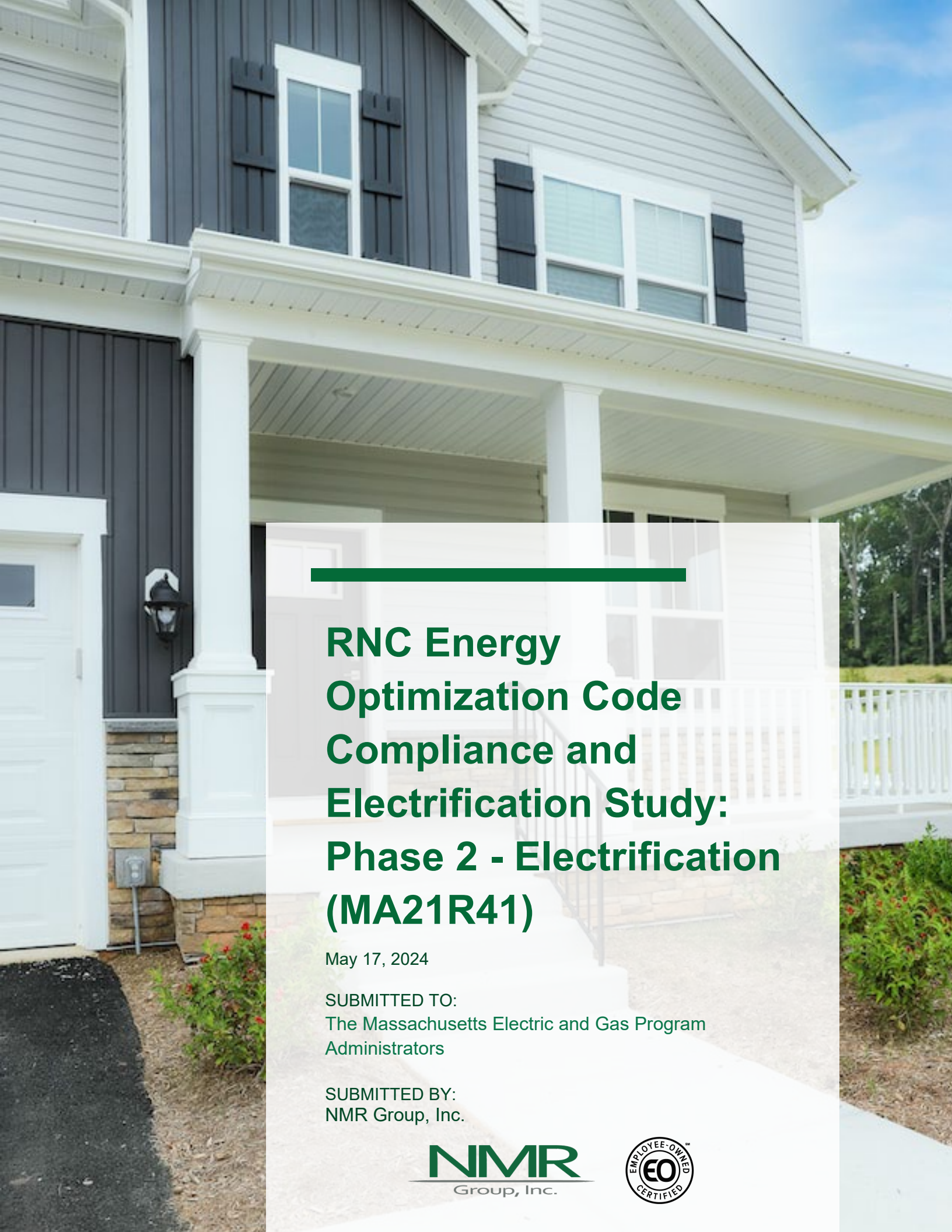

RNC Energy Optimization Code Compliance and Electrification Study: Phase 2 - Electrification (MA21R41)

May 17, 2024

SUBMITTED TO:
The Massachusetts Electric and Gas Program Administrators

SUBMITTED BY:
NMR Group, Inc.

MA Residential New Construction Energy Optimization & Electrification
(21R41 Phase 2)

This study used energy optimization modeling to find cost-effective ways to build energy-efficient, all-electric homes that meet the 10th edition Massachusetts Building Code. It modeled thousands of single-family (SF) and multifamily (MF) home packages, optimizing for factors like construction costs, utility bills, long-term ownership costs, and energy use. The result was optimized, all-electric Net-Zero packages (with solar panels) and Zero Energy Ready Homes (without solar panels).

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Key Findings

General Observations

- Optimized, all-electric homes can be cheaper to own than mixed-fuel homes that only meet code.
- Optimization benefits builders, owners, and program administrators, reducing costs and boosting savings.
- Optimized Net-Zero and Zero Energy Ready Homes are distinct, even ignoring the solar panels.
- Building optimized all-electric homes gives builders more flexibility to meet code than basic, mixed-fuel homes.

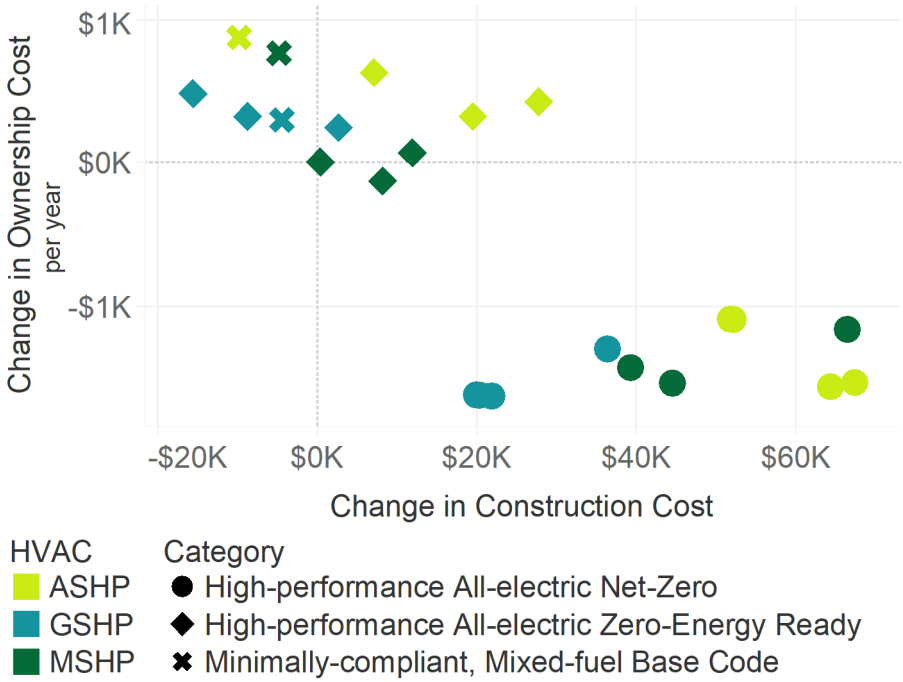
Recommendations for Building All-Electric Homes

- ☑ Reduce air infiltration substantially (≤1.5 ACH_{50})
- ☑ Use high recovery efficiency (≥85%) ventilation
- ☑ Include plenty of continuous wall insulation (≥R-10)
- ☑ Bury any attic ducts under deep insulation
- ☑ Move ducts into conditioned space when possible
- ☑ Install a HPWH in an unconditioned part of the home
- ☑ Invest in other upgrades before improving conventional low-E double-pane windows or R-49 ceiling insulation

Cost-Benefit of Optimized All-Electric vs. Minimally Code Compliant SF Homes

- Base code homes are cheaper to build but more expensive to own and operate compared to stretch code homes.
- Many of the optimized, all-electric homes in this study only cost about $100 more per month to own *and* operate than a less efficient, mixed-fuel home. Some all-electric packages even cost less.

The graph compares non-optimized base code homes (✕) and optimized all-electric homes (◆, ●) to non-optimized mixed-fuel stretch code versions with gas cooking and water heating. Homes left of the vertical $0-axis cost less to build than the mixed-fuel, stretch code version, and homes below the horizontal $0-axis cost less to operate.



MA Residential New Construction Energy Optimization & Electrification

Design: *a prototype home with a specific type of heating and cooling system.*
This study includes the following four designs, three single-family and one multifamily:

Single-Family	*Minisplit heat pump (MSHP)*	*Centrally-ducted air-source heat pump (ASHP)*	*Ground-source heat pump (GSHP)*
Multifamily	*Minisplit heat pump (MSHP)*		

Package: *a combination of energy-related features (wall insulation, heating system efficiency, etc.) that together yield an optimized design.*

Methodology

1. **Design reference home models.** Use NREL's BEopt software to create basic, code-compliant, home designs.
2. **Test different combinations.** Run the software to explore hundreds of combinations of energy-related features (like windows and heat pumps of different efficiencies) to find the best combinations.
3. **Select optimized packages.** Choose four code-compliant, optimized designs with solar panels (Net-Zero) and four without (Zero Energy Ready), each optimized to meet the specific goals shown below.
4. **Compare and analyze.** Compare the optimized, all-electric designs to basic, minimally-compliant stretch code homes that use gas for cooking and water heating.

Reference Package

Unoptimized home, minimally compliant with stretch code; developed in Phase 1 of this study. This is a *mixed-fuel* design with gas cooking and water heating.

Construction Cost Package

Lowest initial cost of energy-related features (materials and labor) among the tested packages.

First Year Cost Package

Lowest cost to the buyer in the first year of ownership. Costs include utility bills, 20% down payment, mortgage payments, and interest tax deduction.

Ownership Cost Package

Prioritizes long-term benefits to the homeowner. Balances upfront construction costs against mortgage payments, future equipment replacements, and utility bills.

Energy Savings Package

Lowest electric usage *among the tested packages*.

Key Study Limitations

Uses generalized floorplans and economic assumptions that might not match every home.
Focuses on efficiency-related costs, assuming other costs, like flooring or wiring, stay the same.
Excludes Mass Save and federal tax incentives for energy-efficient construction.
Future utility costs do not consider the impact of climate change on heating and cooling needs.

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Glossary

Term	Definition
ACH_{50}	Air Changes per Hour with a 50-Pascal pressure gradient
AERC	Annualized Energy-Related Costs, i.e., utility bills, mortgage, and replacement costs
ASHP	Air-Source Heat Pump; a ducted fixed-speed or multi-speed 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
HSPF(2)	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; a variable speed heat pump, usually ductless
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
NZ	Net-Zero homes produce as much energy as they consume in a year (or more) using renewables
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
SEER(2)	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
ZERH	Zero Energy Ready Homes are efficient enough to become NZ with the addition of renewables

Executive Summary

This study uses energy modeling to identify combinations of measures (*packages*) to cost-effectively build new homes that 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 report focuses on high-performance all-electric packages.** For results that are fuel-neutral and focused on minimal code compliance, see the Phase 1 report.

Table 1 provides a high-level summary of the new, residential energy code requirements in Massachusetts. This report focuses on single-family and low-rise multifamily home packages that comply with the new code requirements that will take full effect on July 1, 2024. The results also comply with the less stringent interim code that went into effect in 2023, and the draft tenth edition base code.

Table 1: New Construction Code Compliance Criteria Summary

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

† Specialized code requires other provisions, most notably Passive House compliance for large multifamily buildings.
‡ Prescriptive path mandates certain features in lieu of an ERI. Key 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*

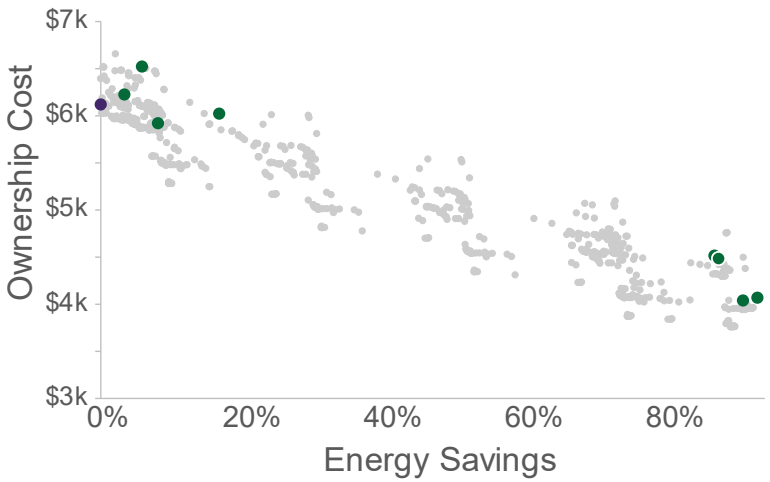
Methodology

Building on previous research. This electrification report builds on past research, including identifying fuel-neutral approaches to comply with the previous code[1] and the new code.[2]

Energy optimization modeling. This study employs NREL's BEopt modeling tool to evaluate various combinations of energy-efficient measures (*packages*).[3] BEopt simulates construction costs, ownership costs, and energy savings associated with a given set of economic parameters and measure combinations and provides ERI values. Appendix A details the modeling inputs.

Core model prototypes. The study used BEopt to test four core prototype *designs*, including a single-family home and a 26-unit, three-story multifamily building. Three single-family designs were modeled with different heating and cooling systems: ducted air-source heat pumps (ASHP), ground-source heat pumps (GSHP), and mini-split heat pumps (MSHP). The multifamily building was modeled with MSHP systems.

[1] https://ma-eeac.org/wp-content/uploads/MA20R23-RNC-EO-Final-Report-10222021.pdf
[2] https://ma-eeac.org/wp-content/uploads/MA21R41-RNC-EO-Code-Compliance-Report_Final_2023.08.11.pdf
[3] https://www.nrel.gov/buildings/beopt.html



Optimized packages and reference homes. The team reviewed hundreds of packages for each core building design. From these, the study identified eight optimized packages, including **four optimized packages with solar panels (Net-Zero) and four without (Zero Energy Ready)**. These optimized packages were compared to the mixed-fuel, stretch code-compliant reference homes included in Phase 1 of this study. The **reference homes minimally comply with the full tenth edition stretch code** in effect on July 1, 2024. The optimized, all-electric homes in this report are compares to references with the **same type of heating system, but the reference homes use gas cooking and water heating**. The optimized packages presented in this report provide templates for code-compliant all-electric homes that meet various goals, e.g., reduce construction costs, minimize long-term operational costs, or even produce more energy than they consume. These packages are optimized within constraints set for this study (see A.1 for details), but they *do not represent the most efficient packages possible*.

The study highlights the following key packages:

Reference Package

an **unoptimized** mixed-fuel home that is approximately compliant with the July 1, 2024, Stretch Code requirement of a 42 HERS rating.

Construction Cost Package

Optimized for the lowest initial cost (including materials and labor) for efficiency-related measures among tested options.

First Year Cost Package

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

Ownership Cost Package

optimized for long-term benefits to the homebuyer, balancing upfront construction costs with operating and replacement costs.

Energy Savings Package

optimized for maximum site energy savings (savings at the utility meter) among the measure options tested in this study. Other technologies may save more energy.

Table 2 summarizes the costs and economic factors that the modeling tool considers when selecting each of the four different optimization packages (more detail in 2.2). A preliminary sensitivity analysis indicated that the rebates available from the Massachusetts RNC program at the time of this report have limited impact on model results. Consequently, the study excluded 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.

Table 2: Summary of Factors Included in Optimized Package Selection

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

KEY FINDINGS

Optimized Net-Zero (NZ) and Zero-Energy Ready Home (ZERH) package are distinct. Net-zero packages often include additional enhancements that reduce their Energy Rating Index (ERI) values to an average of 4.8 points lower than their ZERH counterparts, excluding the credit for solar. Multifamily NZ and ZERH packages are identical except for the addition of solar, and therefore have the same ERIs without PV.

Tighten the building shell. Reducing air infiltration is very cost-effective. Three-fourths of optimized packages feature extremely low air leakage (less than 1 ACH_{50}), including all NZ packages and 59% of ZERH packages; the remainder employed 1.5 ACH_{50}.

Heat pump water heaters (HPWH) are common in optimized all-electric packages and required for all-electric multifamily. Only 25% of single-family packages include electric resistance water heaters, and none of the modeled multifamily buildings satisfied the building code's required pre-renewables rating of 45 without HPWHs.

Reduce heating and cooling loads with high-efficiency ERVs. Seventeen of twenty-four single-family packages include ERVs rated for 85% SRE rather than 75%.

For most designs, there are optimized all-electric packages with a *lower cost of ownership* than the matching mixed-fuel base or stretch code reference homes from Phase 1, which included fossil-fuel water heaters and cooking. Many ZERH single- and multifamily MSHP packages even feature a lower efficiency-related construction cost than the stretch code MSHP reference, while most ZERH GSHP packages are cheaper to construct than the GSHP base and stretch reference homes.

Most construction- and first year cost-optimized packages do *not* meet the current Mass Save all-electric program Level 2 HERS requirement. However, there are optimized packages for each design with a suitable ERI. Similarly, most packages in this report would require extra investment to qualify for the maximum federal tax credit (B.2).

Low-E double-pane windows (0.29 U-factor) suffice in most scenarios. As with previous reports (MA20R23, and Phase 1 of this study), when allowed to select between *good*, *better*, and *best* options (i.e., 0.29, 0.22 and 0.18 U-factors), the tool selected conventional 0.29 U-factor windows 82% of the time.

Double-stud walls are rare, featuring in only 20% of all optimized single-family packages. Double-stud walls are more common in Net-Zero homes (3 of 5 double-stud homes are NZ), ASHP homes (3 of 5 double-stud packages have ASHPs) and energy savings packages (3 of 5 double-stud packages are optimized for energy savings).

Optimization yields affordable ZERH multifamily options. Every ZERH multifamily package in this phase of the study costs less to construct and operate than the Phase 1 stretch code reference package. In fact, the stretch code ZERH construction cost package is cheaper than most of the mixed-fuel multifamily packages in Phase 1.

Typical loads of optimized all-electric homes can be met with 200 Amp service. Larger homes, those with non-negotiating level 2 EV charging, or other challenges may require a service upgrade or smart panels to manage large simultaneous end uses.

Comparison of optimized packages. The following subsections describe the *optimized, all-electric packages examined in this second phase of the study.* The charts contrast the range of performance for Zero Energy Ready (shown in blue) and Net-Zero (green) packages with the Phase 1 mixed-fuel stretch code references (purple). The summaries compare *overall performance (ERI)*, *construction costs*, *long-term annual ownership costs*, *first year ownership costs*, and *energy savings*. The results show *prototypes*; real world results will vary.

