# MA19R05: Residential New Construction Passive House Assessment – Overall Report – Final

Final Report

January 6, 2020

SUBMITTED TO:
The Massachusetts Electric and Gas Program Administrators

SUBMITTED BY:
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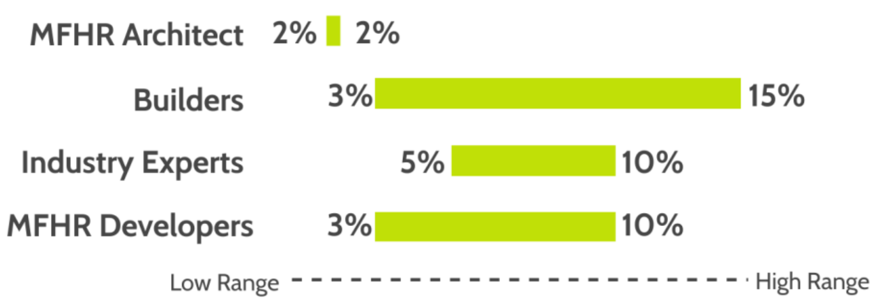


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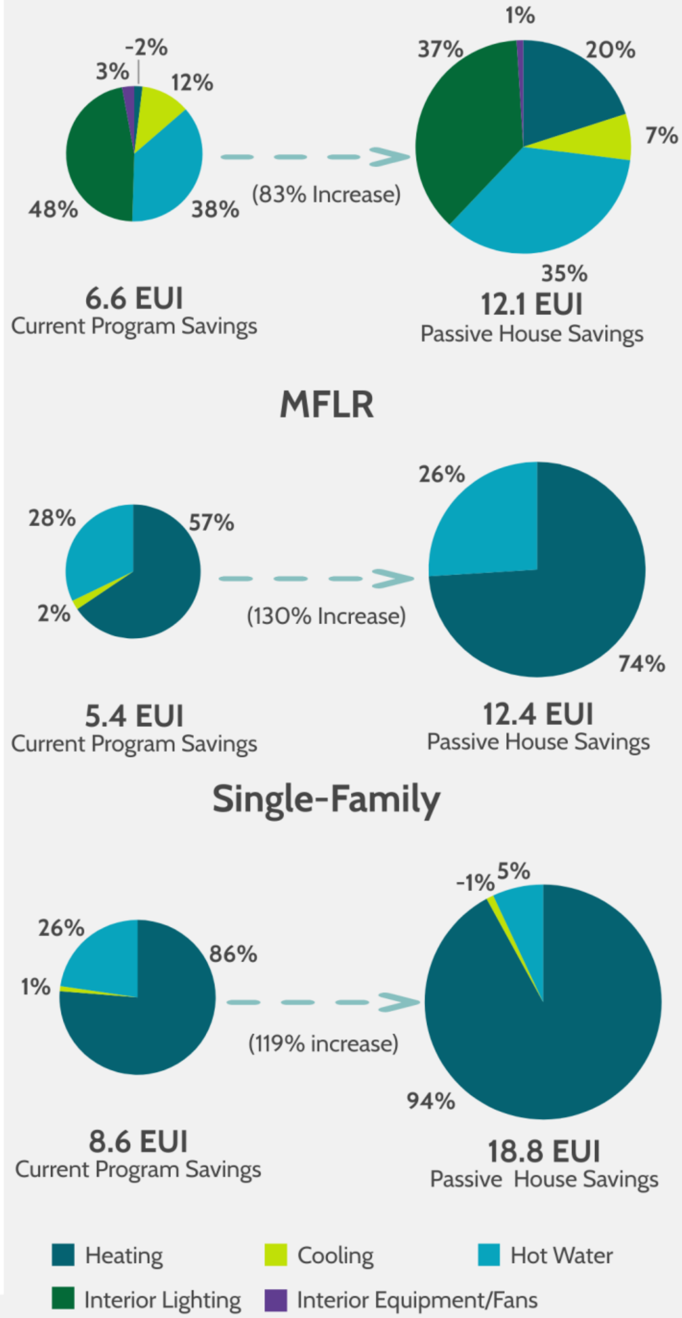


## CURRENT PASSIVE HOUSE MFHR INCENTIVE LEVELS*

| Incentive Timing | Activity | Incentive Amount | Max |
|---|---|---|---|
| Pre-Construction | Feasibility Study | 100% | $5,000 |
| | Energy Modeling | 75% | $20,000 |
| | Pre-Certification | $500/unit | N/A |
| Post-Construction | Certification | $2,500/unit | N/A |
| | Net Performance | $0.75/kWh | N/A |
| | Bonus | $7.50/therm | N/A |

