*	*$35.6k*	*$4.4k*	*DCFW.SR*
	Furnace/CAC	38.6	7.9%	$99.0k	$2.8k	$37.6k	$4.6k	DCFW.S4
	ASHP	38.4	11.7%	$96.2k	$3.4k	$37.6k	$5.2k	DCAW.S4
	GSHP	38.6	19.9%	$130.3k	$3.0k	$45.5k	$4.3k	DCGW.S4
	MSHP	39.1	19.4%	$86.5k	$3.0k	$34.8k	$4.7k	DCMW.S4
MF	*Ref.† Furnace*	*42.0*	*0.0%*	*$902.9k*	*$49.9k*	*$378.3k*	*$68.0k*	*D3FW.SR*
	Furnace/CAC	38.0	5.8%	$1091.3k	$49.2k	$422.6k	$76.7k	D3FW.S4
	MSHP	38.5	7.0%	$857.2k	$48.5k	$371.5k	$65.4k	D3MW.S4

† Package most like prescriptive base code that still complies with stretch/specialized code (4.2).

SF Source Savings

Three differences between the source energy savings optimized GSHP package and the site savings package result in an additional 5% source savings: 1) reverting from an electric storage water heater back to the default gas storage system, 2) upgrading to a higher efficiency heat pump and 3) insulating the roof with spray foam rather than the ceiling with blown-in fiber.

Two differences between the source energy savings optimized MSHP package and the site savings package result in an additional 7% source savings: 1) reverting from an electric storage water heater back to the default gas storage system and 2) installing triple-pane windows in place of the double-pane default.

MF Source Energy Savings

The site and source energy savings packages are identical to each other for both the furnace/CAC and MSHP buildings. See the previous section (MF Ownership Cost) for more details.

Section 5 Specialized Code Compliant Packages

Although the specialized code (also known as the "net-zero" code) includes many provisions that distinguish it from the stretch code, all the packages selected for the specialized code in thus study are identical to the corresponding stretch code package. This is primarily due to the exclusion of three specialized code requirements from our analysis:

1. Large multifamily buildings in specialized code communities are subject to Passive House requirements (RC101.2⇒R405). While our analysis accounts for air infiltration and heating and cooling use intensity requirements, it does not consider the energy per occupant due to differences in modeling assumptions between systems. This metric is also highly dependent on occupant behavior and the selection of appliances, both of which are outside the scope of this study.
2. Mixed-fuel homes in specialized code communities are required to install a minimum level of renewable energy generation capacity via solar panels, architectural and siting conditions permitting (RC104.4). However, to simplify the analysis for this phase of the study while complying with Massachusetts Department of Public Utilities guidance mandating the PAs to focus on energy-efficiency rather than solar PV, solar panels were not modeled.
3. To facilitate future fuel-switching, mixed-fuel homes are required to install the same wiring for any combustion-powered equipment (i.e., stoves, ovens, clothes dryers, water heaters, furnaces, or boilers) as if the equipment is all electric (RC104.3).

Note, an important consequence of item two above is that the actual construction and ownership costs of mixed fuel homes in specialized communities will differ from those provided for a stretch code home in Section 4. The initial cost will be higher and utility costs lower for mixed fuel homes in specialized code communities. The former from the addition of solar panels, and the latter due to reductions in electricity bills from offset consumption and net-metering of the same. Annual ownership costs may be higher or lower, depending on the cost and capacity of the installed solar panels. The second phase of this study will focus on cost-effective all-electric packages. For reference purposes, we anticipate being able to include some packages with solar panels for informational purposes.

Appendix A Model Inputs

A.1 Economic & Energy Distribution Parameters

Table 34: Modeled Parameters

Parameter	Value	Parameter	Value
Annual Inflation	2.80%[47]	Analysis Period (years)	30
Electricity Rate ($/kWh)	$0.236[48†]	Mortgage Period (years)	30
Electricity Rate Escalation	0.40%[48]	Mortgage Down Payment	20.00%
Gas Rate ($/therm)	$1.588[50†]	Marginal Income Tax, Fed	24.00%[49]
Gas Rate Escalation	0.00%[50]	Marginal Income Tax, MA	5.00%
Mortgage Interest Rate	6.2%[51]	Source: Site, Electricity	2.016[52]
Materials Multiplier	1.326[53†]	Source: Site, Natural Gas	1.050[54]
Labor Multiplier	1.547[55†]	CO_2 Emissions, Electricity (lb./kWh)	0.334[56]
Discount Rate (Real)	2.00%[57]	CO_{2e} Emissions, Gas (lb./therm)	14.150[58]

† Adjusted for inflation between data publication and start of study.