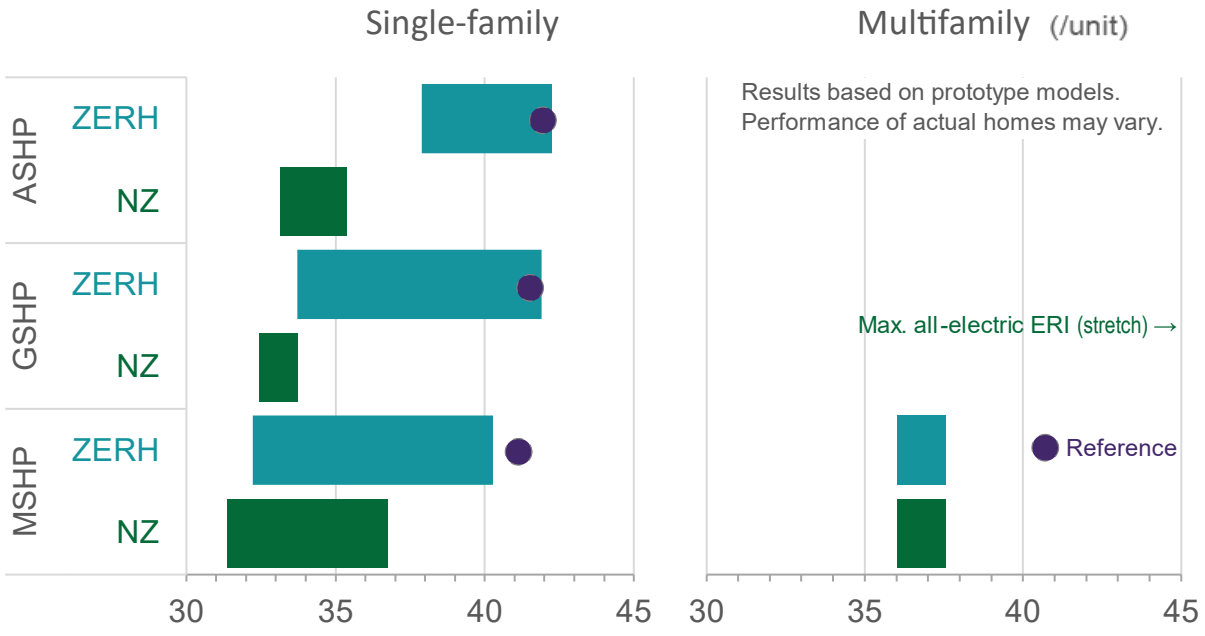
Performance Summary (ERI, without Solar)

This study treats the closely-related HERS and ERI as equivalent. Although the values of the two systems can differ slightly for the same home, the optimization software used does not generate HERS ratings. Furthermore, this study also explores the performance of prototypes rather than specific homes under construction.

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**.

The range of ERIs – excluding the credit for solar panels – among single-family Net-Zero home designs is smaller than for Zero-Energy Ready Homes, and the best-performing Net-Zero packages have lower (better) ERIs than their ZERH counterparts (Figure 1). This indicates that there are additional efficiency improvements available that are more cost-effective than photovoltaics, and good options to meet the Mass Save All Electric Home Level 2 incentive rating threshold of a HERS score of 35. The range of multifamily ratings are identical because the selected efficiency-related measure options of Net-Zero packages match those of their ZERH counterparts, other than the solar panels themselves.

Figure 1: Range of Energy Rating Index Values for Optimized Packages
by Design, *without Renewables*



Construction Costs

Optimized, all-electric single-family homes are cheaper to construct with ductless MSHPs than with other mechanical systems (i.e., ducted ASHPs or GSHPs), particularly in the case of Zero-Energy Ready Homes. However, among optimized single-family packages, the average incremental cost to move from ZERH to Net-Zero is lowest for GSHP homes – approximately $34,000.

Construction costs are limited to labor and materials of energy-related measures that may vary among packages e.g., ducts. These are listed in A.1.5 and A.1.6. ***Costs exclude energy-efficiency incentives.***

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

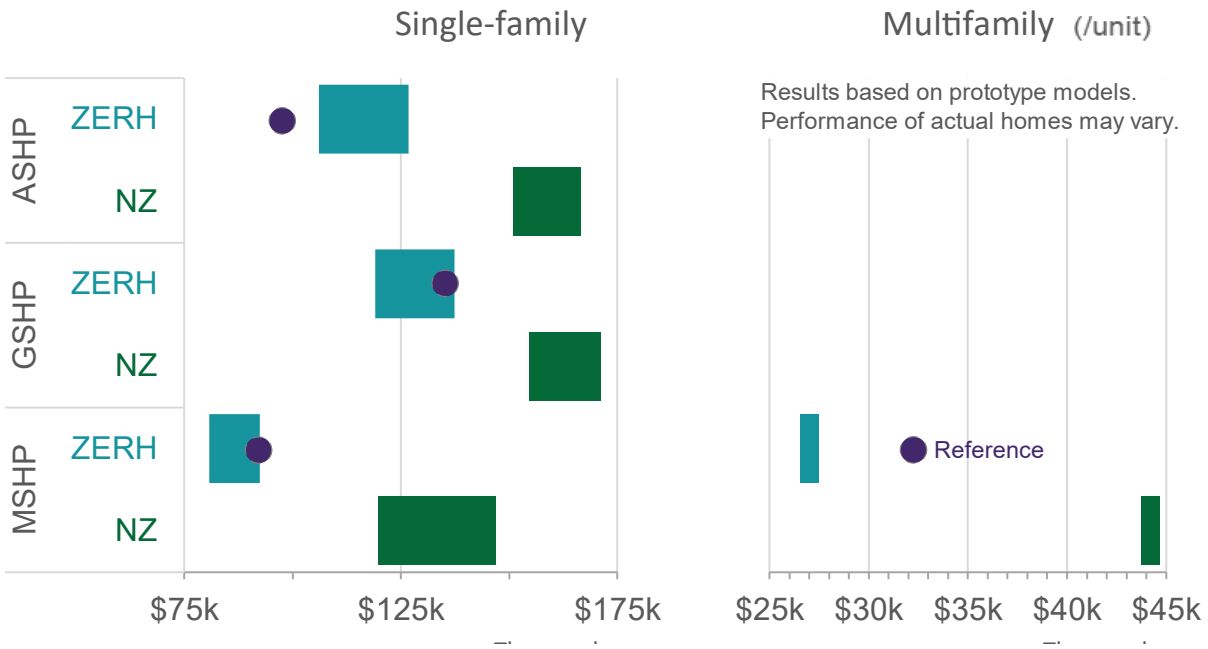


Table 3 presents incremental upfront energy-related construction costs for optimized Net-Zero packages, exclusive of Mass Save or federal incentives. These range from $17,200 to $54,700 more than their optimized ZER counterparts with solar panels, or -$16,700 to $18,700 without. See B.2 for incremental costs relative to the mixed-fuel stretch code reference home.

Table 3: Incremental Construction Costs to Shift from Optimized ZER to Optimized Net-Zero, per Unit
[cost excluding solar in brackets]

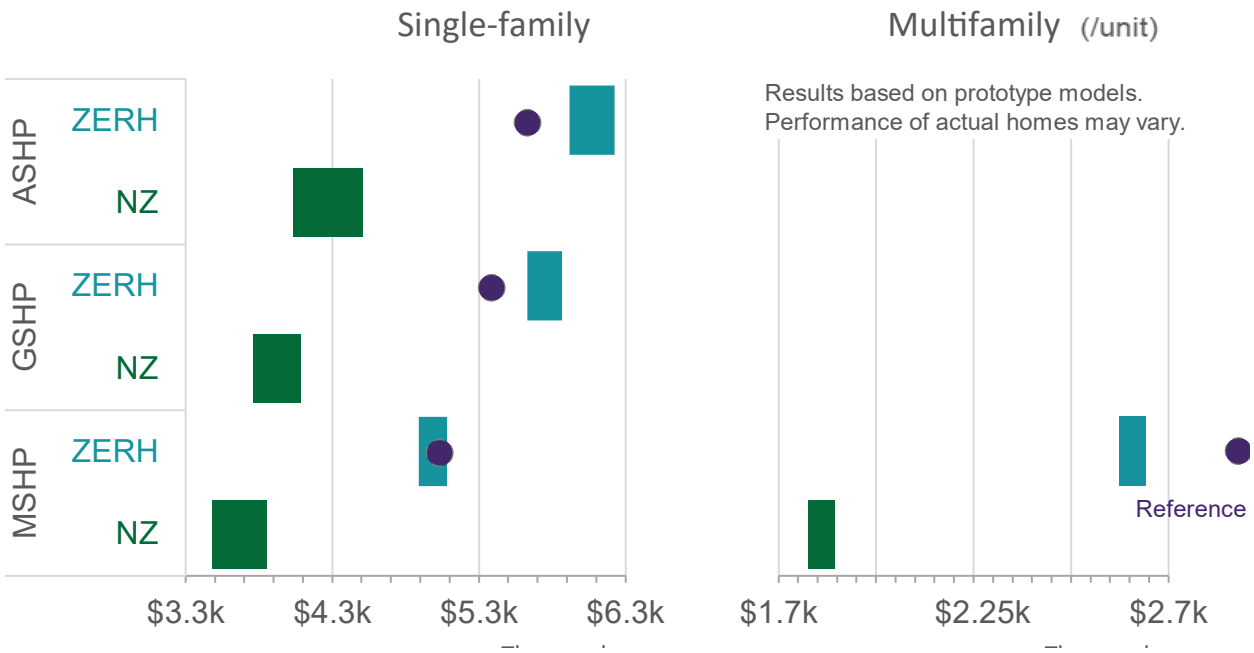
	Design	Construction Cost	First Year Cost	Annual Ownership Cost	Energy Savings
SF	ASHP	$44.8k [$8.8k]	$45.1k [$9.1k]	$44.9k [$8.9k]	$39.7k [$3.7k]
SF	GSHP	$35.7k [-$3.0k]	$36.0k [$0.0k]	$19.3k [-$16.7k]	$45.2k [$9.2k]
SF	MSHP	$39.0k [$3.0k]	$39.0k [$3.0k]	$36.4k [$4.0k]	$54.7k [$18.7k]
MF	MSHP	$34.4k [$0.0k]	$17.2k [$0.0k]	$17.2k [$0.0k]	$17.2k [$0.0k]

Long-Term Annual Ownership Costs

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.***

All Net-Zero packages (including solar panels) have lower long-term ownership costs than the Zero Energy Ready packages (without solar panels) (Figure 3). This is true not only for each design, e.g., Net-Zero vs. ZERH ASHP packages, but across the board. In other words, the optimized Net-Zero package with the highest annual ownership costs (an ASHP package) has lower annual ownership costs than *any* of the optimized ZERH packages, regardless of what mechanical system they use. This is the case even though the energy models in this study do not include net-metering. The differences in ownership cost between the Net-Zero and ZERH packages are starkest for ducted mechanical equipment, i.e., ASHP and GSHP designs.

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

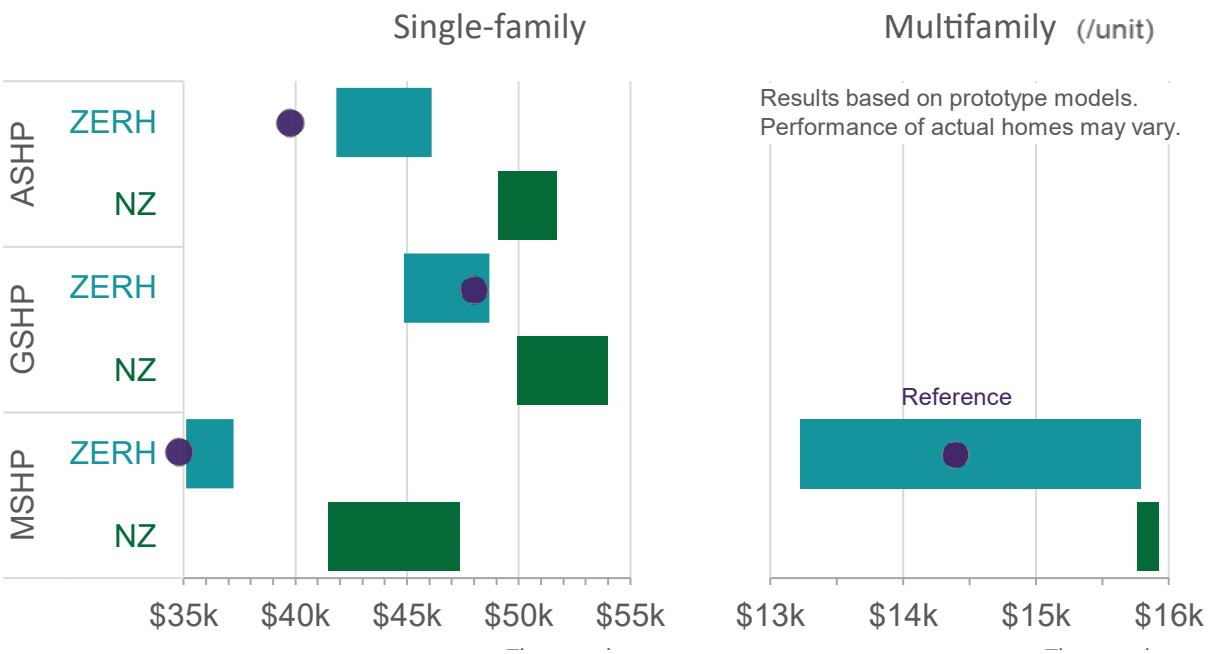


First Year Ownership Costs

Mini-split heat pump packages offer the lowest first-year ownership costs for single-family homes (Figure 4). When choosing among optimized packages, first year costs are higher for Net-Zero homes, but in the long-run, ownership costs are much lower (Figure 3).

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



KEY LIMITATIONS AND SOURCES OF UNCERTAINTY

The study relies on prototype homes, assumptions, and modeling. While this report uses reasonable assumptions, the performance and costs of a real home with differing floor plan, square footage, orientation, etc., will impact these reported estimates. This also applies to the use of HERS ratings instead of ERI, and the associated software. The models also account for replacement costs at the end of a measure's effective useful life, but the software used in this study cannot predict whether more efficient or cheaper versions of a measure will become available. It also cannot account for unforeseen fluctuations in energy or construction costs.

Reported costs do not include all construction-related costs. They cover building components directly impacting energy efficiency, such as exterior wall framing and insulation, but exclude other costs such as foundation excavation or utility connections (2.2). HERS rater costs are also excluded.

Program rebates and other incentives such as the 45L federal tax credit are not included factored into the actual energy models, but those incentives could potentially reduce the costs shown in this study. The PAs and EEAC consultants decided that modeling should exclude RNC program rebates and other available tax credits given that not all homes participate, and when they do, rebates are often treated as cost reductions after the fact. This is consistent with the Department of Energy Resources' work to develop the new code[4] and research from the Home Builders and Remodelers Association of Massachusetts,[5] as neither effort factored incentives into the energy modeling proper.

The defrayed costs of gas service are not credited to the all-electric homes described here. It is subjective whether or not the absence of gas utility connections, gas piping in the home, and monthly gas customer service charges should be counted as cost savings for an all-electric home. Therefore, no such credits are included in this report's results, although readers could consider those additional costs at their discretion.

Some provisions of the specialized code are not accounted for in this study. While the study's analysis accounts for air infiltration and heating and cooling use intensity Passive House requirements for large multifamily buildings, it does not consider the energy per occupant due to differences in assumptions between modeling systems. This metric also depends on occupant behavior and the selection of appliances, both of which are outside the scope of this study.

[4]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)
[5] 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)

RECOMMENDATIONS

Recommendation 1. As recommended in Phase 1 of this study, encourage integrated design and reduce barriers to the use of optimization modeling in the residential sector. This second phase of the 21R41 study continues to validate the results and recommendations of previous optimization research conducted for the Massachusetts PAs, which all show that optimization can benefit builders, homeowners, program administrators, and other emissions reduction advocates by reducing construction costs and energy consumption of new homes. Optimization would provide benefits across the new construction market. Modular and large-volume builders can generate substantial energy and cost savings at scale by incorporating these higher-efficiency practices into their standard practices, and small-scale builders can also use this guidance to keep their costs down and remain competitive. Case studies and additional marketing, training, and technical support may help bring these practices to a wider audience.

Recommendation 2. The RNC program should promote and support Passive House levels of performance for single- and multifamily construction projects. Passive House levels of performance are common in the optimized packages shown in this study. Passive House has also become integrated into the new versions of the Massachusetts energy code as a code-compliance option, particularly for multifamily homes. By aligning program eligibility/incentives with Passive House requirements and using the PAs' Codes and Standards Compliance and Technical Support Initiative (CSCS) to increase market actor facility with Passive House standards, the PAs can continue to support the RNC market's progress toward energy efficiency and decarbonization. As noted, case studies and additional marketing and training could help bring these practices to a wider audience.

Recommendation 3. Increase program support for HPWHs, even for multifamily. Unitary HPWHs have well-documented installation constraints. Accordingly, the study team is aware that multifamily design teams have reported challenges with including unitary HPWHs in their projects. In response, the study team included both unitary and split-system HPWHs among the tested measures. Split HPWHs cost more to install, but they avoid some of the installation challenges because the condenser is located outside of the home. The study showed that HPWHs were necessary to achieve high-performance all-electric multifamily homes. It also showed that split HPWHs could be cost-effectively installed in multifamily projects, providing a realistic alternative to unitary models. Building awareness and comfort with the cost-effective all-electric models here – including split HPWHs – could allow multifamily builders to cost-effectively build truly all-electric projects and remove the need for an RNC program carveout for less efficient fossil fuel or electric resistance water heaters.

CONSIDERATIONS FOR FUTURE RESEARCH

Consideration 1. If of interest to the PAs and EEAC, consider additional research to identify costs associated with meeting the requirements of specific incentive/tax credit programs. By design, this study did not force the optimized packages to comply with available incentive offerings, such as the federal 45L tax credits or the RNC program's Level 2 all-electric incentive. That said, the study team did make initial estimates of the incremental costs associated with changing specific packages in order to be eligible for incentives (see B.3,Incremental Impacts to Increase Incentives). The study team could conduct additional research to investigate the costs and performance of packages that comply with other incentive programs, or to specifically meet Passive House requirements and certification. For low effort, the team could modify the optimized packages included in this study to include any measures that an incentive program might require (e.g., re-running packages with higher-performance ENERGY STAR windows to make them eligible for DOE Zero Energy Ready certification and thus for 45L tax credits). For additional effort, the team could re-do the optimization modeling process from scratch, forcing specific measures to be included in the final packages. For any designs of interest, the latter approach would yield all new, optimized packages, rather than simply taking the packages included in this phase and tweaking them.

Section 1 Introduction and Background

This report presents results from the second phase of the residential new construction (RNC) Energy Optimization Code Compliance and Electrification Modeling study for the Massachusetts Program Administrators (PAs) and the Energy Efficiency Advisory Council (EEAC). It is a follow-up study to the Residential New Construction Energy Optimization Cost Study (20R23),[6] and this second phase of the study focuses on optimization modeling of **high-performance all-electric new homes in Massachusetts**. See the previous Phase 1 report for optimization modeling results supporting the PAs' code compliance efforts under the recently issued tenth edition of the Massachusetts building code.[7]

1.1 Goals

The study phase has two primary goals using energy optimization 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 build all-electric homes that cost-effectively comply with and even outperform the new Massachusetts energy codes.

1.2 Study Background

Traditionally, a home is considered Net-Zero (NZ) if on-site renewables produce at least as much energy per year as the home consumes. However, in the tenth edition of the state building code, the Department of Energy Resources has taken a broader perspective, in which NZ is closer to what some might think of as zero energy ready homes (ZERH), i.e., high-efficiency electrified homes. This would be Net-Zero if renewables were added, *or* the electric grid was 100% renewable. We explore optimizations for both styles of home in this report.

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

[7] This study exists alongside other related, optimization-based research. For example, PSD worked with the Massachusetts DOER to model scenarios to support development of the updated building code in 2020. https://www.mass.gov/lists/stretch-energy-code-development-support-documentation#residential-analysis-documents- (Accessed Sept. 2022). These scenarios include different home designs and assumptions compared to this study and its 2021 predecessor funded by the Massachusetts PAs, MA20R23. More recently, a study commissioned by the Home Builders and Remodelers Association of Massachusetts was published in 2023, using different assumptions and a distinctly different approach to calculating costs and compliance from this study or that of DOER/PSD. https://hbrama.com/wp-content/uploads/2023/05/Public-Policy-for-Net-Zero-Homes-and-Affordability-Final-6-14-23.pdf

1.3 NET-ZERO

These homes are optimized to include sufficient building shell and equipment improvements to become net-zero with the addition of an appropriate level of photovoltaics (2.4.1). As a result, the Net-Zero packages are substantially different from the ZERH packages (4.2). They have lower (better) ERI ratings even before considering the impact of solar panels because the optimization process found other improvements cheaper than PV when pushing a home to net-zero.