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# Executive Summary

The Massachusetts Program Administrators (PAs) and the Energy Efficiency Advisory Council (EEAC) have contracted with NMR Group (from here on referred to as “the Team”) to assist in the design of a new Passive House offering within the Residential New Construction Program. This report presents the results of a detailed modeling comparison for multifamily high-rise (MFHR), multifamily low-rise (MFLR), and single-family projects built with Passive House design principles. In addition, this report presents the results of a series of in-depth interviews (IDIs) with various market actors to better understand the opportunities, barriers, incremental costs, and incentive issues associated with a new Passive House offering.

The interim report[1] focused on MFHR – which the program defines as multifamily buildings four stories or greater in size, or any multifamily buildings with a central HVAC system. Those projects were hypothesized to be the best initial target market for the new program offering. The results of the interim report were used to inform the requirements and incentive levels for the MFHR Passive House program offering (Table 1).[2]

**Table 1: Passive House Incentive Structure for Multifamily (Mid- and High-Rise)**

| Incentive Timing | Activity | Incentive Amount | Maximum Incentive |
|---|---|---|---|
| **Pre-Construction** | Feasibility Study | 100% Feasibility Costs | $5,000 |
| | Energy Modeling | 75% of Energy Modeling Costs | $20,000 |
| | Pre-Certification | $500/unit | N/A |
| **Post-Construction** | Certification | $2,500/unit | N/A |
| | Net Performance Bonus | $0.75/kWh | N/A |
| | | $7.50/therm | N/A |

*The Net Performance Bonus is calculated by determining the final pay for saving incentives and subtracting the pre- and final certification incentives. The result is the Net Performance Bonus.
**Projects that pre-certify but do not achieve certification are eligible for the pre-certification incentive and Net Performance Bonus.
***Projects over 100 units must be pre-approved by the applicable Sponsors of Mass Save.

[1] http://ma-eeac.org/wordpress/wp-content/uploads/MA19R05_PassiveHouse_InterimReport_Final_2019.06.23.pdf
[2] https://www.masssave.com/en/saving/residential-rebates/passive-house-incentives/

This final report also includes MFLR (buildings less than four stories and without central heating) and single-family projects. The results and findings in this report are presented separately for MFHR, MFLR, and single-family buildings when appropriate. Below, we present the key findings of our research, broken into the following categories:

**Model comparison** | **Incremental costs** | **Incentive suggestions and structure** | **Preliminary potential savings**

Additional details, including detailed findings regarding Passive House opportunities and barriers, can be found in the body of this report.

## Model Comparison

The primary objective of the model comparison was to determine the extent to which various energy modeling tools can handle the inputs and detail associated with Passive House new construction, and the extent to which they can be used to model the baseline conditions that will serve as the foundation for calculating program savings. ***Given that the primary purpose of this assessment was to compare the functionality of the modeling tools, and not to calculate potential program savings, the savings values presented here are not necessarily representative of those that may be generated by the new offering. Please note that these are modeled savings which have not been compared to actual energy consumption.***

The Team conducted a detailed comparison of three energy modeling tools for the MFHR program and four energy modeling tools for the low-rise program (both MFLR and single-family). Each of these modeling comparisons leveraged a sample of applicable projects that incorporated Passive House design principles. Each sampled project was modeled in each of the software, and each sampled project had a baseline scenario modeled. The details associated with the sampled projects, including component efficiency levels, can be found in Section 2, Section 3, and Section 4. The tools and a high-level summary of sampled projects included in our assessment are listed in Table 2.