[47] Federal Reserve Bank of Philadelphia. (August 2022). Short-Term and Long-Term Inflation Forecasts. https://www.philadelphiafed.org/surveys-and-data/real-time-data-research/inflation-forecasts (Accessed Oct. 2022)
[48] U.S. Energy Information Administration (2022). Annual Energy Outlook. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2022&region=1-1&cases=ref2022&start=2020&end=2050&f=A&linechart=~ref2022-d011222a.6-3-AEO2022.1-1&map=ref2022-d011222a.4-3-AEO2022.1-1&ctype=linechart&sourcekey=0 (Accessed Oct. 2022)
[49] Income required to purchase median priced new home varies from $83,482–298,218 among core-based statistical areas (CBSA) in Massachusetts. Corresponding marginal federal income tax rates after a standard deduction range from 22–35%. The rate for Worcester is 24% per Joint Center for Housing Studies of Harvard University (2022). High Incomes Are Needed to Afford Homes in Many Metros. https://www.jchs.harvard.edu/son-2022-affordability (Accessed Oct. 12, 2022) and U.S. Internal Revenue Service, (Nov. 10, 2021). IRS provides tax inflation adjustments for tax year 2022. https://www.irs.gov/newsroom/irs-provides-tax-inflation-adjustments-for-tax-year-2022 (Accessed Oct. 12, 2022)
[50] U.S. Energy Information Administration (2022). Annual Energy Outlook. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2022&region=1-1&cases=ref2022&start=2020&end=2050&f=A&linechart=~~ref2022-d011222a.5-3-AEO2022.1-1&map=ref2022-d011222a.4-3-AEO2022.1-1&ctype=linechart&sourcekey=0 (Accessed Oct. 2022)
[51] Google.com (2022). Average rate for a $1,000,000 30-year fixed-rate loan with 20% and 700–719 FICO score. https://www.google.com/search?sclient=psy-ab&hl=en&site=webhp&source=hp&q=mortgage%20interest%20rate&gs_l=&pbx=1 (Accessed Sept & Nov. 2022).
[52] Time weighted average generation source factor from 2023–2050; 22% summer peak, 11% summer off-peak, 45% winter peak, 22% winter off-peak. [Navigant. (2020). Study to Propose a More Refined Method to Account for the Conversion of Electric Savings to MMBtu Savings.] With 9.7% transmission and distribution losses. ["Appendix 2b - 2019 PYR Eversource Electric BCR Model.xlsx" provided by program administrators.]
[53] U.S. Bureau of Economic Analysis. (Dec. 2020). Real Personal Income by State and Metropolitan Area, 2019. https://www.bea.gov/news/2020/real-personal-income-state-and-metropolitan-area-2019 (Accessed Sept. 2022)
[54] MA Board of Building Regulations and Standards. (Feb. 2020). Ninth Edition of MA State Building Code 780. Table C401.2.3 Site to Source Fuel Conversion Factors https://www.mass.gov/doc/780-cmr-ninth-edition-chapter-13-energy-efficiency-amendments-as-of-272020/download
[55] CareerOneStop Salary Finder [Unweighted mean of Plumbers, HVAC Technicians, Electricians, Carpenters, Insulation Workers, Construction Laborers, Miscellaneous Construction] https://www.careeronestop.org/Toolkit/Wages/find-salary.aspx (Accessed Nov. 2022)
[56] Long term average (2023–2050) of annual emissions factors forecast by Navigant (Mar. 2020).
[57] U.S. Environmental Protection Agency, (Sep. 2022). Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances. https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf (Accessed Dec. 2022)
[58] BEopt v2.8 default from ANSI/ASHRAE Standard 105-2014, Appendix J. The beta for BEopt v3 uses a value from the RESNET CO_{2e} index draft that is 4% higher (14.73 lb/therm), which was developed using EPA emissions factors.