Note that, to comply with DPU guidance that the Massachusetts PAs' programs should support energy efficiency independent from any promotion of solar energy, the economic analyses of these packages ***do not include net-metering or renewables production capacity (SMART) incentives***. Consequently, the real-world annual ownership cost of Net-Zero Packages (Section 4) may be lower than reported here. We also created optimized packages without PV (ZERH) as another method of complying with this proviso.

1.4 ZERO-ENERGY READY

The Zero-Energy Ready homes (ZERH) outlined in this study include no-onsite energy generation. They are nearly compliant with DOE's Zero Energy Ready Home program version 2 requirements,[8] but generally require additional investments in efficiency (B.2) to achieve the full compliance necessary for federal tax credits, typically an upgrade to ENERGY STAR windows.

1.5 REPORT ORGANIZATION

This report is not intended to be read cover to cover. Notably, Section 3 and Section 4 are broken out by building design 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 overview of the modeling and analysis undertaken in this study, including key terms used in the report.
- Section 3 Zero-Energy Ready Packages: a description of optimized all-electric packages that comply with all Massachusetts codes but have do not include solar panels.
- Section 4 Net-Zero Packages: a description of the optimized all-electric packages that comply with all Massachusetts code and provide adequate on-site electricity to offset their annual energy consumption.
- Appendix A Methodology: a more in-depth review of the study's methodology, including economic and energy-related modeling inputs, how packages are selected, and so on.
- Appendix B Additional Details: additional analysis results.
- Appendix C Package Composition: an overview of measure options across packages.

[8] U.S. DOE. DOE Zero Energy Ready Home National Program Requirements. https://www.energy.gov/eere/buildings/doe-zero-energy-ready-home-zerh-program-requirements. Accessed January 31, 2024.

Section 2 Methodology Overview

The team used NREL's BEopt software to model hundreds of variations for each of four core building *designs*. The tool tests different combinations of enhancements to a core building design. These are evaluated to identify *packages* that are optimized to 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.*, ground-source heat pump). Table 4 describes the four designs examined in this study, which include three single-family homes and one multifamily building.

Table 4: Electrification (Phase 2) Designs

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

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

- ASHP; mini-split heat pump, ducted or ceiling cassettes (B.1)
- 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 that 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. These are comparable to the packages used in Phase 1.

R. The **Reference Package** is an unoptimized mixed-fuel home—it uses gas cooking and hot water—that is stretch code compliant with an ERI of approximately 42 (2.5).

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

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.

2. The **Ownership Cost Package** balances upfront construction and long-term ownership costs. It includes energy-efficiency upgrades and equipment replacements that exceed their initial upfront costs with utility bill savings over the life of a 30-year mortgage.

3. The **Energy Savings Package** prioritizes energy savings at the utility meter, regardless of upfront or operational costs, and would interest the eco-minded owner. This package does *not* represent the maximum technologically possible savings, rather it is the maximum among the tested combinations in this study.

Table 5: Summary of Factors Included in Optimized Package Selection

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

2.2 Costs Included in Analysis

The list below summarizes the values factored into the optimization modeling. For additional detail, see A.1.2.

- **Construction costs:** labor and materials costs of *energy-related measures* that could vary between packages (listed in Section 3 and Section 4; not every aspect of the home).
- **Material costs:** energy-efficiency related materials and supplies.
- **Labor costs:** for the construction and incorporation of energy-efficiency measures.
- **Utility bills:** the cost of metered electricity.
- **Mortgage:** a 30-year, fixed interest rate of 6.8%, limited to energy-related measures.
- **Ownership cost:** another name for the annualized energy-related costs (AERC) of a home. This is a holistic metric balances initial incremental costs of energy-efficiency upgrades with the lower utility bills that result over the mortgage period (30 years).
- **Replacement costs:** the costs to replace measures at the end of their effective life, particularly heating, cooling, and hot water equipment.

2.3 Incentives Excluded from Analysis

The optimization modeling in this study does not include rebates from the Mass Save RNC program or other incentives, such as those from the Inflation Reduction Act of 2022.[9] Nor does the analysis include any credits from renewable energy production, given the DPU's guidance on PA promotion of photovoltaics.

[9] Like the revisions to the Internal Revenue Code Section 45L, Tax Credits for Zero Energy Ready Homes, which provides tax credits for achieving ZERH status.

Eligibility for additional incentives. Table 6 describes the incentives each of the optimized Phase 2 packages might be eligible for; readers should note that these are current as of the time of this report and they are subject to change. Every optimized single-family home package should be eligible for the current $15,000 Level 1 all-electric home incentive from the Mass Save RNC program, and most could be eligible for the larger $25,000 Level 2 incentive.[10] Similarly, optimized multifamily packages should be eligible for Mass Save Passive House program, which offer a pay-for-savings incentive plus additional support of more than $3,000 per unit to defray certification and modeling costs.[11]

Currently, the federal 45L tax credit for Zero Energy Ready Homes offers $2,500 for ENERGY STAR Residential New Construction single-family homes and $500 per unit for ENERGY STAR Multifamily New Construction, or $5,000 for DOE Zero Energy Ready Homes.[12] However, as discussed in Zero-Energy Ready (1.4), most packages included in this study would require additional improvements to qualify for those tax credits.

Table 6: Estimated Package Incentive Eligibility as Modeled

			ZERH				Net-Zero			
		Optimization	Mass Save		45L		Mass Save		45L	
			Level 1	Level 2	ENERGY STAR	DOE ZERH	Level 1	Level 2	ENERGY STAR	DOE ZERH
Single-Family	ASHP	Construction	✓	–	–	–	✓	–	–	–
		First Year	✓	–	–	–	✓	–	–	–
		Ownership	✓	–	✓	–	✓	✓	✓	✓
		Energy	✓	–	–	–	✓	✓	✓	✓
	GSHP	Construction	✓	–	–	–	✓	✓	–	–
		First Year	✓	–	–	–	✓	✓	–	–
		Ownership	✓	–	–	–	✓	✓	–	–
		Energy	✓	✓	✓	–	✓	✓	–	–
	MSHP	Construction	✓	–	–	–	✓	–	–	–
		First Year	✓	–	–	–	✓	–	–	–
		Ownership	✓	✓	–	–	✓	✓	–	–
		Energy	✓	✓	✓	✓	✓	✓	✓	✓
Multifamily		Optimization	Mass Save		45L		Mass Save		45L	
			Passive House		ENERGY STAR	DOE ZERH	Passive House		ENERGY STAR	DOE ZERH
	MSHP	Construction	✓		–	–	✓		–	–
		First Year	✓		–	–	✓		–	–
		Ownership	✓		–	–	✓		–	–
		Energy	✓		–	–	✓		–	–

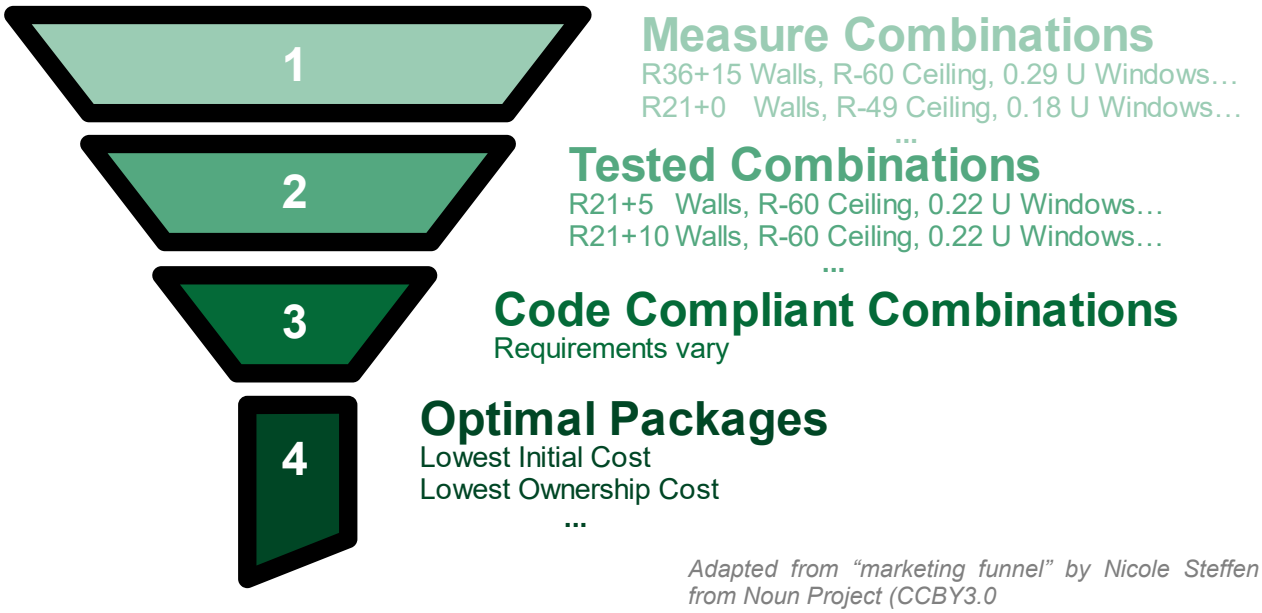
[10] Mass Save (2023). All-Electric Homes. https://www.masssave.com/en/residential/programs-and-services/new-home-construction/all-electric-home Accessed February 20, 2024.
[11] Mass Save (2024). Passive House Incentives. https://www.masssave.com/en/residential/rebates-and-incentives/passive-house-incentives Accessed February 20, 2024.
[12] U.S. Internal Revenue Service (2023). Notice 2023-65: Section 45L New Energy Efficient Home Credi. https://www.irs.gov/pub/irs-drop/n-23-65.pdf Accessed September 29, 2023.

To increase a home's eligibility for additional incentives, a builder or design team could move down the table to select a more energy-oriented package of the same design, and/or shift from a ZERH to a Net-Zero package. For example, a builder contemplating an ASHP construction cost-optimized ZERH package (eligible for the Mass Save Level 1 incentive), could instead move down and over to the NZ Ownership Cost-optimized package, which also meets Mass Save Level 2 and 45L tax credit criteria. See B.3 for additional details.

2.4 Optimized Package Selection

All packages in this report comply with the base, stretch, and specialized code variants.[13,14] They are the result of a multi-step filtering process summarized in Figure 5 to select the top performing combination of measures based on the optimization criteria described in 2.1.1. See A.2 for additional detail.

Figure 5: Package Selection Process



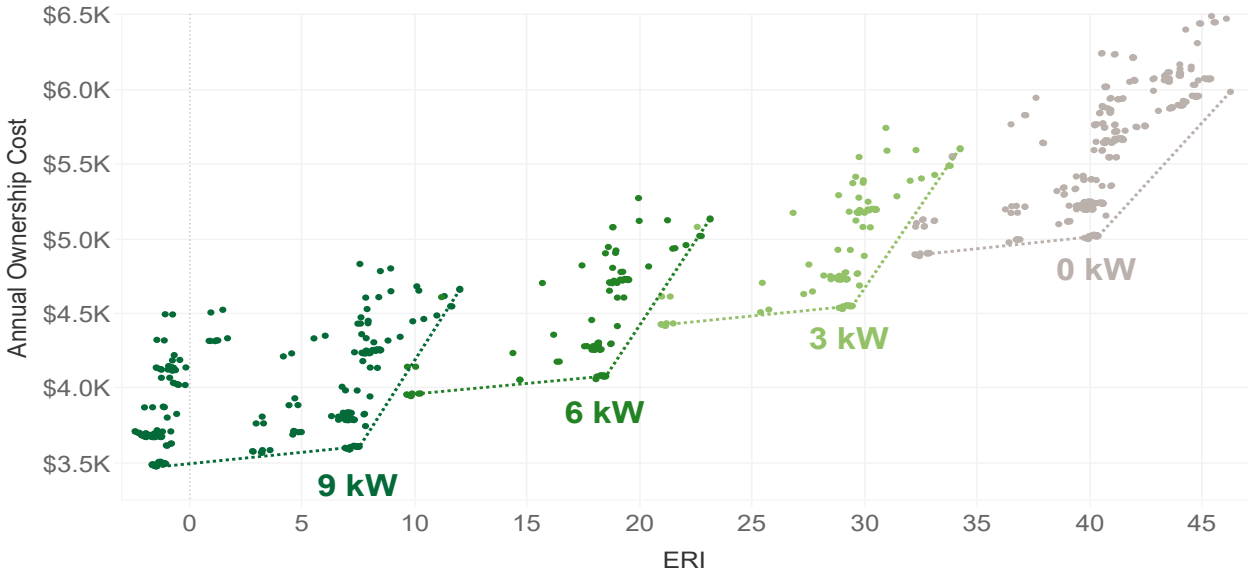
Adapted from "marketing funnel" by Nicole Steffen from Noun Project (CCBY3.0

[13] As in Phase 1, our analysis accounts for air infiltration, plus heating and cooling use intensity requirements. It does not consider the energy per occupant due to differences in modeling assumptions between tools. This metric is also highly dependent on occupant behavior and appliance selection, both of which are outside the scope of this study.
[14] Except for two first year cost multifamily package alternatives that are stretch code compliant (D3MW.Z0 and D3MW.N0), but not specialized code compliant (D3MW.Z0+ and D3MW.N0+). See 3.3.4 or 4.4.4 for details.

2.4.1 Photovoltaics

How BEopt incorporates solar into models. As shown in Figure 6, the first set of tested combinations (shown in grey) do not include solar panels. Similar to the question of building shell versus equipment trade-off explored in Phase 1, BEopt introduces PV to a home model once it becomes cost effective, i.e., it has the lowest annual ownership cost per kWh. It then selects the first solar panel option (3 kW for single-family, shown in light green) and continues to optimize the building, increasing the amount of PV as necessary until it meets its target or runs out of measure options. A consequence of this incremental approach means that the measure selections for ZERH and NZ homes (without and with PV respectively) differ by more than the simple addition of solar panels. These differences are summarized in Key Comparisons to Zero-Energy Ready Packages (4.2).

Figure 6: Photovoltaic Optimization (DCMW)



2.5 Reference Packages

Phase 2 reference homes are minimally compliant stretch code packages from Phase 1. This report uses the Phase 1, minimally compliant stretch code reference packages[15] (i.e., satisfying the ERI requirement of 42 for mixed-fuel homes) as the basis for energy and cost savings calculations. However, since this report includes updated Economic & Energy Distribution Parameters (A.1.1),[16] Phase 1 and 2 results are not directly comparable. Refreshed stretch code reference package costs (using the updated parameters) are included throughout this report, and Section B.4 summarizes how Phase 2 packages compare to the Phase 1 base code reference.

Phase 2 packages are all fully electric, but the references are mixed-fuel (A.1.6). The Phase 1 stretch code references reused in this report include gas cooking ranges and gas water heaters. Options for other key measures of the Phase 1 stretch code reference packages are provided in Table 7, with values identical to prescriptive path base code shown in italics.

Table 7: Stretch Code Reference Package Composition

Design	UCB	Walls	Win.	Attic	ACH_{50}	Heat Pump	Ducts	Vent.	DHW†
SF ASHP	R-38	R-21+15	0.22 U	R-49 ceil.	0.85	8.5 HSPF2/ 17.2 SEER	R-25‡	85% ERV	*0.67 UEF*
SF GSHP	*R-30*	*R-21+05*	*0.29 U*	R-60 roof	0.85	4.0 COP / 21.0 EER	R-8	75% ERV	*0.67 UEF*
SF MSHP	R-38	R-21+15	*0.29 U*	R-49 ceil.	1.50	11.6 HSPF2/ 29.2 SEER2	–	75% ERV	*0.67 UEF*
MF MSHP	R-38	R-21+15	*0.29 U*	*R-49 roof*	0.43	8.7 HSPF2/ 18.7 SEER2	–	85% ERV	0.95 UEF

† Measure values not mandated by stretch code but included in minimally compliant Phase 1 reference packages.
‡ R-25 is the equivalent R-value specified in the building code for deeply-buried ducts.

[15] DCAW.SR, DCGW.SR, DCMW.SR and D3MW.SR.
[16] The ASHP options were also updated in Phase 2, see B.1 for details.

Section 3 Zero-Energy Ready Packages

The following section describes the reference and optimized packages that are **Zero Energy Ready,**[17] and do **not include solar panels**. Net-Zero packages that *include solar panels* are described in the Section 4. The Executive Summary provides high-level comparisons of the ZERH and Net-Zero packages; additional detail can be found in Section 4.2.

This section presents the following information about ZERH packages:

- 3.1 Key Features of Optimized Zero Energy Ready Homes
- 3.2 Package Comparison by Optimization
- 3.3 Package Comparison by HVAC

3.1 Key Features of Optimized Zero Energy Ready Homes

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

Reinvest savings from employing R-49 attic insulation elsewhere. With only one exception, optimized packages employ only R-49 attic insulation, whereas prescriptive path base code specifies R-60.

Standard low-E, double-pane windows are usually sufficient. Like the 20R23 study and the previous phase of this study, few packages include high performance windows. Exceptions include the ASHP and GSHP packages with lowest ownership cost, as well as the MSHP package with the highest energy savings. However, window upgrades may be required to be eligible for the 45L federal tax incentive (B.2).

Pair mini-split systems with tight envelopes and more efficient ERVs. All optimized single- and multifamily MSHP packages reduced air leakage to Passive House levels (0.85 ACH_{50} for SF, 0.43 for MF).[18] In addition, the single-family MSHP packages include 85% efficient ERVs instead of the 75% efficient option.

Heat pump water heaters are helpful but not always necessary for ZERH. Half of the optimized single-family ZERH packages incorporate electric resistance water heaters, including all optimized GSHP packages. All remaining packages, including multifamily, employ HPWHs outside of the home's living space, either in an unconditioned basement or a split system.

Reduce ASHP duct leakage to minimize system losses. Every ZERH ASHP package incorporates a low-level of duct leakage (2% versus 4%) or moves the ductwork into conditioned space.

[18] There is an initial cost MF MSHP package that does not meet Passive House infiltration requirements, but it was specially created to provide a lower-cost option for stretch and Specialized (?) code communities.

3.2 Package Comparison by Optimization

Table 8 provides a ranking of the single-family packages when optimizing for different variables; in some cases, the rankings are quite tight. As a reminder, the study selected packages optimized based on the following four metrics:

- **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
- **Energy Savings:** energy consumption reported on utility bills

Table 8: Best Performing Single-Family ZERH Packages by Optimization Type

Rank	Efficiency Construction Cost	First Year Cost	Annual Ownership Cost	Energy Savings
First	MSHP	MSHP	MSHP	MSHP
Second	ASHP	ASHP	ASHP	GSHP
Third	GSHP	GSHP	GSHP	ASHP

Please also recall that, while this study focuses on all-electric homes, the reference home they are compared to is a minimally stretch code compliant mixed-fuel home. Like the majority of homes in the 19X02 Residential New Construction Baseline/Compliance Study, the reference package includes gas cooking and hot water, but an electric dryer (A.1.6).[19]

3.3 Package Comparison by HVAC

Reference and optimized packages include similar heat pump types. The reference packages in this section are for *homes of comparable 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 a ducted air-source heat pump (ASHP), though potentially of different efficiencies.

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 construction and first year cost packages. In such cases, the table that accompanies each figure will contain identical values and use symbols (✦ or ✿) to indicate that these packages are identical, and that the similarity in attributes values is not a coincidence.