**Table 2: Modeling Tools and Sample Project Details**

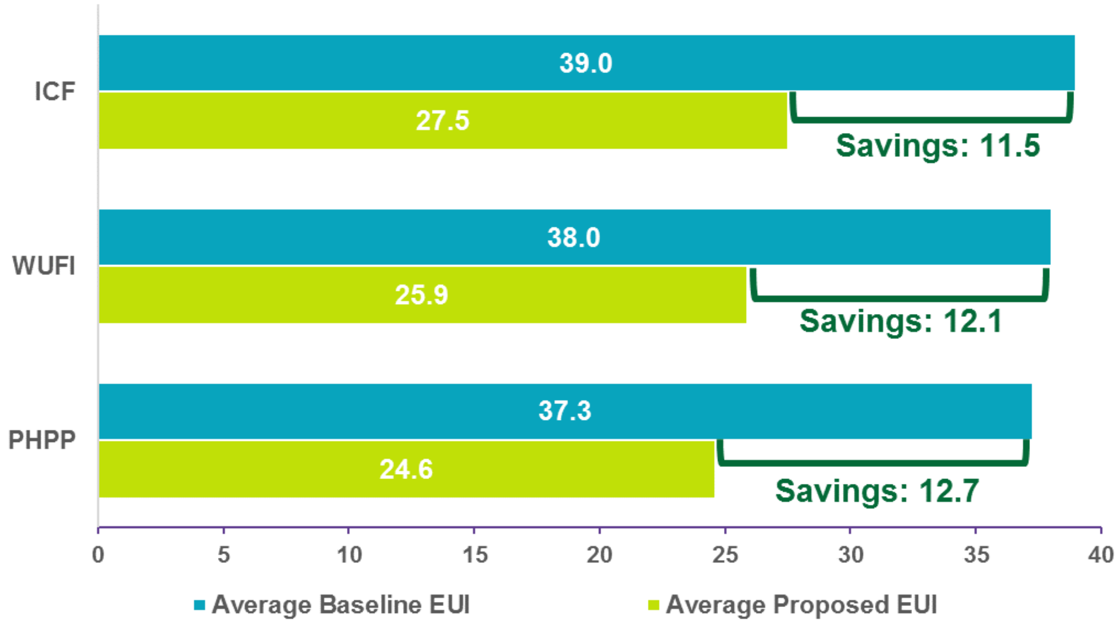
| RNC Sector | Multifamily High-Rise | Multifamily Low-Rise* | Single-Family |
|---|---|---|---|
| *Sample Size* | *n=5* | *n=4* | *n=5* |
| Modeling Tools | ➢ ICF's Multifamily High-Rise Modeling Tool<br>➢ Warme Und Feuchte Instationar (WUFI) Passive<br>➢ Passive House Planning Package (PHPP) | ➢ WUFI Passive<br>➢ PHPP<br>➢ Ekotrope<br>➢ REM/Rate | ➢ WUFI Passive<br>➢ PHPP<br>➢ Ekotrope<br>➢ REM/Rate |
| Sample Project Details | ➢ 4 stories, 28-units<br>➢ 7 stories, 101-units<br>➢ 14 stories, 154-units<br>➢ 11 stories, 249-units<br>➢ 26 stories, 277-units | ➢ 3 stories, 3-units<br>➢ 3 stories, 30-units<br>➢ 3 stories, 49-units<br>➢ 3 stories, 63-units | ➢ 1,428 $ft^2$, 3-bedroom<br>➢ 3,245 $ft^2$, 4-bedroom<br>➢ 3,366 $ft^2$, 6-bedroom<br>➢ 3,680 $ft^2$, 4-bedroom<br>➢ 5,635 $ft^2$, 3-bedroom |

*The Team was unable to perform a comprehensive comparison of WUFI Passive, PHPP, Ekotrope, and REM/Rate for all of the sampled multifamily low-rise projects. This is explained in more detail in Section 3. The executive summary only provides a comparison of WUFI Passive and PHPP for the MFLR sector.

## Multifamily High-Rise Energy Use Intensity Savings

Below, we present the model comparison results for the five sampled MFHR buildings. More detail on the MFHR modeling effort can be found in Section 2. Figure 1 provides a snapshot of the average site energy savings of the five MFHR passive buildings over a modeled baseline condition, developed using efficiency values from the Massachusetts MFHR user-defined reference home (UDRH), for each software. This comparison uses like-for-like equipment types and includes all available end-uses, wrapping the consumption data for the as-built and baseline models into an overall site energy use intensity (EUI) value. PHIUS and PHI develop source-level EUIs in their certification activities, but site-level EUIs are used here to reflect the methodology likely to be used by the program. Overall, site EUI and savings values were similar across models, though the two Passive House software predicted slightly greater savings.