A.1.1 Definitions

- Annual Inflation; year over year increase in costs for goods and services
- Electricity Rate; The statewide average residential price of electricity.
- Electricity Rate Escalation; Combined with inflation to estimate the future cost of electricity.
- Gas Rate; The statewide average residential price of natural gas.
- Gas Rate Escalation; Combined with inflation to estimate the future cost of natural gas.
- Mortgage Interest Rate; additional costs paid to a bank in exchange to cover profit and potential loss of the mortgage principal i.e., loaned amount.
- Material Multiplier; This adjusts the materials costs for any of BEopt's default measure options that may be included in a package, accounting for regional differences and historic inflation since the measure option cost was compiled.
- Labor Multiplier; This is the labor equivalent of the material multiplier.
- Discount Rate; Used to adjust cash flows of various economic metrics over the analysis period; $nominal\ rate = (1 + real\ discount\ rate) \times (1 + inflation\ rate) - 1$.
- Analysis Period; Used in calculating the cash flows and various economic metrics.
- Mortgage Period; Used in calculating the mortgage portion of ownership costs.
- Mortgage Down Payment; This reduces mortgage payments, and therefore the overall cash flows that contribute to the cost of ownership (annualized energy costs, AERC).
- Marginal Income Tax, Fed; Used in conjunction with the state marginal income tax rate to calculate annual tax deductions based on the interest portion of mortgage payments.
- Marginal Income Tax, MA; Used in conjunction with the federal marginal income tax rate to calculate annual tax deductions based on the interest portion of mortgage payments.
- Source: Site, Electricity; This ratio is used to convert modelled electricity savings at the meter into source energy, accounting for long-term growth of renewables, plus generation inefficiency and distribution losses.[52]
- Source: Site, Natural Gas; This ratio is used to convert modelled gas savings at the meter into source energy. This accounts for distribution losses.
- CO_2 Emissions, Electricity; The average projected combustion emissions intensity for electricity generation in New England from 2023 to 2050.[56]
- CO_{2e} Emissions, Gas; The full life cycle carbon dioxide equivalent emissions intensity of natural gas. This accounts for the higher global warming potential of leaks from the production and distribution of natural gas.

This report does not include package emissions results, nor were emissions included in the Phase I optimization process. Rather, these coefficients are inputs expected by the modeling software, which can be used for optimization or certain result reports.

A.2 ARCHITECTURAL PARAMETERS

The architecture of the single-family home model in this study is identical to the 20R23 model and is based on findings from the 19X02 single-family residential new construction baseline study. The multifamily model has been updated to incorporate findings from the 20R30 multifamily new construction baseline, namely fewer, larger units per building. The previous study modeled a 30 unit building versus 26 units, yielding a 15% larger apartment than 20R23's average of 1,100 ft^2.

Table 35: Model Configuration Details

	Single-family	Average MF unit	MF building, 26 units
Square Footage	2,729	1,270	33,000
Ceiling Height	9.0	9.7	9.7
Stories	2	1	3
Bedrooms	4	2	52
Basement	Mixed	Mixed	Unconditioned

A.3 BUILDING SHELL MEASURE OPTIONS

Component	Reference	Option 2	Option 3	Option 4
Air Leakage	*3 ACH50*	*1.5 ACH50*	Passive House	–
			0.85 ACH50 SF, 0.43 ACH50 MF	
Attic, Unfinished (SF)	*R-60 Blown-in, Grade I Ceiling*	*R-49 Blown-in, Grade I Ceiling*	R-60 Open + Closed Cell, Grade I Roof	–
Finished Basement	*R-15 XPS[1], Continuous*	*R-21 FGB, 2×6×24, Grade I*	–	–
Unfinished Basement	*R-30 FGB, Grade I Ceiling*	R-38 FGB, Grade I Ceiling	–	–
Exterior Walls, Stud	*R-21 FGB,[2] 2×6×16, Grade I*	*R-21 FGB, 2×6×24,[3] Grade I*	*R-14 Closed Cell + R-13 FGB, 2×6×24,[3] Grade I*	*R-36 Closed Cell, 2×6×24,[3] Grade I*
Finished Roof (MF)	*R-49 FGB, Grade I*	R-38C FGB + R-24 Polyiso Grade I	–	–
Interzonal Floor	*R-30 FGB, Grade I*	R-38 FGB, Grade I	–	–
Interzonal Walls	R-21 FGB,[1] 2×6×16, Grade I	*R-21 FGB, 2×6×24,[3] Grade I*	R-14 Closed Cell + R-13 FGB, 2×6×24,[3] Grade I	–
Wall Sheathing[4]	*OSB + R-5*	*OSB*	OSB + R-10	OSB + R-15
Windows	*0.29 U*	0.22 U (EnergyStar v.7)	0.18 U	–
	0.35 SHGC	0.29 SHGC	0.40 SHGC	

1. This option satisfies the equivalent U-factor requirements of the building code (Table R402.1.4).
2. Unlike the reference option for other measures, this industry-standard practice, i.e., Reference case, is not included in the performance options because it is more expensive and lower performance than option 2.
3. The International Residential Code—Table R602.3(5)—requires 2×6×16 studs for the ground floor of a three-story building. Consequently, construction costs may be slightly underestimated, and the energy savings marginally overestimated for multifamily packages with 2×6×24 walls due to the difference in framing factor of the ground floor wall.
4. See Section A.3.1 for details.

Values in italics are identical or similar to options in the previous study (20R23).