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

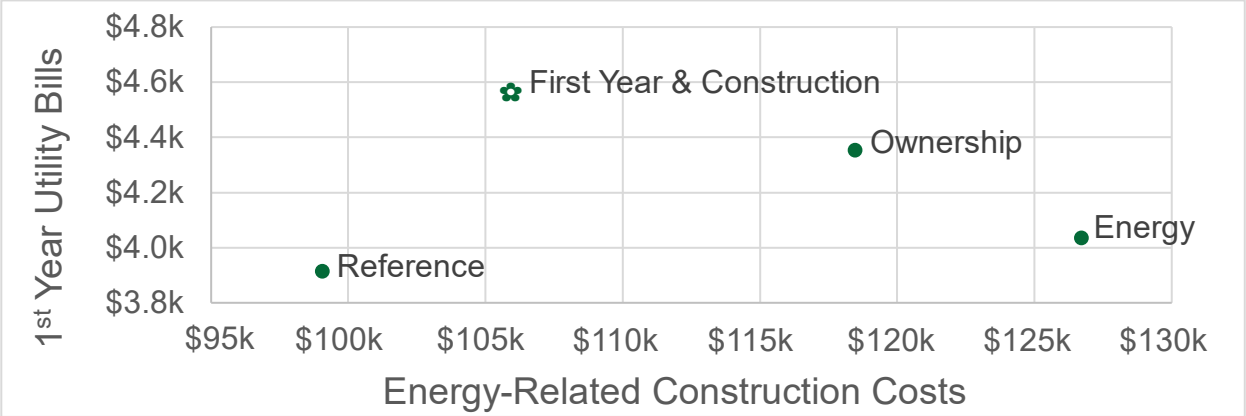
3.3.1 SF ASHP

This report uses ducted mini-split systems for its ASHP packages, unlike the Phase 1 report, which relied on conventional, centrally-ducted air source heat pumps. See B.1.2 for a comparison of the relative performance of these packages.

As shown in Figure 7 and Table 9, three unique combinations of options satisfied the optimization criteria of this study for ASHP homes. The construction/first year package (✿) includes a HPWH in the unconditioned basement, whereas the ownership package opts for a cheaper electric resistance unit and the energy savings package upgrades to a split-system HPWH.

Only the energy savings package includes double-stud walls, although the ownership cost package includes R-15 continuous insulation. The ownership package also stands out as the most like the reference package, maintaining the continuous wall insulation, Passive House levels of air leakage, ENERGY STAR windows, R-38 frame floor, and 85% ERV. It enhances this with a higher efficiency heat pump and ductwork located in a sealed attic, minimizing duct losses.

Figure 7: Single-Family Zero Energy Ready ASHP Packages (DCAW.Z)



The 12% and 20% respective increase in construction costs of the ownership and energy savings packages relative to the construction/first year cost package (✿) in Table 9 reduces annual costs of the ownership cost package by 5%, and 3.5% for the energy savings package. However, the ownership package saves 36% more energy than the construction/first year cost package, while the energy saving package saves nearly twice as much (87%).

Table 9: Single-Family Zero Energy Ready ASHP Package Details (DCAW.Z)

Optimization	ERI	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	42.1	0.0%	$99,100	$3,910	$39,400	$5,590	DCAW.SR
Construction✿	42.0	12.0%	$106,000	$4,570	$41,800	$6,230	DCAW.Z0
First Year✿	42.0	12.0%	$106,000	$4,570	$41,800	$6,230	DCAW.Z1
Ownership	42.3	16.3%	$118,500	$4,350	$44,700	$5,920	DCAW.Z2
Energy	37.9	22.4%	$126,700	$4,040	$46,100	$6,020	2CAW.Z3

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

3.3.2 SF GSHP

As shown in Figure 8 and Table 10, unique combinations of measure options satisfy each of the four optimization criteria. All of them deeply bury ducts and pair a 21.0 EER GSHP with a 75% recovery ERV.

The ownership package stands out as the only one of the four to include Passive House-levels of air infiltration, double-stud walls, and triple-pane windows. Doing so increases savings by 22 percentage points in exchange for a 2% increase in construction costs compared to the reference home—a highly favorable return on investment. Compared to the optimized construction package, it increases savings by 8 percentage points for a 15% higher construction cost.

The energy savings package might be the optimal investment even among all optimized packages, as it more than doubles savings compared to the construction and first-year packages for only 6% greater construction costs. Compared to the ownership package, it increases savings by seven percentage points while decreasing construction costs eight percentage points.

Figure 8: Single-Family Zero Energy Ready GSHP Packages (DCGW.Z)

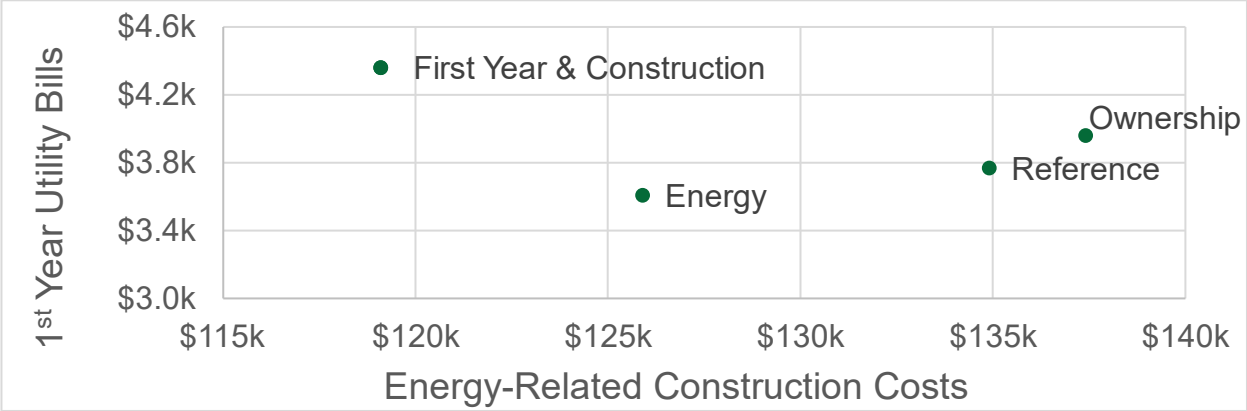


Table 10: Single-Family Zero Energy Ready GSHP Package Details (DCGW.Z)

Optimization	ERI	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	41.6	0.0%	$134,900	$3,770	$48,200	$5,380	DCGW.SR
Construction	41.9	13.6%	$119,100	$4,360	$44,900	$5,870	DCGW.Z0
First Year	41.9	13.7%	$119,100	$4,360	$44,900	$5,860	DCGW.Z1
Ownership	38.1	21.7%	$137,400	$3,960	$48,700	$5,630	2CGW.Z2
Energy	33.7	28.8%	$125,900	$3,610	$45,800	$5,710	DCGW.Z3

3.3.3 SF MSHP

As shown in Figure 9 and Table 11, unique combinations of measure options satisfy each of the four optimization criteria for single-family MSHP homes. All of them reduce infiltration to Passive House standards (0.85 ACH_{50}), add extra continuous wall insulation (R-10 or R-15), and include high-performance 85% recovery ERVs.

While the packages are relatively similar, the ownership and energy savings packages include a HPWH in place of an electric resistance water heater, and the energy savings package upgrades to ENERGY STAR windows.

Opting for either the ownership or energy savings package nearly doubles savings compared to the construction or first year packages, increasing savings by 15 percentage points (nearly twice as much savings) in exchange for 10% and 14% higher construction costs than the construction and first-year packages, respectively.

Figure 9: Single-Family Zero Energy Ready MSHP Packages (DCMW.Z)

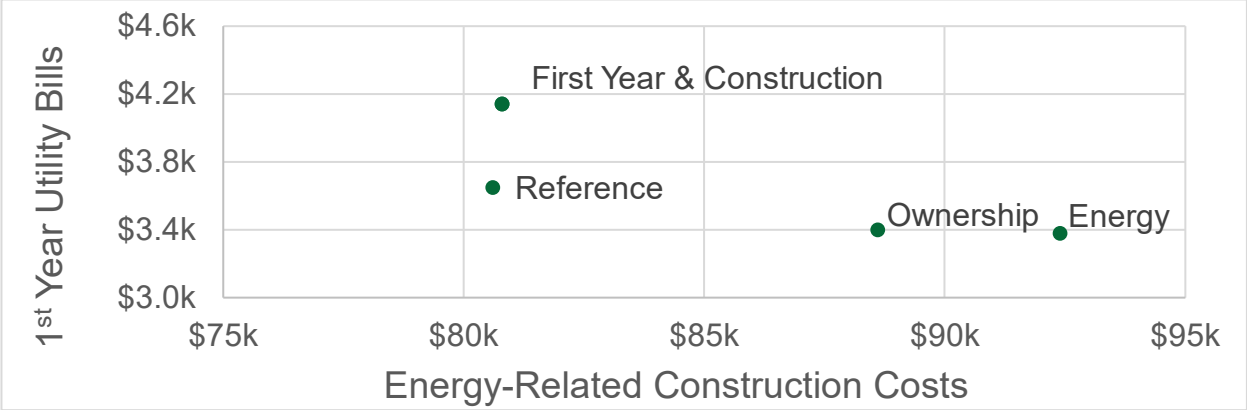


Table 11: Single-Family Zero Energy Ready MSHP Package Details (DCMW.Z)

Optimization	ERI	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	*41.2*	*0.0%*	*$80,600*	*$3,650*	*$34,600*	*$5,010*	DCMW.SR
Construction	40.3	16.1%	$80,800	$4,140	$35,100	$5,020	DCMW.Z0
First Year	40.2	16.2%	$80,800	$4,140	$35,100	$5,020	DCMW.Z1
Ownership	32.4	31.3%	$88,600	$3,400	$36,300	$4,890	DCMW.Z2
Energy	32.2	31.8%	$92,400	$3,380	$37,200	$5,080	DCMW.Z3

3.3.4 MF MSHP

Heat pump water heaters are required to cost-effectively construct all-electric multifamily buildings (A.1.6.6), reducing the 26-unit apartment building's ERI by the same amount as 40 kW of PV.

As shown in Figure 10 and Table 12, there is considerable overlap among optimized packages. The specialized code construction (D3MW.Z0+) and first year packages are identical (✿), as are the ownership and energy savings packages (✦). The stretch code construction cost package (D3MW.Z0-) only differs from its specialized counterpart in the acceptance of a looser envelope - 1.5 ACH_{50} rather than the Passive House levels of 0.43 ACH_{50} required by specialized code. Similarly, the sole distinguishing feature of the ownership/energy savings package (✿) is increased wall sheathing of R-15, compared to the R-5 of other packages.[20]

Figure 10: Multifamily Zero Energy Ready MSHP Packages, per Building (D3MW.Z)

Optimization yields affordable ZERH multifamily options. *Every ZERH optimized multifamily package in this phase of the study costs less to construct and operate than the Phase 1 stretch code reference package.* In fact, the ZERH stretch code construction cost package is cheaper to construct than most of the mixed-fuel multifamily packages in Phase 1.

Table 12: MF Zero Energy Ready MSHP Package Details, per Building (D3MW.Z)

Optimization	ERI	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	*40.6*	*0.0%*	*$826.0k*	*$57.4k*	*$372.8k*	*$75.2k*	D3MW.SR
Construction-	37.6	21.1%	$689.6k	$58.3k	$409.8k	$68.7k	D3MW.Z0-
Construction✿	36.3	22.9%	$697.5k	$57.0k	$410.4k	$67.2k	D3MW.Z0+
First Year✿	36.3	22.9%	$697.5k	$57.0k	$410.4k	$67.2k	D3MW.Z1
Ownership✦	36.0	23.9%	$714.6k	$56.3k	$343.8k	$66.9k	D3MW.Z2
Energy✦	36.0	23.9%	$714.6k	$56.3k	$343.8k	$66.9k	D3MW.Z3

✿✦Packages with identical symbols include the same combination of measure options.
+/- Multifamily packages in specialized code communities require lower (better) levels of air leakage to comply with Passive House (D3MW.Z0+), whereas code compliant stretch code packages (D3MW.Z0-) are possible with higher (worse) levels of infiltration.

[20] For this particular MF set of packages, the study team identified a version that was compliant with the stretch code and a separate package that was compliant with the specialized code, just to increase the options available to builders.

Section 4 Net-Zero Packages

The following section describes the reference and optimized packages that are **Net-Zero**, or near Net-Zero. These are packages modeled **with solar panels, but without net-metering.** This section presents the following for minimally Net-Zero compliant packages:

- 4.1 Key Features of Optimized Net-Zero Homes
- 4.2 Key Comparisons to Zero-Energy Ready Packages
- 4.3 Package Comparison by Optimization
- 4.4 Package Comparison by HVAC

Note: Some packages may have positive utility bills and less than 100% savings despite an ERI of less than one. Due to various assumptions or treatment of measures like thermostats required by the ANSI standards for ERI calculations, the ERI models may not be net-importers of electricity from the grid even though the models used to calculate energy savings are small net-importers. In addition, Net-Zero homes would still have monthly electric bills due to account service fees.

4.1 Key Features of Optimized Net-Zero Homes

Tighten the building envelope as much as possible, coupled with efficient mechanical ventilation. Every Net-Zero package reduces air leakage to Passive House levels (0.85 ACH_{50} for SF, 0.43 for MF).[21] In addition, every single-family package includes 85% efficient ERVs.

Spray foam is not necessary to comply with Net-Zero. Very few optimized packages include any spray foam-insulated major assemblies. The few instances of foam insulation in optimized Net-Zero packages include the walls of the multifamily energy savings package and the roof of the single-family GSHP energy savings package.

R-49 attic insulation is sufficient unless maximizing cost-optimized savings. With few exceptions, optimized single-family packages favored R-49 attic insulation, compared to the R-60 of prescriptive base code. The outliers are the energy savings packages for each design (2CAW.N3, DCGW.N3, 2CMW.N3), and the ASHP package optimized for lowest ownership cost (2CAW.N2).

Choose triple-pane windows only when focusing on minimizing ownership costs or maxing out savings. Like the 20R23 study and the first phase of the 21R41 study, few packages upgrade to high-performance triple-pane windows from the more typical 0.29U, double-pane baseline. Exceptions are the ASHP packages with the lowest ownership cost (2CAW.N2), as well as the ASHP and MSHP packages with the highest energy savings (2CAW.N3 and 2CMW.N3).

[21] There is an initial cost MF MSHP package that does not meet Passive House infiltration requirements, but it was specially created to provide a lower-cost option for stretch code communities.

4.2 Key Comparisons to Zero-Energy Ready Packages

The study also compared optimized Net-Zero packages with Zero-Energy Ready packages optimized for the same parameter e.g., NZ energy savings MSHP versus ZERH energy-savings MSHP. Other than the single-family site energy optimization (DCMW.N2) package, Net-Zero MSHP packages are largely unchanged from ZERH, whereas Net-Zero GSHP and ASHP packages are substantially different from ZERH versions. These differences are evidence that optimization that targets Net-Zero compliance yields more efficient homes than simply adding solar panels to a ZERH package.

The following list summarizes various improvements optimized Net-Zero packages frequently include to surpass the optimized ZERH packages described in the previous section.

Improve the recovery efficiency of mechanical ventilation. All four NZ GSHP packages and three of four NZ ASHP packages include 85% recovery efficiency mechanical ventilation systems versus the 75% efficient option used for ZERH.

Bump ASHP efficiency up to 9.2 HSPF2/19.3 SEER2 (11.7HSPF/20.3 SEER). Bump ASHP efficiency up to 9.2 HSPF2/19.3 SEER2 (11.7 HSPF/20.3 SEER). For the most part, HVAC systems remained the same between NZ packages and their ZERH counterparts. The notable exception is ASHP, where three of four NZ packages called for a higher-efficiency model.

Opt for higher-efficiency heat pump water heaters. 75% of NZ packages include more efficient HPWH than the equivalent ZERH package.

Add wall insulation. Two thirds of NZ packages (every NZ ASHP package, three GSHP packages, and one MSHP package) increase the amount of wall insulation compared to their ZERH equivalents.

Reduce air infiltration in ASHP and GSHP homes. Applies to ASHP and GSHP only: for three of the four optimized packages for each of the ASHP and GSHP designs, NZ versions improve the performance air leakage rate of building shell to SF Passive House standards.

Increase basement insulation. Five ZERH packages include R-30 frame floor insulation, whereas 100% of NZ packages employ R-38. Similarly, the majority of optimizations that included R-15 continuous insulation in the conditioned basement for the ZERH package have upgraded to R-21 cavity with twenty-four inch on-center framing.

All optimized packages converge on the same level of renewable energy. Although three sizes of solar installation were available to the energy model, each optimized single-family package includes 9 kW of generation (approx. $36,000). Similarly, every Net-Zero multifamily package employs 120 kW (approx. $447,000) of solar power.

4.3 Package Comparison by Optimization

Table 13 provides a ranking of how the single-family packages perform when optimizing for different variables. As a reminder, the study selected packages optimized based on the following four metrics:

- **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
- **Energy Savings:** energy consumption reported on utility bills

Table 13: Best Performing Single-Family NZ Packages by Optimization Type

Rank	Eff. Construction Cost	First Year Cost	Annual Ownership Cost	Energy Savings†
First	MSHP	MSHP	MSHP	MSHP
Second	ASHP	ASHP	GSHP	ASHP
Third	GSHP	GSHP	ASHP	GSHP

† Versus reference home of the same design, i.e., the same HVAC type. GSHP reference home energy consumption cost is low enough, and construction cost high enough, that this design has less room for cost-effective optimization than MSHP.

Please also recall that while this study focuses on all-electric homes, the reference home they are compared to is a minimally stretch code compliant mixed-fuel home. Like the majority of homes in the 19X02 Residential New Construction Baseline/Compliance Study, the reference package includes gas cooking and hot water, but an electric dryer (A.1.6).[22]

4.4 Package Comparison by HVAC

Reference and optimized packages include similar heat pump types. The reference packages in this section are for *homes of comparable 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 a ducted air-source heat pump (ASHP), though potentially of different efficiencies.

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 construction and first year cost packages In such cases, the table that accompanies each figure will contain identical values, and symbols (✦ or ✿) are used to indicate that these packages are identical, and that the similarity in attributes values is not a coincidence.

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

4.4.1 SF ASHP

Each of the distinct optimization packages shown in Figure 11 include Passive House levels of infiltration (0.85 ACH_{50}) paired with 85% recovery ERVs. The primary difference between the construction and first year cost packages is a reduced level of duct leakage in the first-year cost package. The approximately $400 investment to cut duct leakage, from 4 CFM_{25} per 100 ft^2 CFA to 2 CFM_{25}, increases energy savings by 0.3 percentage points while saving $10 per year on electricity (Table 14).[23]

Both the ownership cost and energy savings packages include double-stud walls. In fact, the latter is the sole package in the study to employ an offset frame wall method of construction (described in A.1.5.2). The construction and first year packages paired single-stud walls with R-15 continuous insulation. Other distinguishing features of the ownership and energy savings packages are triple-pane windows and R-60 attic insulation, rather than double-pane and R-49, respectively. However, the ownership and energy savings packages incur hefty increases in upfront costs (9% and 20%) for relatively small boosts in savings of 3 and 5 percentage points, and moderate 10% and 11% decreases in annual ownership costs relative to the construction cost package.