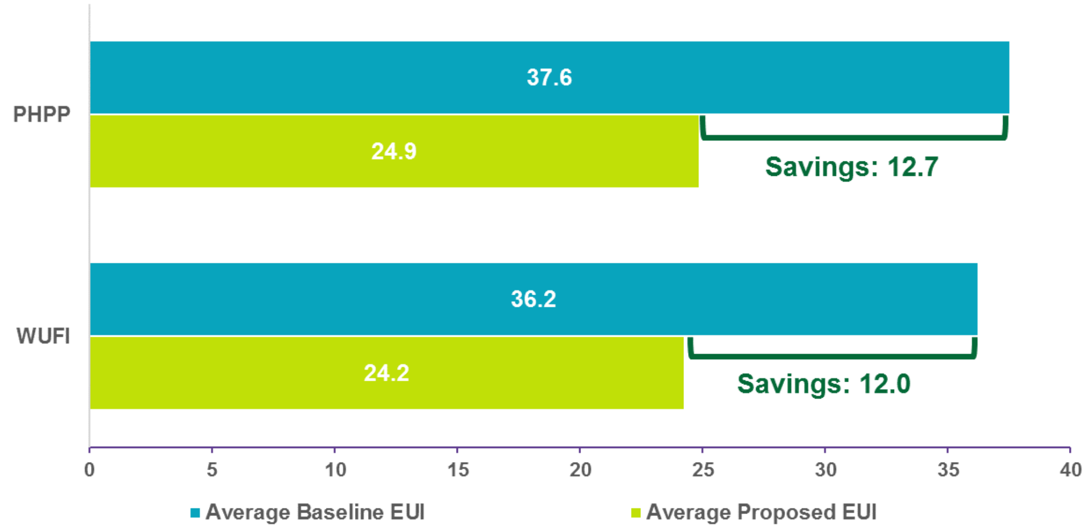
**Figure 1: Average Site EUI Comparisons Across MFHR Models (kBtu/ft²/yr)**




### Multifamily Low-Rise Energy Use Intensity Savings

Below, we present the model comparison results for the four sampled MFLR passive buildings, again expressed in terms of overall site EUI. More detail on the MFLR modeling effort can be found in Section 3. In this limited sample, PHPP and WUFI modeled similar consumption and savings values for the as-built and baseline scenarios, as they did in the MFHR modeling exercise. Not all MFLR sites could be modeled in REM/Rate and Ekotrope due to constraints in modeling methodology, as explained in Section 3.

**Figure 2: Average Site EUI Comparisons Across MFLR Models (kBtu/iCFA/yr)[3]**

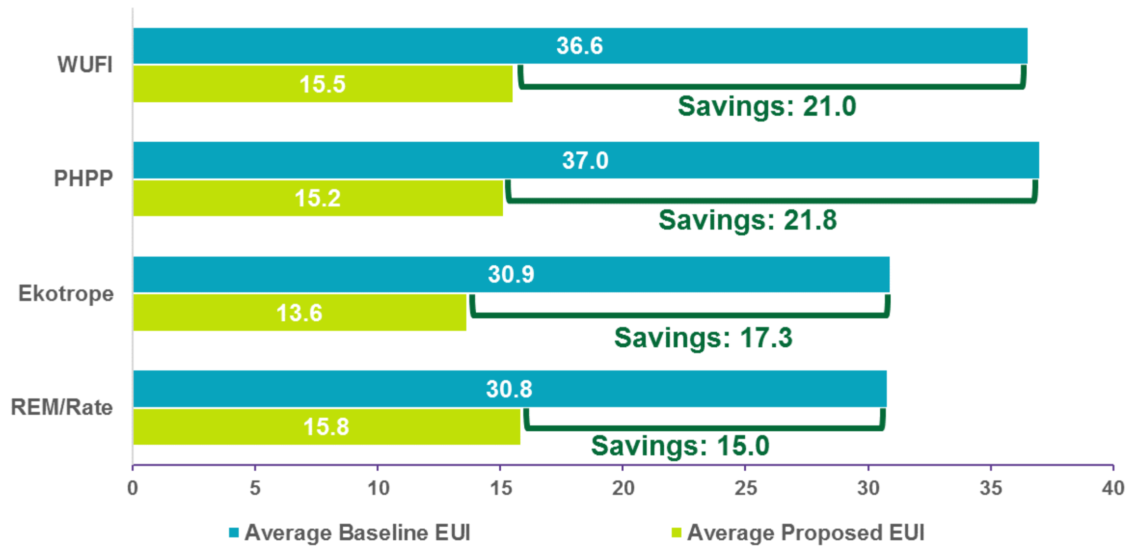



## Single-Family Energy Use Intensity Savings

Figure 3 presents the model comparison results for five sampled single-family passive buildings. Sample size caveats should be noted, but WUFI and PHPP stand out here as estimating greater savings over baseline scenarios created with low-rise UDRH values when compared to REM/Rate and Ekotrope. This is largely driven by baseline estimates in the Passive software that are more energy-intensive than those created by either HERS rating software. WUFI and PHPP also estimate very similar site EUI values for baseline and as-built models, much like they do for MFHR and MFLR. More detail on the single-family modeling effort can be found in Section 4.