A.3.1 Insulation Types

Given the increased emphasis on continuous wall insulation in the new code, NMR researched prices for alternative continuous wall insulation materials, including non-foam materials like high-density mineral wool, and labor-saving options such as sheathing-plus-insulation combination products. Unfortunately, we were unable to obtain adequate data to include novel insulation types in this study as individual options. However, we did observe that the differences in cost by R-value/ft^2 among XPS (R-5/in), polyisocyanurate (R-6/in) and mineral wool (R-4/in) appears to be minor. A similar trend was observed for the blown-in cellulose and fiberglass insulations most likely to be used to meet the R-60 requirement. Therefore, the wall sheathing and blown-in ceiling insulation options do not call out specific materials.[59]

[59] It is worth noting that polyisocyanurate's higher R-value per inch means that it contributes less depth to the façade of a home, potentially simplifying the trim of doors and windows for packages with larger continuous R-values.

Component	Baseline	Option 2	Option 3	Option 4
Air Source HP	*8.5 HSPF2 (10 HSPF)* *17.2 SEER2 (18 SEER)*	*9.3 HSPF2 (11 HSPF)* *19.1 SEER2 (20 SEER)*	–	–
Central Air Conditioner	13.4 SEER2 (14 SEER)	15.2 SEER2 (16 SEER)	17.2 SEER2 (18 SEER)	–
Ducts	4.0% TDL, R-8 Attic	2.0% TDL, R-8 Attic	4.0% TDL, R-0 Cond. Space (SF)	4.0% TDL, R-25 Attic
Furnace	*95 AFUE*	*98.5 AFUE*	–	–
Hot Water Pipes	*R-3* *PEX*	*R-5* *PEX*	–	–
Mini-Split HP (Cold climate)	*8.7 HSPF2 (10.2 HSPF)* *18.7 SEER2 (19.5 SEER)* *Multi-zone*	10.7 HSPF2 (12.6 HSPF) 24.9 SEER2 (26.0 SEER) Single zone	11.6 HSPF2 (13.6 HSPF) 29.2 SEER2 (30.5 SEER) Single zone	–
Ground-Source HP	*4.0 COP* *20.0 EER2 (21.0 EER)*	4.3 COP 21.9 EER2 (23.0 EER)	–	–
Mechanical Ventilation[3]	*Exhaust only*	*75% efficient ERV*	85% efficient ERV	≥98% efficient ATU[1]
Water Heater	*0.67 UEF,* *Gas Storage[2]*	0.95 UEF, Gas Tankless	0.98 UEF, Electric Storage	–
Clothes Washer	2.4 IMEF (2.8 MEF)	–	–	–
Cooking Range	*0.40 EF Range,* *0.06 EF Oven,* *Gas*	*0.84 EF Induction Range,* *0.12 EF Oven,* *Electric*	–	–
Clothes Dryer	*3.76 CEF, Electric*	–	–	–
Dishwasher	*290 kWh/yr*	–	–	–
Lighting	*100% LED,* *80 Lm/W[4]*	–	–	–
Refrigerator	*574 kWh/yr*	–	–	–

1. Air treatment unit (ATU) also known as conditioned energy recovery ventilation (CERV) and ventilating heat pump (VHP).
2. The baseline for water heaters includes a range of technologies. However, running multiple models would have increased the complexity of this analysis several fold. Consequently, a single modest option was chosen as the reference water heater type. 45% of homes in the 19X02 baseline study featured a tankless water heater and 48% had a storage option. 54% of the storage water heaters were combustion heated, 31% were heat pump water heaters, and 15% were electric resistance.
3. See Section A.4.1 for details.
4. Building code lighting efficacy requirements are 65 Lm/W. However, data from the last Delta Watts study (19X09) revealed an average LED efficacy of 80.5 Lm/W for A-lines and reflectors, while the mean efficacy of bulbs in the 2019 Rhode Island shelf-stocking data was 85 Lm/W.

A.4.1 Mini-split Heat Pumps

Table 36 lists the number of compressors and head units modeled for single-family and multifamily packages in this study.

Table 36: MSHP Configuration

	Design	Baseline	Option 2	Option 3
SF	Compressors	2	5	5
	Head units	5	5	5
MF	Compressors	2	2	2
	Head units	2	2	2

A.4.2 Ground Source Heat Pumps

BEopt models all GSHP systems as a forced air distribution system with a closed-loop vertical bore rather than horizontal field or open-loop. The software does not support desuperheaters, therefore the GSHP packages do not include this option to preheat domestic hot water. However, desuperheaters have a relatively modest impact on energy savings for homes in this climate, yielding an approximately 10–20% reduction in hot water energy consumption.[60] Depending on the package, this equates to between one and four million BTUs of natural gas per year, or 2–3% of total energy consumption.