Figure 11: Single-Family Net-Zero ASHP Packages (DCAW.N)

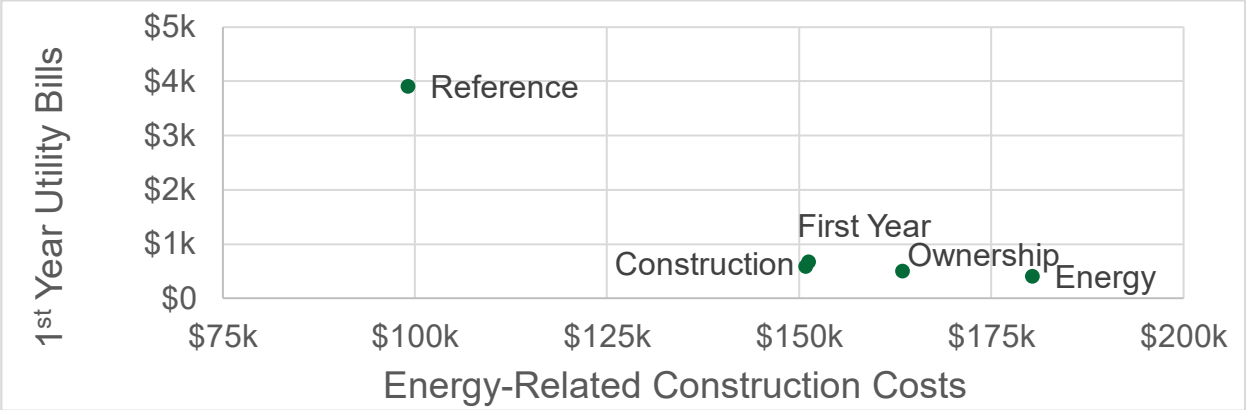


Table 14: Single-Family Net-Zero ASHP Package Details (DCAW.N)

Optimization	ERI	ERI w/o PV	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	*42.1*	*42.1*	*0.0%*	*$99,100*	*$3,910*	*$39,400*	*$5,590*	DCAW.SR
Construction	0.9	35.4	88.2%	$150,800	$690	$49,100	$4,510	DCAW.N0
First Year	0.9	35.3	88.5%	$151,200	$680	$49,200	$4,500	DCAW.N1
Ownership	-0.5	33.9	91.7%	$163,400	$510	$51,700	$4,040	2CAW.N2
Energy	-1.2	33.1	93.7%	$180,300	$410	$49,200	$4,070	2CAW.N3

[23] As previously noted, this report uses ducted mini-split systems for its ASHP packages, unlike the Phase 1 report, which relied on conventional, centrally-ducted air source heat pumps. See B.1.2 for a comparison of the relative performance of these packages.

4.4.2 SF GSHP

As shown in Figure 12 and Table 15, unique combinations of measure options for single-family GSHP homes satisfied each of the four optimization criteria of this study. All of them reduce infiltration to Passive House standards (from 3 to 0.85 ACH_{50}) and include 85% recovery ERVs. The ownership and energy savings packages upgrade continuous insulation from R-10 to R-15.

The energy savings package places ducts in a sealed attic, but this is likely not an optimal investment compared to the ownership cost package. The difference in energy savings is less than one percentage point for nearly 10% greater construction costs, higher annual ownership costs, and little to no reduction in utility bills.

Figure 12: Single-Family Net-Zero GSHP Packages (DCGW.N)

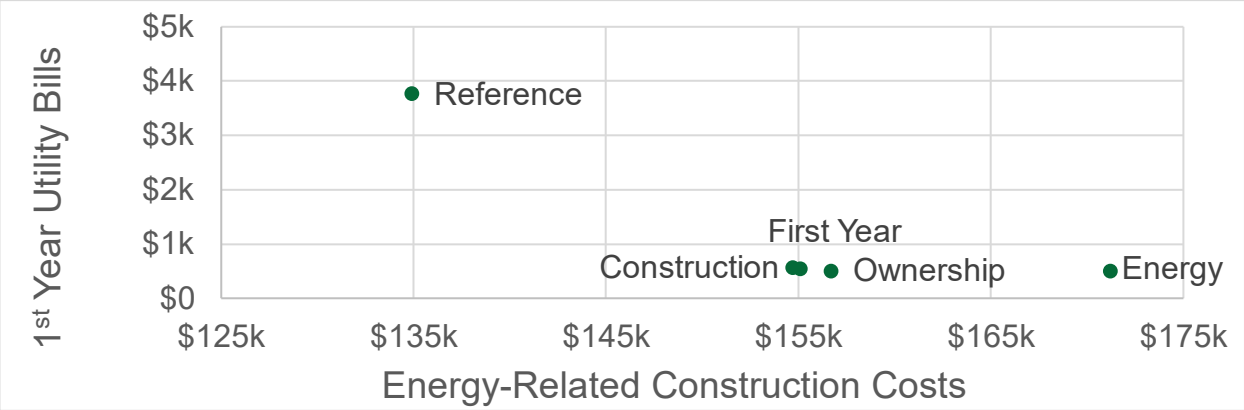


Table 15: Single-Family Net-Zero GSHP Package Details (DCGW.N)

Optimization	ERI	ERI w/o PV	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	*41.6*	*41.6*	*0.0%*	*$134,900*	*$3,770*	*$48,200*	*$5,380*	DCGW.SR
Construction	0.1	36.8	90.3%	$154,700	$570	$49,900	$3,770	DCGW.N0
First Year	0.0	36.8	90.5%	$155,100	$550	$50,000	$3,760	DCGW.N1
Ownership✿	-1.1	32.4	91.3%	$156,700	$510	$50,400	$3,760	DCGW.N2
Energy	-1.1	31.4	91.5%	$171,200	$510	$54,000	$4,090	DCGW.N3

4.4.3 SF MSHP

As shown in Figure 13 and Table 16, three unique combinations of measure options satisfied the optimization criteria of this study for single-family MSHP homes. All packages reduce infiltration to Passive House standards (0.85 ACH_{50}) and include 85% recovery ERVs. Compared to the unconditioned basement HPWH of the construction/first year packages (✿), the ownership and energy savings include a higher-efficiency split-system HPWH (3.2 UEF versus 3.7).

The energy savings optimization was the only MSHP package to include double-stud walls, while the others paired single-stud walls with continuous insulation. It was also the only package to use R-60 attic insulation instead of R-49. However, the energy savings package is not an optimal investment compared to the ownership cost package, given that the three-percentage point increase in savings relative to the reference package is accompanied by an 18% increase in construction cost and 11% increase in annual ownership cost.

Figure 13: Single-Family Net-Zero MSHP Packages (DCMW.N)

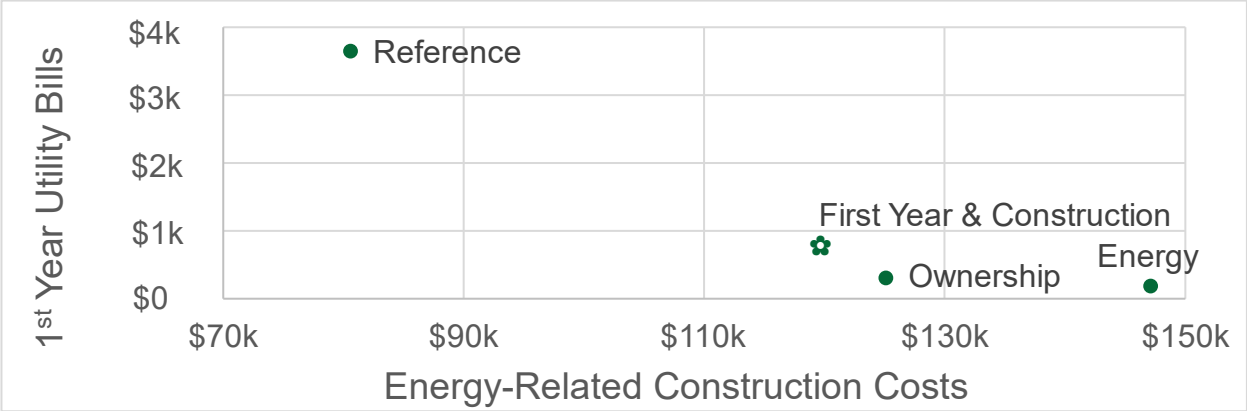


Table 16: Single-Family Net-Zero MSHP Package Details (DCMW.N)

Optimization	ERI	ERI w/o PV	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	*41.2*	*41.2*	*0.0%*	*$80,600*	*$3,650*	*$34,600*	*$5,010*	*DCMW.SR*
Construction✿	3.6	36.8	84.1%	$119,800	$790	$41,500	$3,590	DCMW.N0
First Year✿	3.6	36.8	84.1%	$119,800	$790	$41,500	$3,590	DCMW.N1
Ownership	-1.5	32.4	95.3%	$125,100	$310	$42,300	$3,480	DCMW.N2
Energy	-2.5	31.4	97.9%	$147,100	$190	$47,300	$3,850	2CMW.N3

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

4.4.4 MF MSHP

The composition of every Net-Zero multifamily package is identical to the equivalent ZERH package, except for the addition of 120 kW of solar panels. Further discussion of the measure differences between package optimization levels is available in 3.3.4.

Table 17 provides a summary of these solar-enhanced packages, revealing that the 60% increase in construction cost (from the cost of the solar panels) compared to the solar-free ZERH versions of these packages results in the Net-Zero packages having operating costs, which are 30% lower.

Figure 14: Multifamily Zero Energy Ready MSHP Packages, per Building (D3MW.N)

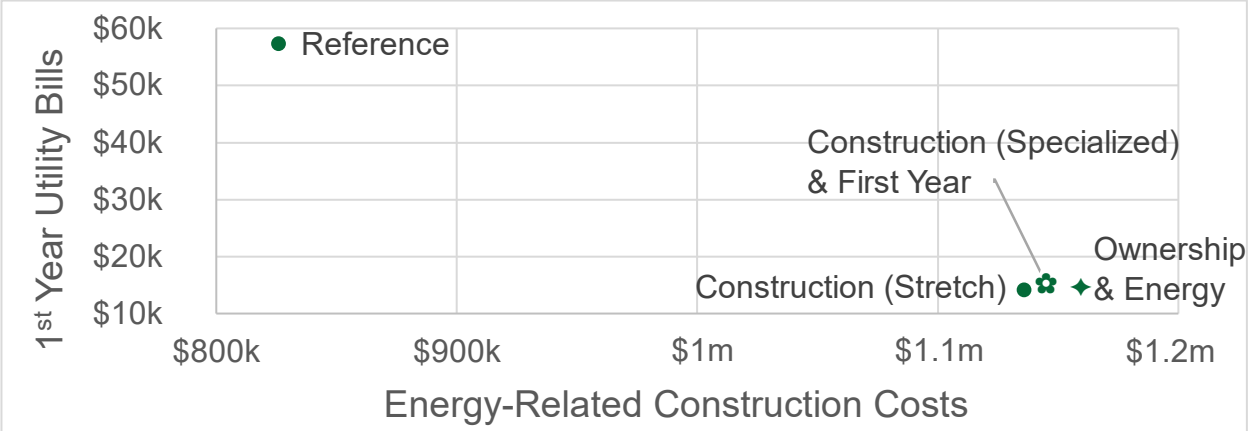


Table 17: MF Net-Zero MSHP Package Details, per Building (D3MW.N)

Optimization	ERI	ERI w/o PV	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
Reference	40.6	40.6	0.0%	$826k	$57.4k	$372.8k	$75.2k	D3MW.SR
Construction-	-0.8	37.6	78.8%	$1,136k	$17.3k	$409.8k	$48.0k	D3MW.N0-
Construction✿	-2.1	36.3	80.7%	$1,144k	$16.0k	$410.4k	$46.5k	D3MW.N0+
First Year✿	-2.1	36.3	80.7%	$1,144k	$16.0k	$410.4k	$46.5k	D3MW.N1
Ownership✦	-2.4	36.0	81.7%	$1,161k	$15.3k	$414.0k	$46.2k	D3MW.N2
Energy✦	-2.4	36.0	81.7%	$1,161k	$15.3k	$414.0k	$46.2k	D3MW.N3

✿✦ Packages with identical symbols include the same combination of measure options.
+/- Multifamily packages in specialized code communities require lower levels of air leakage to comply with Passive House (D3MW.N0+), whereas code compliant stretch code packages (D3MW.N0-) are possible with higher levels of infiltration.

Appendix A Methodology

This section describes the model inputs used to assess home performance, and how high-performing homes were selected from the hundreds of explored scenarios.

A.1 Model Inputs

A.1.1 Economic & Energy Distribution Parameters

Table 18: Modeled Parameters

Parameter	Value	Parameter	Value
Annual Inflation	2.36%[24]	Analysis Period (years)	30
Discount Rate (Real)	2.00%[25]	Mortgage Period (years)	30
Electricity Rate ($/kWh)	$0.277[26]†	Mortgage Down Payment	20.00%
Electricity Rate Escalation	0.30%[26]	Mortgage Interest Rate	6.8%[27]
Materials Multiplier	1.352[28]†	Marginal Income Tax, Fed	24.00%[29]
Labor Multiplier	1.590[30]†	Marginal Income Tax, MA	5.00%
Source: Site, Electricity	2.016[31]	CO_2 Emissions, Electricity (lb./kWh)	0.334[32]

† Adjusted for inflation between data publication and the start of Phase 2 in October 2023.

[24] 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 Aug. 2023)
[25] U.S. EPA, (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)
[26] U.S. Energy Information Administration (2023). Electricity sales to ultimate customer by state and sector (number of customers, average price, revenue, and megawatt hours of sales) [Monthly]. https://www.eia.gov/opendata/browser/electricity/retail-sales?frequency=monthly&data=price;&facets=stateid;sectorid;&stateid=MA;&sectorid=RES;&start=2020-01&end=2023-01&sortColumn=period;&sortDirection=desc; (Accessed Aug. 2023)
[27] 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).
[28] U.S. BEA. (Dec. 2020). Real Personal Income by State and Metropolitan Area, 2021. https://www.bea.gov/news/2022/real-personal-consumption-expenditures-state-and-real-personal-income-state-and (Accessed Aug. 2023)
[29] Income required to purchase median new home varies from $83k–$298k among core-based statistical areas in MA. Corresponding marginal federal income tax rates after standard deduction range from 22–35%. Rate for Worcester: 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. 2022) and U.S. IRS, (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. 2022)
[30] CareerOneStop Salary Finder [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)
[31] Time weighted avg. 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.], 9.7% transmission/distribution losses. [“Appendix 2b-2019 PYR Eversource Electric BCR Model” provided by PAs.]
[32] Long term average (2023–2050) of emissions factors forecast by Navigant (Mar. 2020) MA MMBTU Factors Study.

A.1.1.1 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.
- Discount Rate; Used in calculating cost of cash flows over project analysis period for various economic metrics; nominal rate = (1 + real discount rate) × (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 generation inefficiency and distribution losses.
- Source: Site, Natural Gas; This ratio is used to convert modelled gas savings at the meter into source energy. This accounts for distribution losses.
- CO2 Emissions, Electricity; The average projected combustion emissions intensity for electricity generation in New England from 2023 to 2050.[32]
- This report does not include emissions results, nor were emissions included in the Phase I optimization process.

A.1.2 Costs Included in Analysis

Construction costs: the labor and materials costs of *energy-related measures* that could vary between packages listed in Section 3 and Section 4 (not every aspect of the home).

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

Other aspects of the home that 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)[33] or in-home distribution systems, such as wiring or plumbing[34]
- 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 2023.

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.

[33] 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.

[34] 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 Massachusetts 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.

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 ground source heat pump typically requires labor for ductwork that is not required for MSHPs.

Utility bills represent the cost of metered electricity, including variable and fixed costs (consumption and service fees, respectively). The price of electricity is the most recent average available from the EIA at the time of modeling, with an annual electric rate escalation of 0.3%. Defrayed monthly gas customer service charges (currently about $130/yr) are not credited to the all-electric home, since such adjustments may be inappropriate for some readers' needs.

Mortgage in this study is a standard 30-year arrangement, with a fixed interest rate of 6.8%. 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.

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 that includes the net present value of the mortgage, mortgage interest tax deduction,[35] 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 cannot consider factors such as whether more efficient or cheaper versions of these systems will become available.

A.1.3 Rebates and Incentives Excluded from Analysis

Readers should note that this study does not include rebates from the Mass Save RNC program or other incentives, such as those that may be available through the Inflation Reduction Act of 2022.[36] However, it does include federal income tax deductions for mortgage interest.[35] Ultimately, the PAs and EEAC consultants decided to exclude incentives from modeling, considering the following factors:

[35] Since BEopt only models energy-related features, the deduction rarely exceeds $3,000, and is typically about $1,400.
[36] Like the revised 45L, Tax Credits for Zero Energy Ready Homes.

- The small but predictable impact incentives have on package composition and total energy savings 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,[37] and a recent study commissioned by the Home Builders and Remodelers Association of Massachusetts.[38]

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 Energy Savings.

A.1.4 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 19: 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

[37] 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)
[38] 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)

A.1.5 Building Shell Measure Options

Reference home options of Phase 1 stretch code packages vary by design, see 2.5 for specifics.

Component	Option 1	Option 2	Option 3	Option 4
Air Leakage	~~3.0 ACH_{50}~~ ~~Not used, based on Phase 1 results~~	1.5 ACH_{50}	Passive House SF: 0.85 ACH_{50} MF: 0.43 ACH_{50}	–
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	R-20 XPS[1], Continuous	–
Unfinished Basement	R-30 FGB, Grade I Ceiling	R-38 FGB, Grade I Ceiling	–	–
Exterior Walls, Single Stud	R-21 FGB, 2×6×16, Grade I	R-21 FGB, 2×6×24,[3] Grade I	R-36 Closed Cell, 2×6×24,[3] Grade I	–
Exterior Walls, Double stud (SF)	R-26 Blown-in + R-13 Closed Cell, 2×4×20,[4] Grade I	R-38 Blown-in+ R-13 Closed Cell, 2×4×20,[4] Grade I	R-21 Blown-in+ R-29 Closed Cell offset frame, 2×6×24, 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, 2×6×24,[3] Grade I	–	–	–
Wall Sheathing[4]	OSB (Double-stud only)	OSB + R-5	OSB + R-10	OSB + R-15
Windows	0.29 U 0.35 SHGC	0.22 U (EnergyStar v.7) 0.29 SHGC	0.18 U 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 (IRC)—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. The IRC requires 2×4×16 studs for the ground floor of a two-story building. Twenty inches is the average spacing of both floors.