[3] Interior Conditioned Floor Area (iCFA) is any interior space at least 7' in height, drywall-to-drywall. This includes stairs, cabinets, interior walls, mechanical spaces, storage, etc. This excludes open-to-below areas and unconditioned spaces.

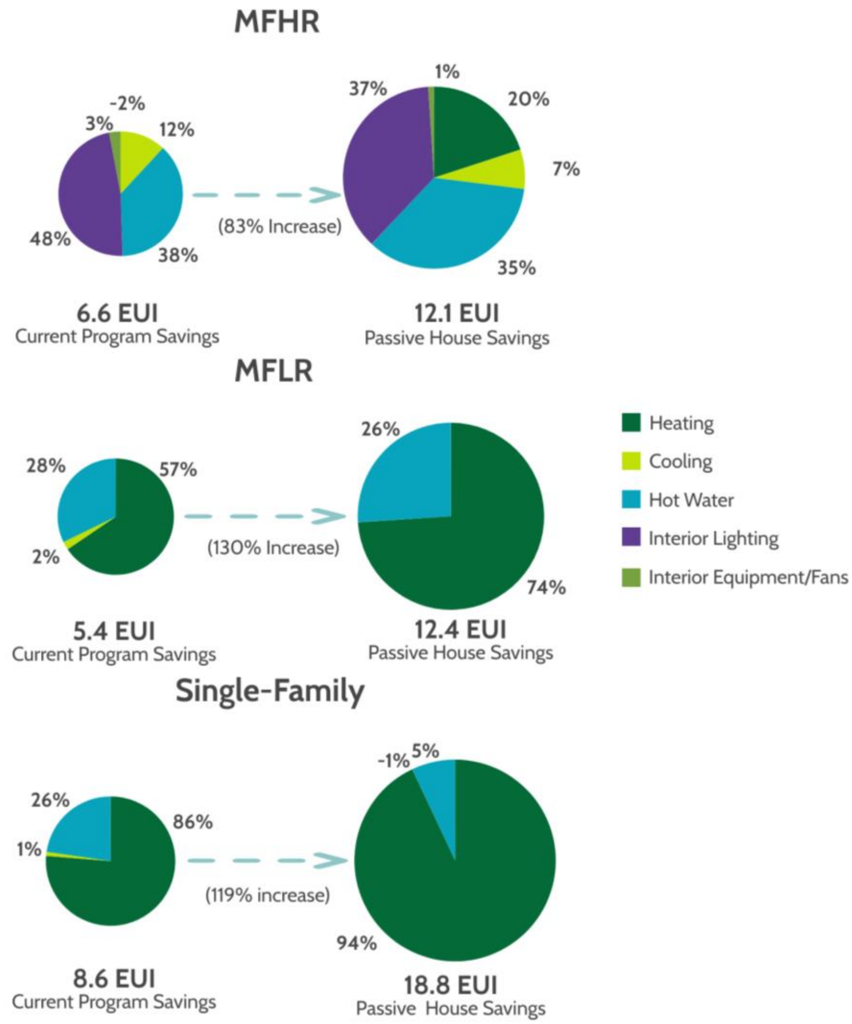
**Figure 3: Average EUI Comparisons Across Single-Family Models (kBtu/iCFA/yr)**




## PASSIVE HOUSE AND PROGRAM SAVINGS COMPARISON

Figure 4 shows the average energy savings, expressed in site EUI, of passive house energy models and program as-built energy models, over the baseline modeling conditions (Program UDRH) for each building sector. The average energy savings of the Passive House models are derived from each of the modeling software results combined into one overall average savings value, by end-use, to remove any specific software bias from the modeling comparison. The savings are also broken out by end-use, to the extent different end-uses are factored into the savings methodology. These data provide some example of the potential that passive design holds for providing savings beyond what is being achieved by current program participants. For each building type, the results show that models meeting passive design standards saved considerably more than the program as-built model. Sample size and other caveats apply, which are explored in more detail in the sections covering the modeling exercises and program data.

**Figure 4: Site Energy Savings of Passive House Models and Program participants over Baseline Models**




## Incentive Suggestions and Structure

The Team conducted 25 IDIs with market actors that have experience with Passive House projects to provide relevant insights and context for the program to draw upon. One objective of the IDIs was to understand the level of incentives that may be required to promote Passive House design strategies so they will be included in new construction projects, regardless if the project met certification. Market actors often suggested that the incentive structure should include certification. In addition, market actors were asked about the design and distribution of potential program incentives. Of particular interest was when in the construction and/or Passive House certification process incentives would be most useful and who the incentive should be distributed to.