A.4.3 Recovery Ventilation

While the stretch code only requires mechanical ventilation with a rating of 65% sensible energy recovery, the lowest efficiency option in this study is 75%. NMR's research suggests that the cost differences between lower efficiency equipment (such as 65% and 75% SRE) are negligible. Therefore, the higher value was adopted. Similarly, a sensitivity analysis indicates that the difference between heat recovery ventilation (HRV) and energy recovery ventilation (ERV) in the modeled climate is quite small. Based on this finding, only ERVs were included in the study to reduce the model complexity.

A.4.4 Heat Pump Water Heaters

HPWH were omitted from this phase of the study based on the findings in 20R23. In that study's results heat pump water heaters were only included in maximum energy savings packages, rather than the minimally code compliant packages that are the focus of this report. However, HPWH will be featured in the all-electric high performance phase two of this study.

[60] Ekotrope (2018). Desuperheater. https://ekotrope.freshdesk.com/support/solutions/articles/17000074547-desuperheater (Accessed June 14, 2024)

Appendix B Additional Details

B.1 Efficiency-Related Construction Costs

The efficiency related construction costs used in this study include materials and labor for the following measures:

- Air sealing
- Above grade walls; framing, insulation, sheathing
- Attic/Roof insulation
- Finished basement walls; framing, insulation, drywall
- Frame floor insulation
- Windows
- Heating & Cooling
    - Air-source heat pump
    - Furnace and central air conditioner
    - Ground-source heat pump
    - Mini-split heat pump and electric baseboard backup
- Cooking range
- Ductwork; ducting, sealing, insulation
- Hot water pipes and insulation
- Mechanical ventilation such as HRVs/ERVs
- Water heater

B.2 Global Minimum Ownership Cost

The packages in this section are the lowest points of the optimization curves in Section 2.4, and therefore have the lowest possible cost of ownership possible given the model inputs in 0. All global minima in Table 37 are base code compliant, except the struck-out single-family furnace/CAC package (DCFW.GO). The multi-family furnace/CAC package (D3FW.GO) is identical to the base code ownership cost package (D3FW.B2), while the packages for both ASHP and MSHP designs save more energy than the corresponding base code ownership cost packages with marginally higher construction costs.[61] Of particular note is the multifamily MSHP package, which increases source energy savings by 11 percentage points (from 7.7 to 18.8%) by reducing heat pump capacity through higher heat pump and recovery ventilation efficiencies.

[61] ASHP saves 15.5% more source energy, after a 4.2% increase in energy related construction costs. SF MSHP saves an additional 11.5%, after an investment of 8% more for energy efficiency.

Table 37: Global Minimum Ownership Cost Packages Compared to Base Code

	HVAC	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*58.7*	*0.0%*	*$82.8k*	*$3.4k*	*$34.0k*	*$4.5k*	*DCFW.BR*
SF	~~Furnace/CAC~~	~~54.4~~	~~8.6%~~	~~$82.7k~~	~~$3.2k~~	~~$34.1k~~	~~$4.3k~~	~~DCFW.GO~~
SF	ASHP	42.8	27.4%	$92.7	$3.5k	$36.8k	$4.9k	DCAW.GO
SF	GSHP	39.2	35.7%	$113.7k	$3.1k	$41.5k	$4.0k	DCGW.GO
SF	MSHP	40.0	35.0%	$79.9k	$3.1k	$33.2k	$4.5k	DCMW.GO
MF	*Ref.† Furnace*	*63.0*	*0.0%*	*$743.7k*	*$54.7k*	*$343.8k*	*$65.7k*	*D3FW.BR*
MF	Furnace/CAC	60.6	4.3%	$762.1k	$53.3k	$347.1k	$64.7k	D3FW.GO
MF	MSHP	45.7	18.8%	$637.2k	$51.2k	$314.1k	$58.2k	D3MW.GO

† Built to prescriptive base code, except for an R408 additional efficiency measure (3.2.1).
Packages that are struck out are not compliant with code.

As shown in Table 38, only the GSHP and MSHP global minimum ownership cost packages are stretch code compliant. In fact, these are identical to the respective stretch code ownership cost packages (DCGW.S2 and DCMW.S2). On the other hand, the AHSP package is a near miss and not compliant due to the presence of gas appliances that require an ERI of 42 or less.