A.1.5.1 Insulation Types

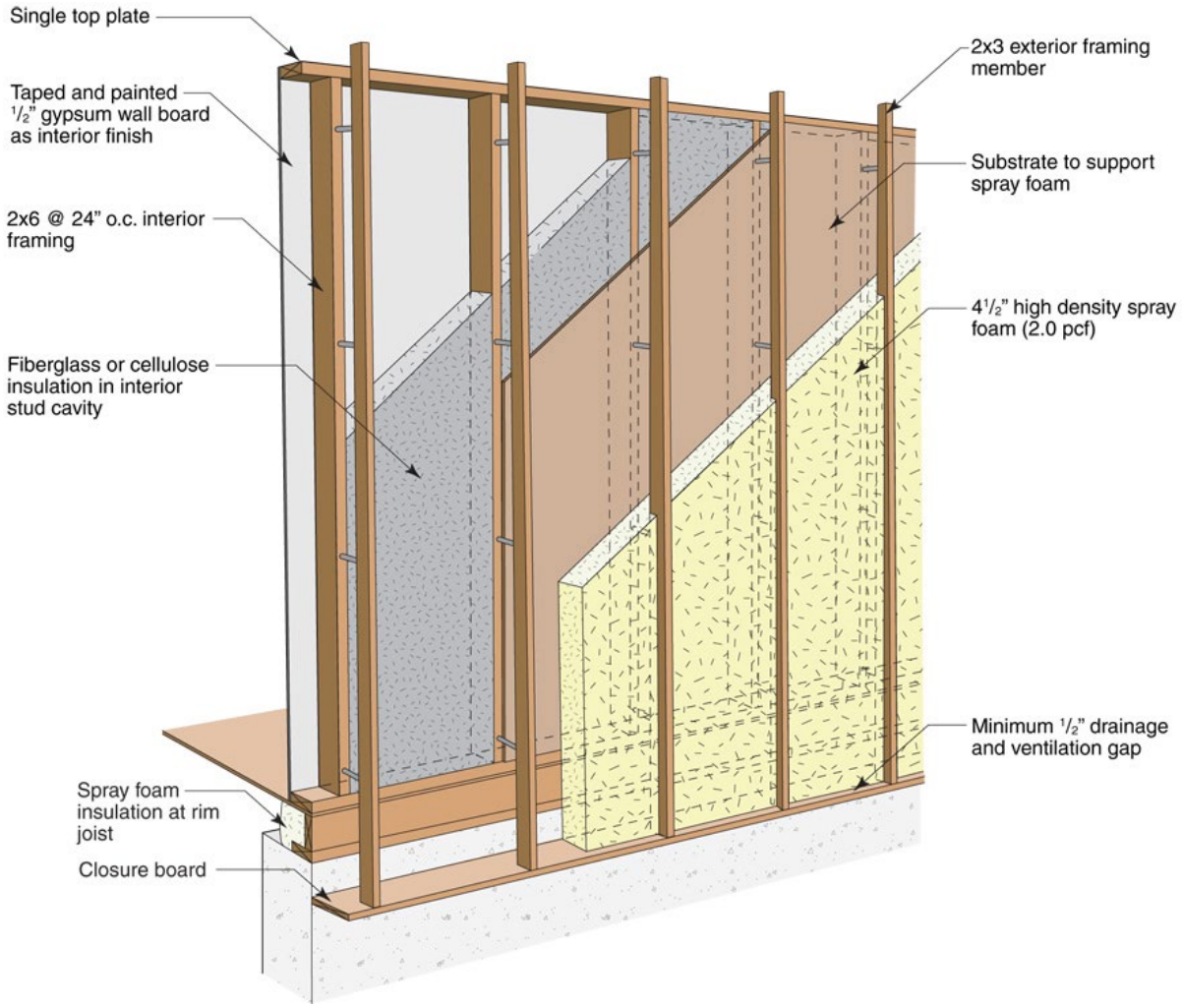
Given the increased emphasis on continuous wall insulation in the new code, NMR researched prices for alternative continuous wall insulation materials, including non-foam materials like high-density mineral wool, and labor-saving options such as sheathing-plus-insulation combination products. Unfortunately, we were unable to obtain adequate data to include novel insulation types in this study as individual options. However, we did observe only minor differences in cost by R-value/ft^2 among XPS (R-5/in), polyisocyanurate (R-6/in), and mineral wool (R-4/in). A similar trend was observed for the blown-in cellulose and fiberglass insulations most likely to be used to provide an R-60 ceiling insulation installation. Therefore, the wall sheathing and blown-in ceiling insulation options do not call out specific materials.[39]

A.1.5.2 Double-Stud Wall

In addition to true double-stud construction, a novel construction technique known as an offset frame wall (a cousin of the Larsen Truss) shown in Figure 15 was also explored. Both techniques permit the construction of high R-value walls with thick continuous insulation. The walls themselves are thicker than most single-stud walls with exterior insulation: 9.5 inches for a 2×6 single-stud wall with R-15 exterior continuous insulation versus 11 inches or more for double stud or offset frame. However, the extra nailing surface in packages with a true double-stud wall should help mitigate this. The true double-stud walls are modeled with a thin layer of cavity spray foam to control condensation and serve as a moisture barrier. This is a recommended practice for double-stud construction in cold climates in the same Building America research paper describing the offset frame wall.[40]

[39] 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.

Figure 15: Offset frame wall[40]



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[40] Straube, J. and Smegal, J. (2014). Building America Special Research Project: High-R Walls Case Study Analysis. https://buildingscience.com/commerce-file/5833/download (Accessed Nov. 2021)

A.1.6 Equipment Options

Reference home options of Phase 1 stretch code packages vary by design, see 2.5 for specifics.

Component	Option 1	Option 2	Option 3	Option 4
Ducts	4.0% TDL, R-8 Attic	4.0% TDL, R-25 Attic	2.0% TDL, R-25 Attic	4.0% TDL, R-0 Cond. Space
Air Source HP (cold climate)	9.2 HSPF2 (10.4 HSPF) / 18.9 SEER2 (19.8 SEER) Ducted mini-split ENERGY STAR	9.2 HSPF2 (11.7 HSPF) / 19.3 SEER2 (20.3 SEER) Ducted mini-split ENERGY STAR	–	–
Ground-Source HP	4.0 COP 21.0 EER ENERGY STAR	4.3 COP 23.0 EER ENERGY STAR	–	–
Mini-Split HP (Ductless, cold climate)	8.7 HSPF2 (10.2 HSPF) / 18.7 SEER2 (19.5 SEER) Multi-zone ENERGY STAR	10.7 HSPF2 (12.6 HSPF) / 24.9 SEER2 (26.0 SEER) Single zone ENERGY STAR	12.4 HSPF2 (13.6 HSPF) / 25.1 SEER2 (26.4 SEER) Single zone ENERGY STAR	–
Mechanical Ventilation	75% efficient ERV	85% efficient ERV	≥98% efficient ATU[1]	–
Water Heater	0.98 UEF, Electric Stand-alone[2]	3.2 UEF, Unitary HPWH, Conditioned	SF: 3.2 UEF, Unitary HPWH, Unconditioned (SF only)	3.7 UEF, Split HPWH ENERGY STAR
Hot Water Pipes	R-5 PEX	–	–	–
Hot Water Fixtures	Low-flow (WaterSense)	–	–	–
Photovoltaics	0 kW	SF: 3 kW MF: 80 kW	SF: 6 kW MF: 120 kW	SF: 9 kW MF: 160 kW
Clothes Washer	2.4 IMEF (2.8 MEF)	2.4 IMEF (2.8 MEF)	–	–
Cooking Range	0.84 EF Induction Range, 0.12 EF Electric Oven	–	–	–
Clothes Dryer	3.76 CEF, Electric	–	–	–
Dishwasher	290 kWh/yr	–	–	–
Lighting	100% LED, 80 Lm/W[2]	–	–	–
Refrigerator	574 kWh/yr	–	–	–

1. Air treatment unit (ATU) also known as conditioned energy recovery ventilation (CERV) and ventilating heat pump (VHP).
2. 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.1.6.1 ASHP/MSHP Ratings

The rating systems for these categories of equipment changed on January 1, 2023, from SEER/EER/HSPF to SEER2/EER2/HSPF2. Unfortunately, these ratings rely on different testing standards and it is not possible to precisely convert between them.[41] In other words, older models meeting the HSPF/SEER ratings of the options above may have higher or lower HSPF2/SEER2 ratings than the approximate values listed in Equipment Options (A.1.6). In addition, some options in this report differ from Phase 1. They were updated to reflect the average AHRI-listed ratings of modern heat pump models with a similar HSPF to the Phase 1 options as in Table 20.

Table 20: MSHP Option Revisions

	Option 1 (10.2 HSPF)	*Option 2 (12.6 HSPF)*	Option 3 (13.6 HSPF)
Phase 1	*8.7 HSPF2 (10.2 HSPF) / 18.7 SEER2 (19.5 SEER)*	*10.7 HSPF2 (12.6 HSPF) / 24.9 SEER2 (26.0 SEER)*	11.6 HSPF2 (13.6 HSPF) / 29.2 SEER2 (30.5 SEER)
Phase 2	*Same as Phase 1*	*Same as Phase 1*	**12.4** HSPF2 (13.6 HSPF) / **25.1** SEER2 (**26.4** SEER)

A.1.6.2 ASHP / Ducted MSHP

This report uses ducted mini-split systems for its ASHP packages, unlike the Phase 1 report, which relied on conventional centrally-ducted air source heat pumps. Ducted mini-splits are less efficient than ductless units, and the penalty increases with compressor efficiency. As a result, the Phase 1 and Phase 2 ASHP options have nearly identical ratings. However, the Phase 2 ducted mini-split option in this report should be more efficient than the Phase 1 centrally-ducted ASHP due to the continuously variable speed drive of the mini-split compressor. See B.1.2 for a comparison of the relative performance of these packages.

A.1.6.3 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 modest impact on energy savings for homes in this climate, yielding an approximately 10−20% reduction in hot water energy consumption.[42]

A.1.6.4 Ductless Mini-split Heat Pumps

Table 21 lists the number of compressors and head units modeled for single-family and multifamily packages in this study.

[41] Nevertheless, the ANSI standard followed by RESNET-compliant energy modelling software still relies on the older units, and rough conversions are performed on any ratings supplied in the modern units.
[42] Ekotrope (2018). Desuperheater. https://ekotrope.freshdesk.com/support/solutions/articles/17000074547-desuperheater (Accessed June 14, 2024)

Table 21: MSHP Configuration

	Design	Reference	Option 1	Option 2	Option 3
SF	Compressors	2	2	5	5
	Head units	5	5	5	5
MF	Compressors	2	2	2	2
	Head units	2	2	2	2

A.1.6.5 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 in energy savings between similarly rated 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.1.6.6 Heat Pump Water Heaters

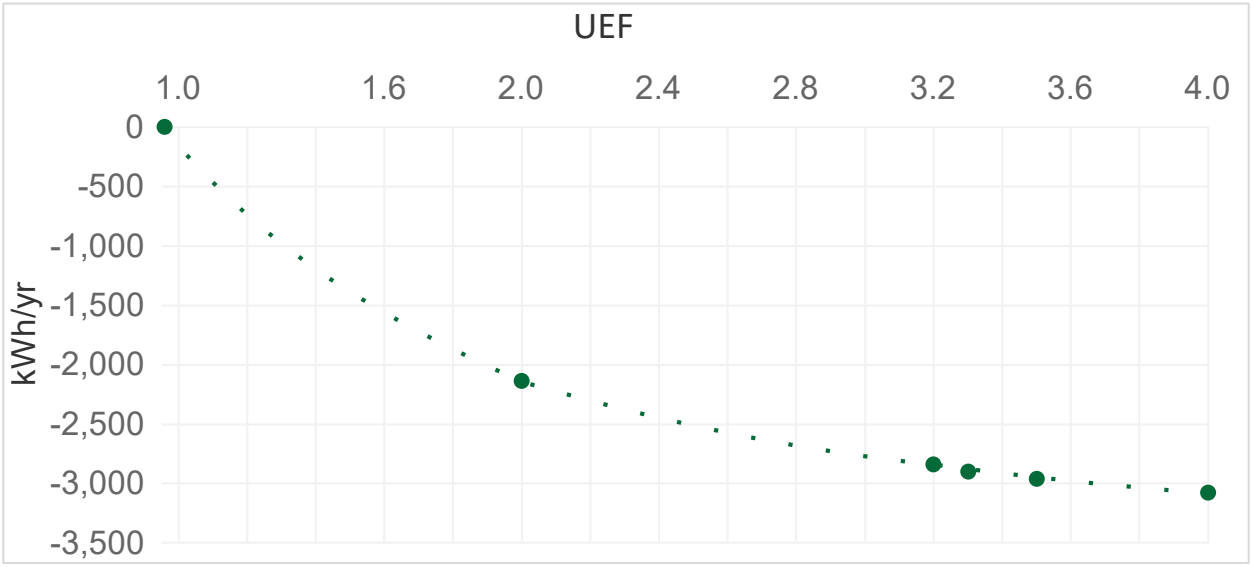
Heat pump water heaters are a valuable tool for electrification, due to their significantly higher efficiency compared to electric resistance water heaters. The previous optimization study (20R23) included a 3.2 UEF unitary HPWH and a 3.7 UEF split HPWH. At time of writing, the most common ENERGY STAR heat pump water heater efficiency is 3.5 UEF, and the maximum is approximately 4.0 UEF. Phase 1 of this study included a limited analysis of the 3.2 UEF unitary HPWH to support R408 compliance in base code homes. For all of its other strengths, BEopt does not yet appear able to capture all of the nuances of higher efficiency HPWHs (Table 22). Because the software could not model any benefit after the upgrade from a resistance storage tank to a modern 3.2 UEF unitary heat pump water heater, we have included options for different water heater locations rather than multiple efficiencies of unitary equipment.

Table 22: Approximate Incremental impacts of Heat Pump Water Heaters in BEopt v2.8

	0.96 UEF UCB	2.0 UEF UCB	3.2 UEF UCB	3.5 UEF UCB	4.0 UEF UCB	3.7 UEF split	3.2 UEF CB	4.0 UEF CB
ERI	0	-3.1	-3.8	-3.8	-3.8	-7.6	-1.4	-1.4
Construction†	$0	-$1.6k	+$2.5k	+$2.7k	$3.1k	+$6.2k	+$2.5k	+$3.1k
Ownership	$0	-$188	-$23	$0	+$38	-$118	+$101	+$163
DHW kWh	0	-451	-698	-698	-698	-2,359	-1,732	-1,732
Heating kWh	0	21	+26	+26	+26	-185	+1,298	+1,298
Net kWh	0	-437	-680	-680	-680	-2,462	-434	-434

However, this does not mean that there is no actual benefit provided by HPWH with higher ratings. Figure 16 shows the results of modeling these same water heaters with REM/Rate v16.3.2, which indicates that more efficient heat pump water heaters do in fact provide additional energy savings. Nevertheless, similar to BEopt's results in Table 22 above, the incremental benefit of HPWH with ratings higher than 3.2 UEF are marginal compared to the shift from either an electric resistance (0.96 UEF) or low-efficiency (2.0 UEF) heat pump water heater.

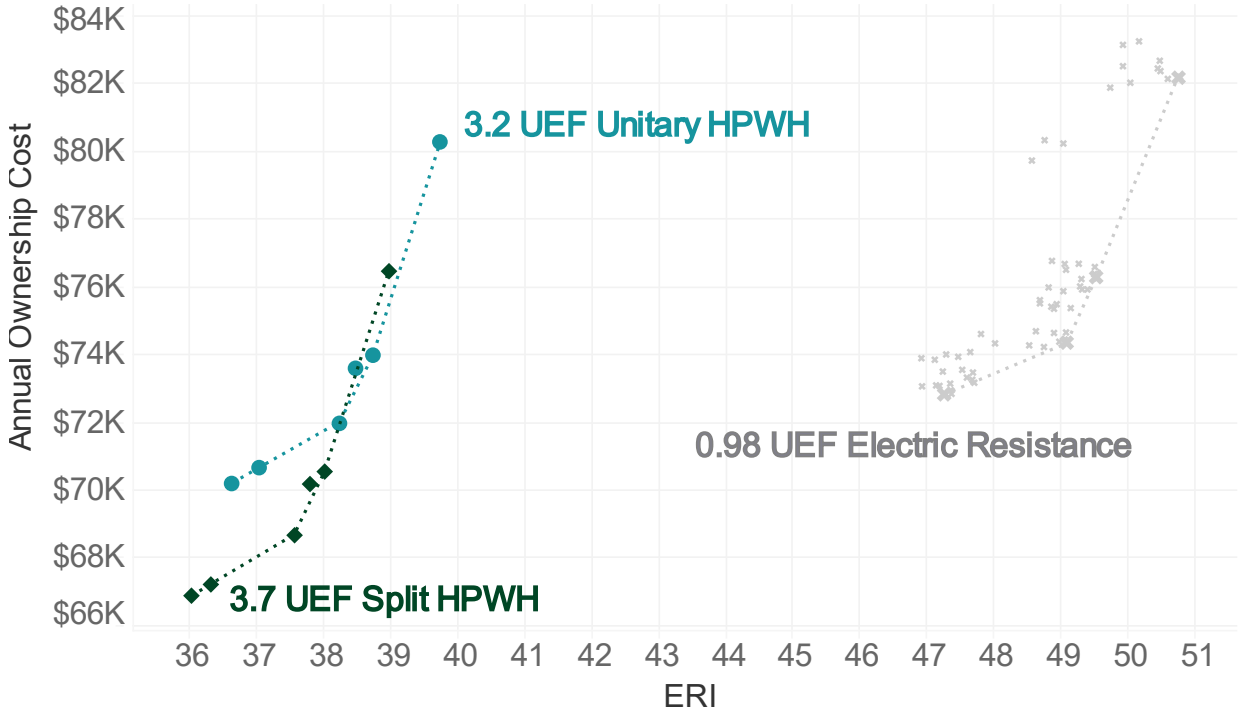
Figure 16: Net Incremental Savings of Heat Pump Water Heaters
in Unconditioned Basements with REM/Rate v16.3.2



The previous study limited multifamily HPWHs to a centralized pool of ten shared 83-gallon split systems (one per three units) over concerns about there being sufficient ambient heat in a central equipment room for many unitary HPWH to draw upon, or noise and draughts from in-unit HPWH. These remain legitimate concerns, and this study therefore includes a similar split-system water heater option. However, spreading equipment across multiple mechanical rooms, or placing water heaters in closets off main corridors rather than in individual units could mitigate these issues.[43] To explore the performance of this latter approach, the Phase 2 models also include an option for corridor closet unitary heat pump water heaters. As demonstrated in Figure 17, regardless of the configuration, HPWH are required for high-performance all-electric multifamily homes. While centralized split-system water heaters are favored due to a lower ownership cost, the contributions to overall home efficiency of unitary HPWH are similar and the centralized system could substitute the latter if desired.

[43] The latter option increases the heating loads of the common area HVAC systems, but decreases its cooling load.

Figure 17: Multifamily Water Heater Option Sensitivity



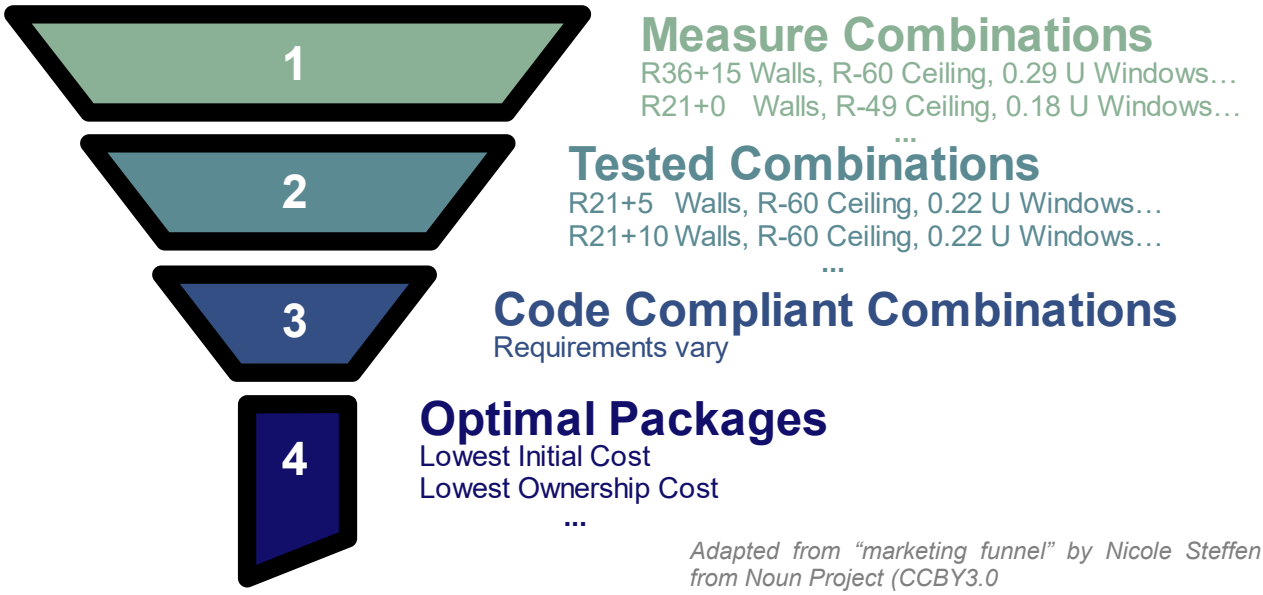
A.1.7 Climate/Weather

Both phases of this study, and the previous energy optimization investigation (20R23), employ NREL's TMY3 weather data. For simplicity, 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. As such, the equipment and operating costs for Manual J-sized heat pumps may be lower in other parts of the state than those included in this report.