The Team asked market actors about incentive amounts and timing, Table 3 presents a summary of responses (additional details can be found in Table 37). As shown, most market actors suggested an incentive amount falling somewhere between $4,000 and $5,000 per unit. This incentive range was consistent among respondents for multifamily buildings, as was the belief that single-family buildings may require additional incentives to overcome perceived increases in incremental costs. It should be noted that IDI responses primarily focused on multifamily incentives, and only a few responses were geared towards the single-family or the small multifamily market.

Multifamily developers suggested that cost certainty was important in any initial program offering. Given the nascent nature of the Passive House market, developers suggested that confirmation on financial incentives would assist them in their determination of whether to pursue Passive House design strategies. The program can reduce the potential risk or uncertainty developers assume with a Passive House project through the development of an easy to interpret incentive structure.

Most market actors suggested distributing incentives at various stages. The most common suggestions for incentive distribution were associated with the following project and/or certification steps: initial modeling, pre-certification, and final certification. Finally, most market actors suggested that the owner and/or developer should be provided with the bulk of the incentive dollars as they are the ones ultimately responsible for the finances of the project.

**Table 3: Incentive Structure Summary**

| Incentive Recipient | Incentive Timing | Incentive Amount |
|---|---|---|
| **Primary Response:** Owner/Developer | **Primary Response:** Distributed at initial modeling, pre-certification, and final certification | **Primary Response:** $4,000 to $5,000 per unit |
| **Other Mentions:** Builder, architect | **Other Mentions:** Design stage, post certification (based on usage) | **Other Mentions:** $7,000 per unit for MFLR and SF, $10,000 per unit for MFHR |

## INCREMENTAL COSTS

The IDIs also explored the incremental costs associated with building Passive House certified projects. Incremental costs are difficult to assess as market actors have different reference points – some might consider costs relative to code buildings and others to above code construction. Additionally, the project size, the project team experience, and the location of the project are unique factors that contribute to incremental costs. As a result, the Team was unable to procure definitive incremental cost numbers from the IDIs. However, we believe the results presented below provide valuable insight regarding the percentage cost increase a Passive House project might present compared to typical new construction practices.

Table 4 presents a summary of the incremental costs associated with Passive House construction practices. As shown, incremental cost estimates, covering both construction costs and certification costs, ranged from 2% to 15%. The most commonly cited incremental cost was 5% compared to typical new construction practices. The responses were limited for MFLR and single-family projects, but one builder suggested a 3% incremental cost, while another estimated that costs were 12% to 15% more than their previous projects that were built to code. Interviewees of all types believed that with proper planning and an evolution in approach, multifamily passive buildings could be constructed for the same cost as non-passive designs.

### Table 4: Passive House Incremental Cost Estimates

| Market Actor Group | Sample Size | Incremental Cost - Low Range | Incremental Cost – High Range |
|---|---|---|---|
| MFHR Architect/Engineer | 1 | 2% | 2% |
| Builders[1] | 7 | 3% | 15% |
| Industry Experts | 5 | 5% | 10% |
| MFHR Developers | 5 | 3% | 10% |

[1]The two single-family/low-rise builders represent the low and high ends of this range.

There was agreement across industry experts, architects, and engineers that incremental costs, as a percentage of project costs, decrease as the size of the building increases. Increasing surface to volume ratio (making it easier to achieve air leakage levels), increasing internal gains (lowering insulation and heating load requirements), and decreasing marginal costs of modeling and certification fees were all cited as explanations for this. Larger projects may also reduce costs through economies of scale, particularly discounted first costs due to buying measures such as high-performance windows in bulk.

Overall, respondents were unable to provide specific construction costs associated with measure-level upgrades. However, a couple of developers provided details on the actual costs for certification and the associated administrative and/or modeling requirements. Note that actual costs varied based on project size and specifications, consultants performing the service, certification pursued, and level of experience.[4] For example, one early Passive House adopter suggested modeling costs were five to ten times higher in early projects than in more recent ones. Cost data from affordable housing multifamily projects in Pennsylvania also show that Passive House construction costs have decreased over time, and even suggest cost parity with non-passive house construction projects (Appendix A). The actual project estimates from the IDIs are provided in Table 5.

[4] The certification costs below are associated with projects pursuing certification with PHIUS. The Team was unable to procure specific costs for PHI projects and was unable to uncover certification costs during the literature review as they are project dependent. PHI costs were noted to likely be a little higher per-unit than costs provided below, and are subject to an increased fee (approximately 20% more) if the project is considered mixed-use.