Table 38: Global Minimum Ownership Cost Packages Compared to Stretch Code

	HVAC	ERI	Source Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF	*Ref.† Furnace*	*41.4*	*0.0%*	*$82.8k*	*$3.0k*	*$34.0k*	*$4.4k*	*DCFW.SR*
SF	~~Furnace/CAC~~	~~54.4~~	~~-16.7%~~	~~$82.7k~~	~~$3.2k~~	~~$34.1k~~	~~$4.3k~~	~~DCFW.GO~~
SF	~~ASHP~~	~~42.8~~	~~7.3%~~	~~$92.7~~	~~$3.5k~~	~~$36.8k~~	~~$4.9k~~	~~DCAW.GO~~
SF	GSHP	39.2	17.9%	$113.7k	$3.1k	$41.5k	$4.0k	DCGW.GO
SF	MSHP	40.0	17.0%	$79.9k	$3.1k	$33.2k	$4.5k	DCMW.GO
MF	*Ref.† Furnace*	*42.0*	*0.0%*	*$743.7k*	*$49.9k*	*$378.3k*	*$68.0k*	*D3FW.SR*
MF	~~Furnace/CAC~~	~~60.6~~	~~-19.1%~~	~~$762.1k~~	~~$53.3k~~	~~$347.1k~~	~~$64.7k~~	~~D3FW.GO~~
MF	~~MSHP~~	~~45.7~~	~~-1.1%~~	~~$637.2k~~	~~$51.2k~~	~~$314.1k~~	~~$58.2k~~	~~D3MW.GO~~

† Package most like prescriptive base code that still complies with stretch/specialized code (4.2).
Packages that are struck out are not compliant with code.

B.3 Electrification Impacts

Phase 2 of this study will explicitly study home electrification, while this report focuses on minimal compliance with code. Nevertheless, one might expect site savings packages to generally be electrified. However, due to various quirks of the methodology outlined in Section 2, this may not always be the case; see footnote 39 for details. We therefore provide the following tables that show the difference in performance of the available cooking and hot water options. With these, rough adjustments may be applied to any packages that include combustion cooking or hot water equipment. Note that both tables show the differential values compared to the option installed in a furnace/CAC reference home (*italics*), but the differences in performance are similar when assessed relative to a mini-split reference home.

Table 39: Differential Impacts of Hot Water Options vs. Reference Package

	Water Heater	ERI	Source Energy (kBTU/y)	Site Energy (kBTU/y)	Eff. Const. Cost	Utilities (1st Year)	First Year Cost	Annual Own. Cost
SF	*0.67 UEF, Gas Storage*	*0.0*	*0*	*0*	*$0*	*$0*	*$0*	*$0*
SF	0.95 UEF, Gas Tankless	-5.0	-4,650	-4,380	$3.4k	-$71	$756	$66
SF	0.98 UEF, Electric Storage	2.2	5,930	-5,580	-$0.2k	$602	$545	$600
MF	*0.67 UEF, Gas Storage*	*0.0*	*0*	*0*	*$0*	*$0*	*$0*	*$0*
MF	0.95 UEF, Gas Tankless	-6.8	-64,880	-60,250	$93.8k	-$1,112	$21,984	$3,005
MF	0.98 UEF, Electric Storage	5.9	127,650	-78,090	-$3.8k	$11,047	$10,101	$10,927

Despite the fuel switching, electric cooking results in a only modest source energy increase (Table 40) compared to the increase in site energy because of greater appliance efficiency (A.4). In fact, single-family homes appear to benefit from electric cooking less than multifamily buildings since the former have lower summer cooling load intensities (kBTU/ft^2) and receive greater benefit from the waste heat of low-efficiency appliances when cooking in a gas-heated home during the winter.

Table 40: Differential Impacts of Cooking Range Options vs. Reference Package

	Range and Oven	ERI	Source Energy (kBTU/y)	Site Energy (kBTU/y)	Eff. Const. Cost	Utilities (1st Year)	First Year Cost	Annual Own. Cost
SF	*Gas Range and Oven*	*0.0*	*0*	*0*	*$0*	*$0*	*$0*	*$0*
SF	Induction Range & Elec. Oven	-0.8	147	1,470	$1.4k	$56	$401	$195
MF	*Gas Range and Oven*	*0.0*	*0*	*0*	*$0*	*$0*	*$0*	*$0*
MF	Induction Range & Elec. Oven	-1.4	-5,710	-30,220	-$35.8k	$993	$9.821	$4,536

B.4 Energy Rating Index Compliance Margin

Builders frequently rely on the ability to improve a building's air sealing to bring completed but out-of-spec buildings in line with code. However, three fourths of the optimized packages in this study already include Passive House levels of air leakage due to the cost-effectiveness of this measure. What other alternatives exist if a home receives a higher-than-expected rating due to imperfect (non-Grade I) insulation installation, or other reasons? Drawing upon other results for single-family furnace/CAC homes (Table 8 and Table 39), Table 41 presents the approximate incremental costs (positive values) and benefits (negative values) of relatively easy upgrades to mechanical ventilation systems and water heaters that could help a completed single-family home meet energy rating requirements.[62]

[62] This assumes that the removed equipment can be reused in another home.