A.2 Optimized Package Selection

The packages featured in this report are the result of a multi-step filtering process summarized Figure 18, and described in greater detail below.

Figure 18: Package Selection Process



Package Selection Step 1. There are far more levels of efficiency for most measures than it is possible to examine in this study. For example, water heaters are available in a wide variety of rated efficiency values: 0.95 UEF, 2.1 UEF, 2.3 UEF, 3.2 UEF, 3.5 UEF and more. Therefore, the study uses a narrower set of possibilities for each measure (e.g., 0.98, 3.2 and 3.7 UEF water heaters). 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.1.5) and Equipment Options (A.1.6).

Package Selection Step 2. BEopt begins modeling many different measure combinations (grey points in Figure 19), 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 that 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. The tenth edition building code uses HERS Index scores to specify home performance levels (lower is better). NMR reviewed tested packages in BEopt's output to select those compliant with the full tenth edition stretch and specialized codes' HERS requirement of 45 for all-electric homes.[44] However, BEopt only supplies Energy Rating Index (ERI) scores. Fortunately, ERI is closely related to the HERS score. In fact, the IECC model building code references ERI rather than HERS, and the previous version of the Massachusetts stretch code accepted either score.[45] Although the values of the two systems can differ slightly for the same home, this is also true for scores generated with different software, different versions of the same software, etc. Therefore, treating ERI as equivalent to HERS was deemed adequate for our purposes, particularly since this study explores the performance of prototypes rather than specific homes seeking occupancy permits. The precise floor plan, square footage, orientation, etc. of a real home will impact performance as much or more than the use of ERI instead of HERS.

The NZ thresholds with PV in Table 23 select a range of candidate combinations since it is unlikely for any set of tested measures to have an ERI of precisely 0. A lower limit also ensures that the home is not producing significantly more energy than necessary for its occupants needs.

Table 23: Electrification (Phase II) Home Energy Rating Criteria

	Maximum Rating	Minimum Rating
Zero Energy Ready (no PV)	45 without PV	–
Net-Zero (includes PV)	45 without PV 5 with PV	None without PV -2 with PV

BEopt requires that double-stud and single-walls be modeled separately. The code compliant combinations from these separate models are combined into a single pool from which optimized packages are drawn in Step 4. With such an approach, short-term oriented packages favor single-stud framing, while some long-term packages upgrade to double-stud or offset frame walls.

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 NZ MSHP single-family home is selected from the list of NZ MSHP single-family homes by sorting the list from lowest initial cost to highest. The first MSHP home is then designated the optimal Construction Cost package (for Net-Zero single-family homes using MSHPs; DCMW.N0).[46]

[44] The updated stretch code goes into full effect July 1, 2024. Interim requirements are 52 for mixed-fuel homes, 55 for all-electric homes, and 58 for all-electric homes with solar panels.
[45] Massachusetts Board of Building Regulations and Standards (2020). BRS Energy Code Advisory to the 2018 International Energy Conservation Code with the Massachusetts Amendments, Effective October 13, 2020. https://www.mass.gov/doc/780-cmr-ninth-edition-residential-chapter-11-energy-efficiency-bbrs-advisory-as-of-10132020-0/download
[46] 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.

A.2.1 Design and Package Shorthand

The study uses the following coding system, where major aspects of the specific package are represented by a single letter or number. For example, "DCMW.Z1" refers to a Zero-Energy Ready stud-construction colonial with a MSHP system, optimized for lowest first year cost.

Table 24: 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=ZERH	1. First Year Cost
		M: MSHP		N=Net-Zero	2. Ownership Cost
				- = Stretch	3. Energy Savings
				+=Specialized	4. Source Savings‡

† Single-family only. ‡ Phase I only.

A.2.2 Tested Models

The figures below show all tested combinations (grey points) modeled for each of the four core designs in this study. Clusters of optimized packages (large blue points) inside the dotted rectangles represent the optimized ZERH and NZ packages. Clicking on a rectangle will take you to the corresponding section of report (i.e., clicking on the Zero Energy Ready box of the single-family GSHP figure will take you to the section comparing geothermal Zero Energy Ready packages (3.3.3).

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

Note: The blank space between the reference home on the y-axis and the optimization curve or cluster of Zero-Energy Ready packages present in many of these figures is due to the model inputs to improve the process and results. Based on the findings of the Phase 1 report, the model defaults for some measures such as air infiltration were replaced with better-performing, commonly selected options; 1.5 ACH_{50} instead of 3 ACH_{50}. This resulted in immediate savings for the Phase 2 models compared to the reference homes,

Figure 19: Single-Family ASHP Optimization

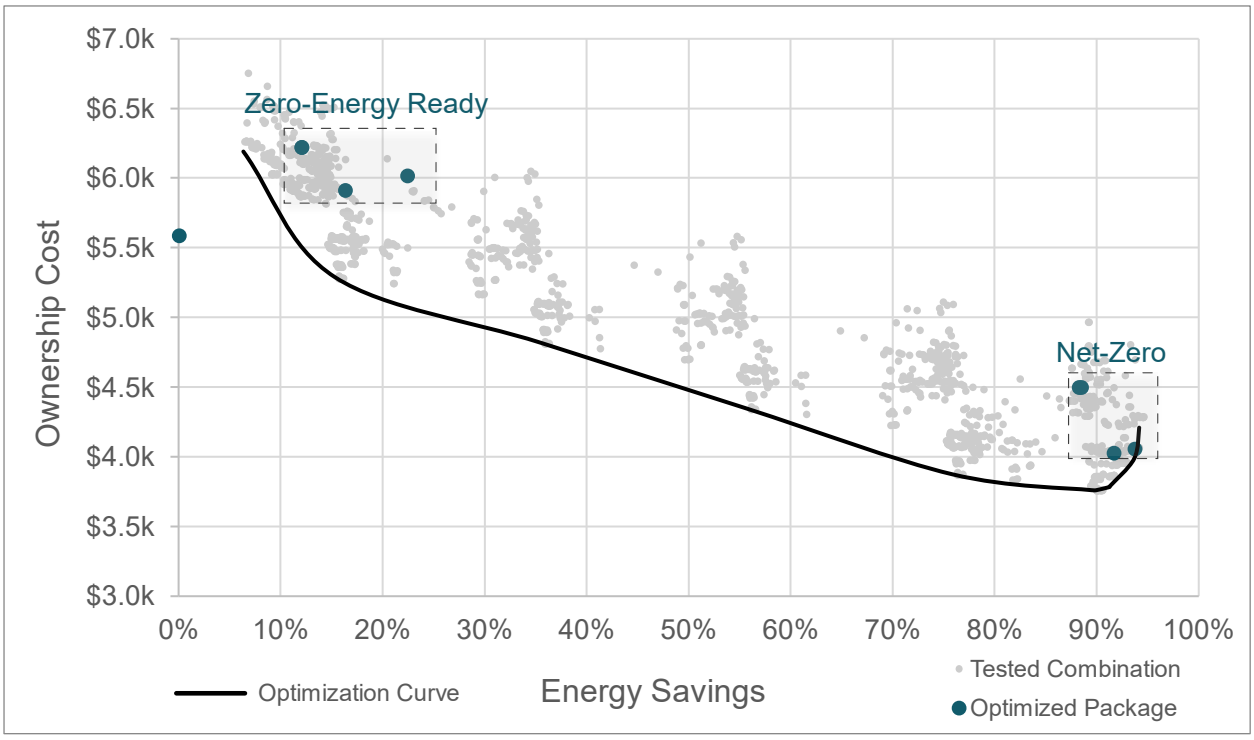


Figure 20: Single-Family GSHP Optimization

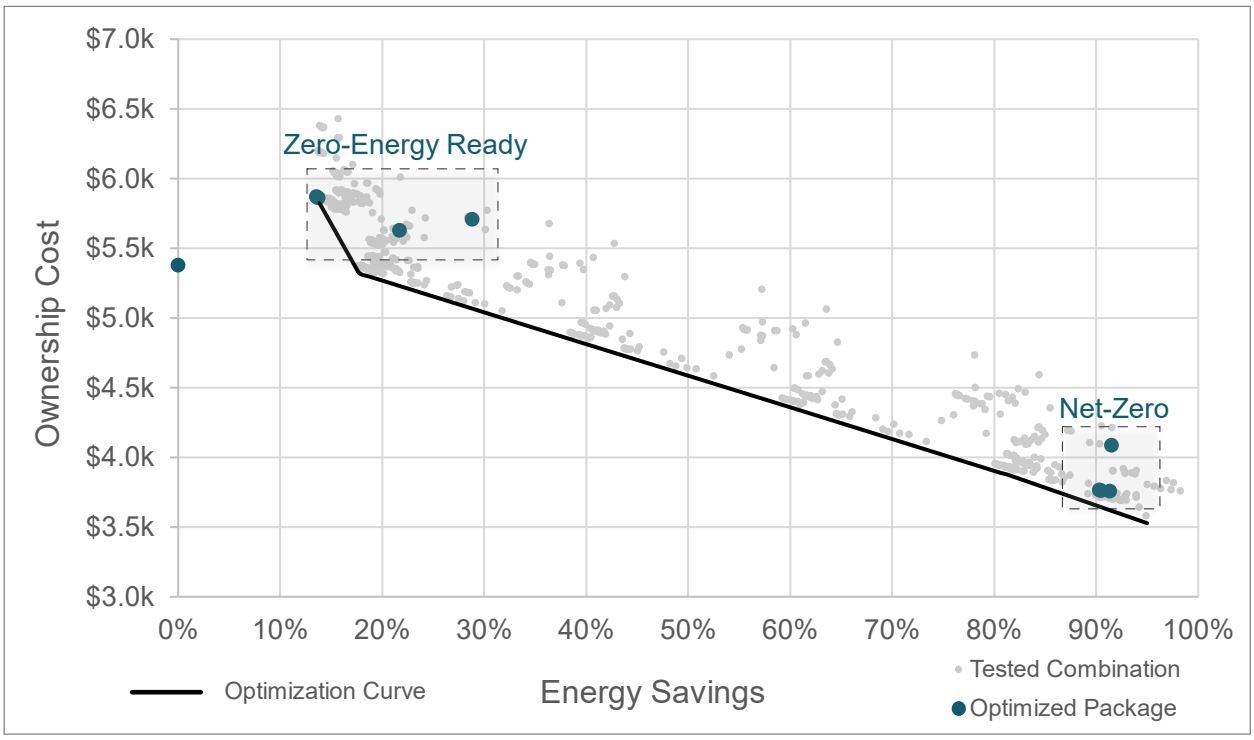


Figure 21: Single-family MSHP Optimization

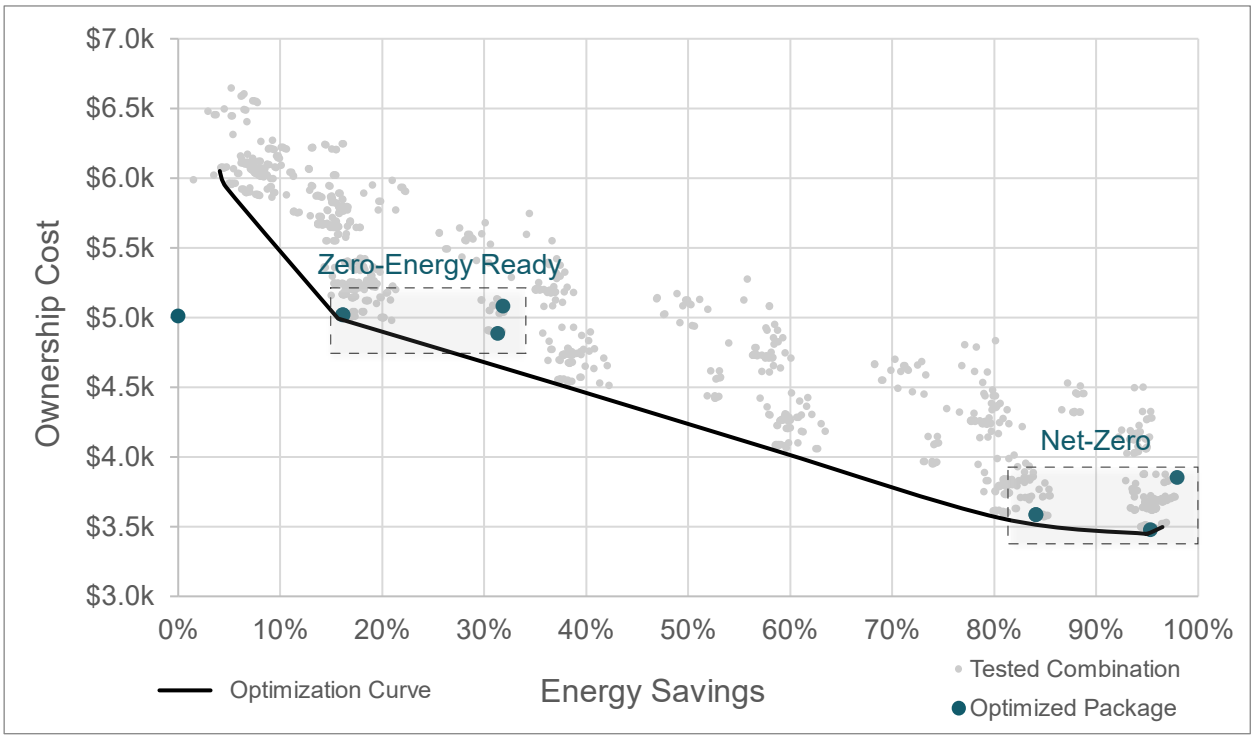
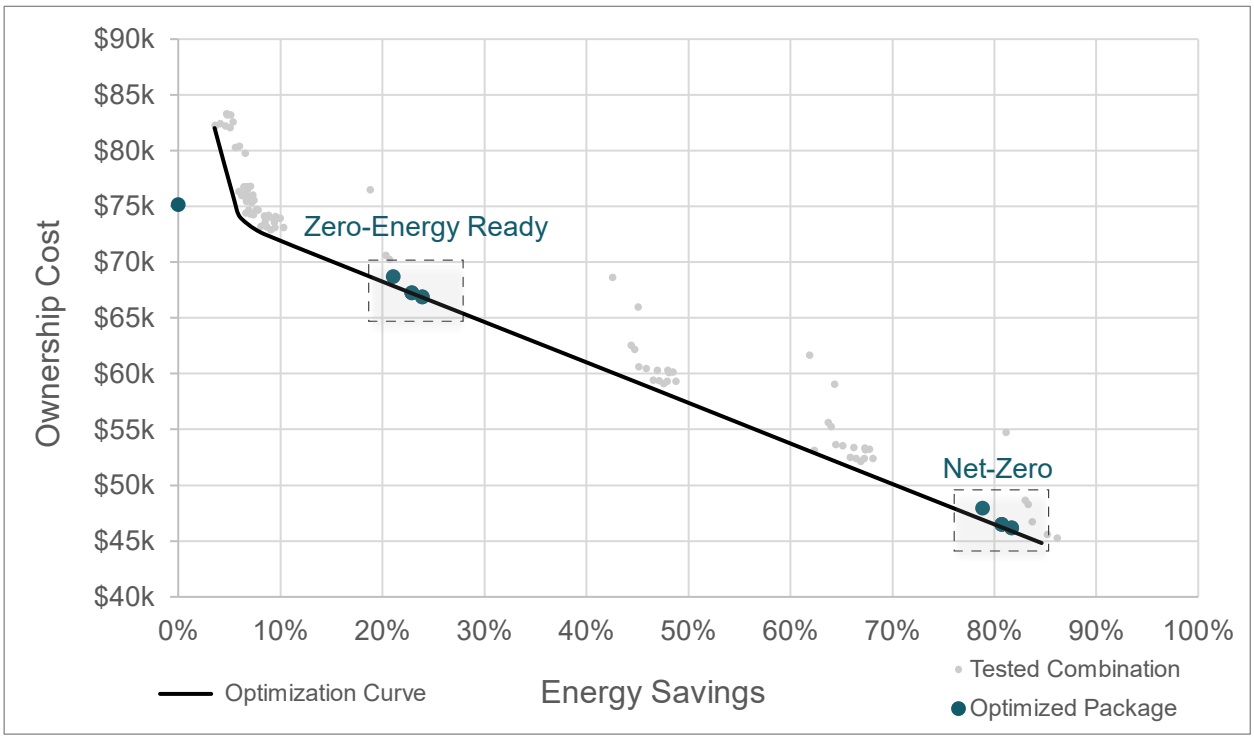


Figure 22: Multifamily MSHP Optimization



Appendix B Additional Details

B.1 Differences Between Phase 1 and Phase 2 Results

Phase 2 modeled all-electric homes starting from a combination of approximately stretch code compliant measures, rather than mixed-fuel homes starting from prescriptive path base code.

B.1.1 Conventional ASHP versus Centrally-ducted MSHP

This phase of the study modeled homes with higher-performance, ducted mini-split heat pumps rather than the more traditional, centrally ducted ASHPs included in Phase 1, given that the market appears to have embraced inverter-driver MSHPs, even in ducted applications.

Table 25 compares the costs and energy performance of Phase 1 and Phase 2 ASHP packages, with costs given as a percentage of the appropriate phase's reference package cost. While the ducted mini-split packages in this report (Phase 2) have higher construction costs than their Phase 1 counter-parts, the investment results in much higher energy savings.

B.1.2 Overall Performance Differences

In addition to the change in heat pump type, several other aspects of the packages differ between phases. In particular, the Phase 2 packages typically have higher efficiency water heaters (heat pump vs. tankless gas) and electric cooking but less efficient building shells; more infiltration (1.5 ACH_{50} versus Passive House 0.85 ACH_{50}), less continuous wall insulation (R-10 vs. R-15), less ceiling insulation (R-49 vs. R-60), lower recovery efficiency mechanical ventilation (75% vs. 85%). However, energy savings from the heat pump water heater plus electric stove and oven more than offset the increased consumption from a larger space heating load. The Phase 2 packages also use less back-up resistance heating than the Phase 1 packages due to the better cold-climate performance of the mini-split compressor. Of course, the ductless MSHP packages perform even better given the absence of HVAC distribution system losses and lower construction costs.