**Table 5: Specific Cost Estimates Identified by Developers**

| Cost Category | Details |
|---|---|
| Initial Feasibility Modeling | ➢ Approximately 5,000 for initial project feasibility modeling |
| Energy Modeling | ➢ $15,000 for 135-unit project ($111/unit)<br>➢ Between $10,000 and $20,000 for a 98-unit project and 108-unit project ($102-$204/unit)<br>➢ Between $30,000 and $50,000 for an early Passive House project that included multiple modeling entities ($1,071-$1,786/unit) |
| Rater Fees | ➢ $50,000 for a 135-unit project ($370/unit) |
| Certification Costs | ➢ $12,000 for a 28-unit project ($429/unit)<br>➢ $22,000 for a 135-unit project ($163/unit)<br>➢ $17,000 for a 98-unit project ($173/unit) |

## Recommendations and Considerations

Based on the findings presented above, the Team makes the following recommendations and considerations regarding the new program offerings. The Team provides more detailed rationale and additional considerations in Section 9. Supplemental program considerations can be found throughout the body of the report. Note that the Team will be conducting an additional task to develop a detailed Program Theory and Logic Model (PTLM) that will focus on the ability of the Passive House offering to generate market effects.

***Recommendations:***

**Allow for the use of both the WUFI Passive and PHPP models to calculate savings for their new offerings.** The Team recommends these tools be used to model both the proposed case and the baseline case to ensure consistency in the modeling of program savings. Specifically, the Team recommends using one modeling tool per project to assess savings; projects pursuing PHIUS certification should use WUFI Passive models, while projects pursuing PHI certification should use PHPP models.

**Monitor the energy performance of early program participants.** As part of the IDIs, developers indicated that they would be more likely to build to Passive House standards if they had proof that the buildings perform as efficiently as the modeling tools indicate they should. As a result, having monitored performance data from early participants may help recruit additional builders and developers into the programs.

***Considerations:***

**Revisit the current UDRH assumptions for both the MFHR and low-rise programs to ensure they are capturing all the savings opportunities associated with Passive House projects.** The Team suggests that stakeholders, including evaluation, implementation, and Passive House experts (such as PHIUS and Steven Winter Associates), revisit the current baseline assumptions and ensure they are appropriate for the new offerings.

**Conduct additional research that explores the accuracy of the modeling tools compared to actual billing data.** The question regarding which modeling software is more reliable and accurate can be further explored by leveraging non-program energy models from previous baseline studies that now have a few years of post-occupancy billing data available. The Team suggests that the PAs consider a study that compares each of the low-rise modeling tools included in this study to billing data to assess the accuracy of the modeling tools. The Team has all the schematics and energy models needed to conduct this assessment for low-rise non-program homes that participated in the 2015 baseline study.[5] A comparable effort could also be completed for the small number of buildings that participated in the most recent MFHR baseline study.[6] This study, coupled with the requirement to monitor energy consumption in participant projects, should answer most questions about the accuracy of the modeling tools discussed in this report.

**Offer an incentive that provides a reasonable amount of financial certainty for initial participants and is substantial enough to capture the attention of the market.** The current incentive levels for the MFHR Passive House offering are substantially larger than the traditional MFHR RNC program incentives (Table 1). The current MFHR incentive structure should be considered for all multifamily projects over five units. Projects that are five units or less and single-family projects should receive an incentive that is larger than the MFHR incentive on a per-unit basis, between $5,000 and $7,000 per unit.

**Spread incentives across various stages to provide upfront incentives to market actors and to provide flexibility in the program design regarding certification.** For multifamily projects with more than five units, the PAs should consider offering incentives for design team charrettes and initial modeling, pre-certification, and final certification; as done in the current MFHR incentive structure. For single-family and multifamily projects less than five units, the PAs should consider offering incentives for pre-certification and final certification (or Net Performance Bonus for projects that do not achieve or pursue final certification).

**Work closely with initial program participants to monitor the program design and allow for flexibility in programmatic changes when more information is available.** The Team recommends that the PAs work closely with initial participants to determine the extent to which the initial incentive amounts and incentive structure motivate potential market actors and cover the incremental costs associated with Passive House certification. Close collaboration can also inform the development of a best practice guide by the program for cost-effective project solutions – aimed at helping project teams achieve cost parity with non-passive house projects. As Passive house experts have suggested, incremental costs can be significantly reduced or eliminated with proper planning, experience, and training.