Table 41: Approximate Impacts of Late-Construction Upgrades

Upgrade	ERI	Source Energy (kBTU/y)	Site Energy (kBTU/y)	Eff. Const. Cost	Utilities (1st Year)	First Year Cost	Annual Own. Cost
DHW: 0.67 to 0.95 UEF Gas	-5.0	-4,650	-4,380	$3.4k	-$71	$756	$66
DHW: 0.67 to 3.2 UEF HPWH†	-4.8	-4,800	-9,710	$2.3k	$165	$722	$378
DHW: 0.96 to 3.2 UEF HPWH†	-7.0	-10,730	-4,130	$2.1k	-$437	$177	-$222
Vent: Exhaust only to 75% ERV	-3.8	-2,800	-3,740	$1.4k	$4	$347	$103
Vent: Exhaust only to 85% ERV	-4.5	-4,770	-5,600	$1.9k	-$28	$449	$108
Vent: 75% to 85% ERV	-0.7	-1,970	-1,860	$0.5k	-$32	$102	$5

† There may be interactive effects between the HPWH and other systems in a home that are not captured here.

Making the late upgrade from gas to a heat pump water heater would be simpler in a specialized code community since RC104.3 requires that the wiring necessary for the HPWH would already be in place. If this were undertaken at the same time as an upgrade to an induction range, then the rating required to comply with code increases by 3 points.[63,64] However, as shown in Table 40, electric cooking incurs a 0.8 ERI penalty, resulting in an total effective rating decrease of 7 (-4.8+0.8-3) for a single-family package starting with a gas storage water heater and cooking.

B.5 Base Code Compliance Path

Most optimized single-family base code packages in Table 42 comply via the ERI path, which may incur additional costs for a HERS rating. In contrast, every multifamily package is prescriptive path compliant.

Table 42: Base Code Package Compliance Paths

	Design	Source Energy Savings	Source Energy Savings	Efficiency Construction Cost	First Year Cost	Annual Ownership Cost
SF	ASHP	ERI	ERI	ERI Prescriptive	ERI	Prescriptive
SF	Furnace/CAC	ERI	ERI	ERI	ERI	ERI
SF	GSHP	ERI Prescriptive	ERI Prescriptive	ERI	ERI	ERI
SF	MSHP	ERI	ERI	ERI	ERI	ERI
MF	Furnace/CAC	ERI Prescriptive	Prescriptive	ERI Prescriptive	Prescriptive	Prescriptive
MF	MSHP	ERI Prescriptive	ERI Prescriptive	Prescriptive	Prescriptive	Prescriptive

[63] From 52 to 55 for the base code, or through June 30, 2024, for the interim stretch code. After July 1, 2024, the three-point increase permits a score of 45 for all-electric homes compared to 42 for mixed-fuel.
[64] A similar three-point boost is available with the addition of a 4 kW or larger photovoltaic system per unit in base code communities, and until June 30, 2024, in stretch code or specialized code communities.

Appendix C Package Composition

Darker blues indicate higher efficiency in Table 43. This heat map presents the selected options for major measures of the optimized packages in this study. Scan the table columns to observe general trends about which measures receive upgrades from the reference home, and to what extent. Numbers in the table indicate the specific option from sections A.3 and A.4. Package codes are explained in **Error! Reference source not found.**, and details about other measures are included in the spreadsheet that accompanies this report.

Legend
Lower efficiency; Option 2 for sheathing & SF ceilings
Average efficiency; Option 1
High efficiency; Usually Option 2, #3 for sheathing
Higher efficiency; Usually Option 3; #4 for sheathing
Highest efficiency; Option 4