Table 25: Phase 1 vs. Phase 2 ASHP Package Performance Comparisons

	Optimization	ERI	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
	Reference	*42.1*	*0.0%*	100%	100%	100%	100%	DCAW.SR
Phase 1	Construction	40.4	1.4%	96%	106%	98%	100%	DCAW.S0
Phase 1	First Year	41.9	0.8%	96%	106%	98%	100%	DCAW.S1
Phase 1	Ownership	38.4	5.7%	99%	100%	99%	98%	DCAW.S2
Phase 1	Site Energy	38.4	5.9%	99%	100%	99%	102%	DCAW.S3
Phase 2	Construction✿	42.0	12.0%	107%	117%	106%	111%	DCAW.Z0
Phase 2	First Year✿	42.0	12.0%	107%	117%	106%	111%	DCAW.Z1
Phase 2	Ownership	42.3	16.3%	120%	111%	113%	105%	DCAW.Z2
Phase 2	Energy	37.9	22.4%	128%	103%	117%	107%	2CAW.Z3

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

B.2 Incremental Construction Cost vs. Stretch Code Reference

These upfront costs exclude Mass Save and federal incentives. For a summary of incremental costs from ZER to Net-Zero see Construction Costs in the Key Findings.

Table 26: Incremental Construction Costs to Shift from Mixed-fuel Stretch Reference to Optimized All-electric ZER, per Unit

	Design	Construction Cost	First Year Cost	Annual Ownership Cost	Energy Savings
SF	ASHP	$7.0k	$7k	$19.4k	$27.7k
SF	GSHP	-$15.8k	-$15.8k	$2.5k	-$8.9k
SF	MSHP	$0.2k	$0.3k	$8.1k	$11.8k
MF	MSHP	-$5.0k	-$5.0k	-$4.3k	-$4.3k

Table 27: Incremental Construction Costs to Shift from Mixed-fuel Stretch Reference to Optimized All-electric Net-Zero, per Unit

[cost excluding solar in brackets]

	Design	Construction Cost	First Year Cost	Annual Ownership Cost	Energy Savings
SF	ASHP	$51.8k [$15.3k]	$52.1k [$15.7k]	$64.3k [$27.9k]	$67.4k [$31k]
SF	GSHP	$19.8k [-$16.6k]	$20.2k [-$16.2k]	$21.8k [-$14.6k]	$36.3k [-$0.1k]
SF	MSHP	$39.2k [$2.8k]	$39.2k [$2.8k]	$44.5k [$8.1k]	$66.5k [$30k]
MF	MSHP	$12.2k [-$5.0k]	$12.2k [-$5.0k]	$12.9k [-$4.3k]	$12.9k [-$4.3k]

B.3 Incremental Impacts to Increase Incentives

The energy optimization modeling in this study tested different combinations of measures described in A.1.5, and did not limit this exploration to outcomes that should be eligible for any particular incentive (e.g., Mass Save) or tax credit (e.g., federal 45L tax credits). Consequently, to obtain certain incentives builders may need to address measures not included in the scope of this study, or to upgrade select measures of the optimized packages in this report. For example, in addition to a required HERS score of 35 or less, the Mass Save All-Electric Level 2 incentive requires continuous insulation throughout the home. However, BEopt does not model below-grade slab insulation, and many optimized packages include R-21 2×6 conditioned basement walls. Fortunately, changing these foundation walls to R-13+5 2×4 construction can likely be done for less than $500 and only slightly increases the assembly's U-factor from 0.0599 to 0.0606.

The tables below identify where each of the optimized packages in the study might fall short in terms of achieving a particular incentive or program requirement, and the approximate cost to alter that package to become eligible for the corresponding incentive or text credit. The leftmost columns show the initial packages and the columns to the right describe the replacement or upgraded packages. An unusual example is the energy savings optimized ZERH GSHP package, which requires a reduction in air infiltration from 1.5 ACH50 to less than 1 ACH50 to qualify for the Level 2 incentive. The incremental cost of a reduction to Passive House levels of infiltration is estimated at $340. Note that the cost of continuous foundation wall insulation is not included in

these tables due to space constraints, and because every Level 2 option below would require this, except for the energy savings optimized ZERH MSHP package.

The current Mass Save Level 2 incentives for all-electric homes is $25,000, $10,000 more than the Level 1 incentive.[10]

Table 28: Incremental Costs to Adjust ZERH SF Packages to Qualify for Mass Save Level 2 Incentives

Initial			Replacement				
Design	Package	Missing	Package	ERI w/ PV	Efficiency Const. Cost w/ PV	ERI w/o PV	Efficiency Const. Cost w/o PV
Construction✿	DCAW.Z0	ERI	2CAW.N2	-0.5	+$57,400	33.9	$21,000
First Year✿	DCAW.Z1	ERI	2CAW.N2	-0.5	+$57,400	33.9	$21,000
Ownership	DCAW.Z2	ERI, HPWH	2CAW.N2	-0.5	+$44,900	33.9	$8,500
Energy	2CAW.Z3	ERI	DCAW.N3	-1.2	+$39,800	33.1	$3,400
Construction	DCGW.Z0	ERI, HPWH	DCGW.N0	0.1	+$35,600	33.7	-$800
First Year	DCGW.Z1	ERI, HPWH	DCGW.N0	0.1	+$35,600	33.7	-$800
Ownership	2CGW.Z2	ERI, HPWH	DCGW.N0	0.1	+$17,300	33.7	-$19,100
Energy	DCGW.Z3	Air Leakage	*0.85 ACH_{50}*	–	–	–	$340
Construction	DCMW.Z0	ERI	DCMW.Z2	–	–	32.4	+$7,800
First Year	DCMW.Z1	ERI	DCMW.Z2	–	–	32.4	+$7,800
Ownership	DCMW.Z2	–	–	–	–	–	–
Energy	DCMW.Z3	–	–	–	–	–	–

Table 29: Incremental Costs to Adjust NZ SF Packages to Qualify for Mass Save Level 2 Incentives

	Initial			Replacement				
	Design	Package	Missing	Package	ERI w/ PV	Efficiency Const. Cost w/ PV	ERI w/o PV	Efficiency Const. Cost w/o PV
SF ASHP	Construction	DCAW.N0	ERI	2CAW.N2	-0.5	$12,600	33.9	–
	First Year	DCAW.N1	ERI	2CAW.N2	-0.5	$12,200	33.9	–
	Ownership	2CAW.N2		–	–	–	–	–
	Energy	2CAW.N3		–	–	–	–	–
SF GSHP	Construction	DCGW.N0		–	–	–	–	–
	First Year	DCGW.N1		–	–	–	–	–
	Ownership	DCGW.N2		–	–	–	–	–
	Energy	DCGW.N3		–	–	–	–	–
SF MSHP	Construction✿	DCMW.N0	ERI	DCMW.N2	-1.5	$5,300	32.4	
	First Year✿	DCMW.N1	ERI	DCMW.N2	-1.5	$5,300	32.4	
	Ownership	DCMW.N2		–	–	–	–	–
	Energy	2CMW.N3		–	–	–	–	–

At time of writing, the federal New Energy Efficiency Home Credit (45L) for ENERGY STAR homes is $2,500 per single-family home or multifamily unit, and the DOE ZERH incentives are double that: $5,000 and $1,000 respectively.[12]

Table 30: Incremental Costs to Adjust ZERH Packages to Qualify for 45L DOE ZERH Tax Credits

	Design	Initial		DOE ZERH	With Mass Save Level 2 Upgrades		
		Package	Missing	Efficiency Const. Cost	Package	Missing	Efficiency Const. Cost
SF ASHP	Construction✿	DCAW.Z0	ES WIN	$5,500	2CAW.N2	–	–
	First Year✿	DCAW.Z1	ES WIN	$5,500	2CAW.N2	–	–
	Ownership	DCAW.Z2	HPWH	$2,700	2CAW.N2	–	–
	Energy	2CAW.Z3	ES WIN	$5,500	2CAW.N3	–	–
SF GSHP	Construction	DCGW.Z0	ES WIN, HPWH	$8,200	2CGW.Z2	HPWH	$21,000
	First Year	DCGW.Z1	ES WIN, HPWH	$8,200	2CGW.Z2	HPWH	$21,000
	Ownership	2CGW.Z2	HPWH	$2,700	–	–	–
	Energy	DCGW.Z3	ES WIN	$5,500	–	–	–
SF MSHP	Construction	DCMW.Z0	ES WIN, HPWH	$8,200	DCMW.Z2	ES WIN	$13,300
	First Year	DCMW.Z1	ES WIN, HPWH	$8,200	DCMW.Z2	ES WIN	$13,300
	Ownership	DCMW.Z2	ES WIN	$5,500	–	–	–
	Energy	DCMW.Z3	–	–	–	–	–
MF MSHP	Construction	D3MW.Z0	ES WIN	$29,200	–	–	–
	First Year	D3MW.Z1	ES WIN	$29,200	–	–	–
	Ownership	D3MW.Z2	ES WIN	$29,200	–	–	–
	Energy	D3MW.Z3	ES WIN	$29,200	–	–	–

B.4 Base Code Referenced Results

Table 31 and Table 32 provide the incremental costs of the optimized all-electric packages in Phase 2 compared to the Phase 1 prescriptive path base code reference package of the same HVAC type with gas cooking and hot water. Perhaps somewhat unexpectedly, the Phase 2 ZERH ownership cost packages for all four designs are cheaper than the base code reference, essentially due to optimization yielding measure combinations that yield better outcomes than a package based on the code's prescriptive path. Other ZERH packages of interest include:

- GSHP energy savings, initial and construction cost packages, which have lower construction costs than the base code reference.
- GSHP first year cost package, which has a lower first year cost than the base code reference, and equal ownership cost.

Table 31: Incremental Costs of Optimized ZERH All-Electric Packages vs. Base Code Reference

	Optimization	ERI	ERI w/o PV	Energy Savings	Efficiency Const. Cost	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF ASHP	Reference	59.5	59.5	0.0%	$0	$0	$0	$0	DCAW.BR
	Construction✿	42	42	30.4%	+$17.0k	-$650	+$3.6k	-$200	DCAW.Z0
	First Year✿	42	42	30.4%	+$17.0k	-$650	+$3.6k	-$200	DCAW.Z1
	Ownership	42.3	42.3	33.8%	+$29.4k	-$870	+$6.4k	-$600	DCAW.Z2
	Energy	37.9	37.9	38.6%	+$37.6k	-$1.2k	+$7.8k	-$400	2CAW.Z3
SF GSHP	Reference	47.6	47.6	0.0%	$0	$0	$0	$0	DCGW.BR
	Construction	41.9	41.9	19.4%	-$11.2k	+$280	-$2.5k	+$200	DCGW.Z0
	First Year	41.9	41.9	19.6%	-$11.2k	+$270	-$2.5k	+$200	DCGW.Z1
	Ownership	38.1	38.1	27.0%	+$7.1k	-$120	$1.3k	-$100	2CGW.Z2
	Energy	33.7	33.7	33.6%	-$4.3k	-$470	-$1.5k	$0	DCGW.Z3
SF MSHP	Reference	54.1	54.1	0.0%	$0	$0	$0	$0	DCMW.BR
	Construction	40.3	40.3	31.1%	+$5.2k	-$520	+$800	-$800	DCMW.Z0
	First Year	40.2	40.2	31.2%	+$5.2k	-$520	+$800	-$800	DCMW.Z1
	Ownership	32.4	32.4	43.6%	+$13.0k	-$1.3k	+$2.0k	-$900	DCMW.Z2
	Energy	32.2	32.2	44.0%	+$16.7k	-$1.3k	+$2.9k	-$700	DCMW.Z3
MF MSHP	Reference	59.7	59.7	0.0%	$0	$0	$0	$0	D3MW.BR
	Construction-	37.6	37.6	35.1%	+$22.5k	-$7.750	+$68.0k	-$8.0k	D3MW.Z0-
	Construction✦	36.3	36.3	36.6%	+$30.3k	-$9.040	+$68.7k	-$9.4k	D3MW.Z0+
	First Year✦	36.3	36.3	36.6%	+$30.3k	-$9.040	+$68.7k	-$9.4k	D3MW.Z1
	Ownership◉	36	36	37.4%	+$47.5k	-$9.760	+$2.1k	-$9.7k	D3MW.Z2
	Energy◉	36	36	37.4%	+$47.5k	-$9.760	+$2.1k	-$9.7k	D3MW.Z3

✿✦ ◉ Packages with identical symbols include the same combination of measure options.
+ Multifamily packages in specialized code communities require lower levels of air leakage to comply with Passive House (D3MW.N0+), whereas code compliant stretch code packages (D3MW.N0) are possible with higher levels of infiltration.

All Net-Zero ownership cost packages have lower ownership costs than the base code reference package (Table 32).

Table 32: Incremental Costs of Optimized Net-Zero All-Electric Packages vs. Base Code Reference

	Optimization	ERI	ERI w/o PV	Energy Savings	Efficiency Const. Cost‡	Utilities (1st Year)	First Year Cost	Annual Ownership Cost	Package
SF ASHP	Reference	59.5	59.5	0.0%	$0	$0	$0	$0	DCAW.BR
	Construction	0.9	35.4	90.7%	+$61.7k	-$4.5k	+$10.8k	-$2.0k	DCAW.N0
	First Year	0.9	35.3	90.9%	+$62.1k	-$4.5k	+$10.9k	-$2.0k	DCAW.N1
	Ownership	-0.5	33.9	93.4%	+$74.3k	-$4.7k	+$13.5k	-$2.4k	2CAW.N2
	Energy	-1.2	33.1	95.0%	+$77.4k	-$4.8k	+$10.9k	-$2.4k	2CAW.N3
SF GSHP	Reference	47.6	47.6	0.0%	$0	$0	$0	$0	DCGW.BR
	Construction	0.1	33.7	91.0%	+$24.4k	-$3.5k	+$2.6k	-$1.9k	DCGW.N0
	First Year	0	33.6	91.2%	+$24.8k	-$3.5k	+$2.6k	-$1.9k	DCGW.N1
	Ownership	-1.1	32.4	91.9%	+$26.4k	-$3.6k	+$3.0k	-$1.9k	DCGW.N2
	Energy	-1.1	32.5	92.1%	+$40.9k	-$3.6k	+$6.6k	-$1.6k	DCGW.N3
SF MSHP	Reference	54.1	54.1	0.0%	$0	$0	$0	$0	DCMW.BR
	Construction✿	3.6	36.8	86.9%	+$44.2k	-$3.9k	+$7.1k	-$2.2k	DCMW.N0
	First Year✿	3.6	36.8	86.9%	+$44.2k	-$3.9k	+$7.1k	-$2.2k	DCMW.N1
	Ownership	-1.5	32.4	96.2%	+$49.4k	-$4.3k	+$8.0k	-$2.3k	DCMW.N2
	Energy	-2.5	31.4	98.3%	+$71.4k	-$4.5k	+$13.0k	-$1.9k	2CMW.N3
MF MSHP	Reference	59.7	59.7	0.0%	$0	$0	$0	$0	D3MW.BR
	Construction-	-0.8	37.6	82.6%	$469.1k	-$10.8k	+$68.0k	-$28.7k	D3MW.N0-
	Construction✦	-2.1	36.3	84.1%	$477.0k	-$50.1k	+$68.7k	-$30.1k	D3MW.N0+
	First Year✦	-2.1	36.3	84.1%	$477.0k	-$50.1k	+$68.7k	-$30.1k	D3MW.N1
	Ownership◉	-2.4	36	84.9%	$494.2k	-$50.8k	+$72.2k	-$30.5k	D3MW.N2
	Energy◉	-2.4	36	84.9%	$494.2k	-$50.8k	+$72.2k	-$30.5k	D3MW.N3

‡ All SF packages include $36.4k for 9kW of solar panels. Similarly, all MF packages include $447k for 120 kW.

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

+ Multifamily packages in specialized code communities require lower levels of air leakage to comply with Passive House (D3MW.N0+), whereas code compliant stretch code packages (D3MW.N0) are possible with higher levels of infiltration.

Appendix C Package Composition

Darker blues indicate higher efficiency in Table 33. 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 and to what extent. Numbers in the table indicate the specific option from sections A.1.5 and A.1.6. Package codes are explained in A.2.1, and details about other measures are included in the spreadsheet that accompanies this report.

Legend
Low efficiency; Option 2 for single-family ceiling; -1=Phase 1 Option 1, gas DHW
Average efficiency; 0=Phase 1 Option 2, gas DHW or Option 1, non-recovery vent.
Average efficiency; Option 1
High efficiency; Usually Option 2, except SF ceiling
Higher efficiency; Usually Option 3
Highest efficiency; Option 4

Table 33: Package Measure Options for Significant Home Components

Package Code	Infil.	Floor	Cond. Bsmt.	Single Stud	Cont.	Dbl. Stud	Win.	Ceil.	HP	Mech. Vent.	Ducts	DHW	PV
DCAW.BR	1	1	1	1	2		1	1	1	0	1	-1	1
DCAW.SR	3	2	2	3	4		2	2	1	2	2	-1	1
DCAW.Z0	2	1	1	2	2		1	2	1	1	3	3	1
DCAW.Z1	2	1	1	2	2		1	2	1	1	3	3	1
DCAW.Z2	3	2	1	2	4		2	3	2	2	4	1	1
2CAW.Z3	2	1	1			1	1	2	1	1	3	4	1
DCAW.N0	3	2	2	2	4		1	2	2	2	2	4	4
DCAW.N1	3	2	2	2	4		1	2	2	2	3	4	4
2CAW.N2	3	2	2			2	3	1	2	2	3	4	4
2CAW.N3	3	2	2			3	3	3	2	2	4	4	4
DCMW.BR	1	1	1	1	2		1	1	1	0		-1	1
DCMW.SR	2	2	2	3	4		1	2	3	1		-1	1
DCMW.Z0	3	1	1	2	3		1	2	3	2		1	1
DCMW.Z1	3	2	1	2	3		1	2	3	2		1	1
DCMW.Z2	3	2	2	2	4		1	2	3	2		4	1
DCMW.Z3	3	2	1	2	3		2	2	3	2		4	1
DCMW.N0	3	2	1	2	3		1	2	3	2		3	4
DCMW.N1	3	2	1	2	3		1	2	3	2		3	4
DCMW.N2	3	2	2	2	4		1	2	3	2		4	4
2CMW.N3	3	2	2			2	3	1	3	2		4	4

Package Code	Infil.	Floor	Cond. Bsmt.	Single Stud	Cont.	Dbl. Stud	Win.	Ceil.	HP	Mech. Vent.	Ducts	DHW	PV
DCGW.BR	1	1	1	1	2		1	1	1	0	1	-1	1
DCGW.SR	3	1	1	1	2		1	3	1	1	4	-1	1
DCGW.Z0	2	1	1	2	2		1	2	1	1	3	1	1
DCGW.Z1	2	2	1	2	2		1	2	1	1	3	1	1
2CGW.Z2	3	2	2			2	3	2	1	1	3	1	1
DCGW.Z3	2	2	2	2	2		1	2	1	1	3	4	1
DCGW.N0	3	2	2	2	3		1	2	1	2	2	2	4
DCGW.N1	3	2	2	2	3		1	2	1	2	3	2	4
DCGW.N2	3	2	2	2	4		1	2	1	2	2	2	4
DCGW.N3	3	2	2	2	4		1	3	1	2	4	2	4
D3MW.BR	1	1		1	2		1	1	1	0		-1	1
D3MW.SR	3	2		3	4		1	1	1	2		0	1
D3MW.Z0-	3	2		2	2		1	1	3	1		4	1
D3MW.Z0+	2	2		2	2		1	1	3	1		4	1
D3MW.Z1	3	2		2	2		1	1	3	1		4	1
D3MW.Z2	3	2		2	4		1	1	3	1		4	1
D3MW.Z3	3	2		2	4		1	1	3	1		4	1
D3MW.N0-	3	2		2	2		1	1	3	1		4	3
D3MW.N0+	2	2		2	2		1	1	3	1		4	3
D3MW.N1	3	2		2	2		1	1	3	1		4	3
D3MW.N2	3	2		2	4		1	1	3	1		4	3
D3MW.N3	3	2		2	4		1	1	3	1		4	3