Table 43: Package Measure Options for Significant Home Components

Package	Leak	Wall	Cont.	Window	Roof	H	V	AC	Ducts	DHW
D3FW.BR	1	1	1	1	1	1	1	1	1	1
D3FW.B0	1	2	1	1	2	1	1	1	3	1
D3FW.B1	2	2	1	1	2	1	1	1	3	1
D3FW.B2	2	2	4	1	1	1	1	1	3	1
D3FW.B3	3	2	4	1	2	1	2	1	3	3
D3FW.B4	3	2	4	3	1	1	2	1	3	1
D3FW.GO	2	2	4	1	1	1	1	1	3	1
D3FW.SR	3	2	4	1	1	1	2	1	3	2
D3FW.S0	3	2	4	1	1	1	2	1	3	2
D3FW.S1	3	2	4	1	1	1	2	1	3	2
D3FW.S2	3	2	4	1	1	1	2	1	3	2
D3FW.S3	3	4	3	3	2	1	3	3	3	2
D3FW.S4	3	4	3	3	2	1	3	3	3	2
D3MW.BR	1	1	1	1	1	1	1			1
D3MW.B0	1	2	1	1	1	2	1			3
D3MW.B1	1	2	1	1	1	2	1			1
D3MW.B2	3	2	4	1	1	2	1			1
D3MW.B3	3	2	3	3	2	2	3			2
D3MW.B4	3	2	4	1	1	3	1			1
D3MW.GO	3	2	4	1	1	3	2			1
D3MW.SR	3	2	4	1	1	1	3			2
D3MW.S0	3	2	2	1	1	3	3			2
D3MW.S1	3	2	1	1	1	3	3			2
D3MW.S2	3	2	4	1	1	3	2			2
D3MW.S3	3	4	4	3	2	3	3			2
D3MW.S4	3	4	4	3	2	3	3			2

Package	Leak	Wall	Cont.	Window	Roof	H	V	AC	Ducts	DHW
DCAW.BR	1	1	1	1	1	1	1		1	1
DCAW.B0	1	2	1	1	2	1	2		4	1
DCAW.B1	1	2	1	1	1	1	2		4	1
DCAW.B2	1	2	4	1	2	1	1		4	1
DCAW.B3	1	2	4	1	2	1	1		4	1
DCAW.B4	1	2	4	1	1	1	1		4	1
DCAW.GO	3	2	4	1	1	1	3		4	1
DCAW.SR	3	2	4	2	2	1	3		4	1
DCAW.S0	3	2	1	1	1	1	3		4	2
DCAW.S1	3	2	4	1	2	1	3		4	1
DCAW.S2	3	2	4	1	1	1	3		4	2
DCAW.S3	3	2	1	1	1	2	3		4	2
DCAW.S4	3	2	1	1	1	2	3		4	2
DCFW.BR	1	1	1	1	1	1	1	1	1	1
DCFW.B0	3	2	1	2	2	1	3	1	4	1
DCFW.B1	3	2	1	2	2	1	3	1	4	1
DCFW.B2	3	2	4	1	2	1	3	1	4	1
DCFW.B3	3	2	4	1	1	2	3	2	4	4
DCFW.B4	3	2	4	1	1	2	3	2	4	4
DCFW.GO	1	2	4	1	2	1	1	1	4	1
DCFW.SR	3	2	3	1	1	2	3	1	4	2
DCFW.S0	3	2	4	1	2	1	3	1	4	2
DCFW.S1	3	2	4	1	2	1	3	1	4	2
DCFW.S2	3	2	4	1	2	1	3	1	4	2
DCFW.S3	3	2	4	3	1	2	3	2	4	2
DCFW.S4	3	2	4	3	1	2	3	2	4	2
DCGW.BR	1	1	1	1	1	1	1		1	1
DCGW.B0	3	2	3	1	1	2	3		4	4
DCGW.B1	3	2	3	1	1	2	3		4	1
DCGW.B2	3	2	4	1	1	2	3		4	1
DCGW.B3	3	2	4	1	1	1	3		4	3
DCGW.B4	3	2	4	1	3	2	3		1	1
DCGW.GO	3	2	4	1	2	1	3		4	1
DCGW.SR	3	2	1	1	3	1	2		3	1
DCGW.S0	3	2	3	1	2	1	3		4	3
DCGW.S1	3	2	3	1	2	1	3		4	1
DCGW.S2	3	2	4	1	2	1	3		4	1
DCGW.S3	3	2	4	1	1	1	3		4	3
DCGW.S4	3	2	4	1	3	2	3		1	1

Package	Leak	Wall	Cont.	Window	Roof	H	V	AC	Ducts	DHW
DCMW.BR	1	1	1	1	1	1	1			1
DCMW.B0	1	2	1	1	2	1	1			4
DCMW.B1	1	2	1	1	2	1	1			1
DCMW.B2	1	1	1	1	2	1	1			1
DCMW.B3	1	2	4	1	2	1	1			4
DCMW.B4	1	1	1	1	2	1	1			1
DCMW.GO	3	2	4	1	2	3	3			1
DCMW.SR	2	2	4	1	2	3	2			1
DCMW.S0	2	2	1	1	2	3	3			1
DCMW.S1	3	2	1	1	2	3	3			1
DCMW.S2	3	2	4	1	2	3	3			1
DCMW.S3	3	2	4	1	2	3	3			3
DCMW.S4	3	2	4	3	2	3	3			1