**Provide bonus incentives to initial participants for additional data to inform programmatic decisions.** The PAs should consider additional project incentives to initial participants that provide detailed cost information to better understand the incremental costs associated with Passive House certification and design techniques. Additional incentives may also be provided for project teams that share monitored energy consumption by end-use or non-energy impacts with the program.

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[5] http://ma-eeac.org/wordpress/wp-content/uploads/Single-Family-Code-Compliance-Baseline-Study-Volume-2.pdf
[6] http://ma-eeac.org/wordpress/wp-content/uploads/MA-Multifamily-High-Rise-Baseline-Study-Report.pdf

**Provide training specific to Passive House design and construction.** This includes trainings for contractors on best practices for air-sealing, avoiding thermal bridging, and proper HVAC system sizing. The program should also leverage the design and construction trainings established by the Passive House certification bodies.

**The PAs should consider leveraging the PHIUS certification rater checklist and project verification procedure for all participant projects.** The Passive House offering allows program participants to choose pursuing either PHIUS or PHI certification. While the two certification bodies share similar design principles, they have different performance requirements, as well as different verification requirements to achieve certification. PHIUS requires that a PHIUS certified rater is a part of the project team and completes an extensive verification checklist.[7] To verify that modeled inputs match the final construction, the program should consider requiring the PHIUS verification checklist or a similar checklist for all projects, regardless of which certification body is pursued.

**Work with multifamily project teams to develop occupant education plans aimed to reduce overall energy consumption.** The program has an opportunity to aid participants in the development of occupant education plans that aim to reduce the impact of occupant-driven variables on overall energy consumption, especially in larger multifamily buildings. The program could work with initial project teams to develop pilot occupant education plans to compare the actual performance of those buildings to similar buildings that have not administered an occupant education plan.

[7] https://www.phius.org/phius-certification-for-buildings-products/project-certification/documents-for-download

# Section 1 Introduction and Approach

This report presents findings from the MA19R05 Passive House evaluation. The Team presented an interim report that covered a detailed model comparison for five multifamily high-rise (MFHR) projects that incorporate Passive House design principles.[8] The results of the interim report were used by the Program Administrators (PAs) to inform their initial program offering for the MFHR new construction market (Table 6).[9]

**Table 6: Passive House Incentive Structure for Multifamily (Mid- and High-Rise)**

| Incentive Timing | Activity | Incentive Amount | Maximum Incentive |
|---|---|---|---|
| **Pre-construction** | Feasibility Study | 100% Feasibility Costs | $5,000 |
| | Energy Modeling | 75% of Energy Modeling Costs | $20,000 |
| | Pre-certification | $500/unit | N/A |
| **Post-Construction** | Certification | $2,500/unit | N/A |
| | Net Performance Bonus | $0.75/kWh | N/A |
| | | $7.50/therm | N/A |

*The Net Performance Bonus is calculated by determining the final pay for saving incentives and subtracting the pre- and final certification incentives. The result is the Net Performance Bonus.
**Projects that pre-certify but do not achieve certification are eligible for the pre-certification incentive and Net Performance Bonus.
***Projects over 100 units must be pre-approved by the applicable Sponsors of Mass Save.

In addition to those findings, the final report includes the model comparisons for four multifamily low-rise (MFLR) and five single-family projects that incorporate Passive House design principles. The results from the final report will be used by the PAs to inform their initial program offering for the MFLR and single-family new construction markets. The additional components to the interim report are found primarily in Section 3, Section 4, and Section 9.

The MFHR model comparison included three different energy modeling tools: the ICF MFHR tool, WUFI Passive, and PHPP. The low-rise and single-family portion of the model review compared the outputs from WUFI and PHPP to REM/Rate and Ekotrope – the past and present energy modeling software used by the program.

In addition to the modeling comparison, this report presents key findings from IDI's with 25 market actors. Market actors were asked to provide their perspective on various Passive House issues, the most important being the incremental costs associated with incorporating Passive House design principles into projects and the most useful incentive structure and amounts for the upcoming program. The Team included additional findings from the four interviews conducted after the interim report directly into the main body of the report.

[8] http://ma-eeac.org/wordpress/wp-content/uploads/MA19R05_PassiveHouse_InterimReport_Final_2019.06.23.pdf
[9] https://www.masssave.com/en/saving/residential-rebates/passive-house-incentives/

## 1.1 Introduction and Program Background

The Passive House Design concept began in the 1970's in response to the energy crisis. The approach to Passive House is to build a structure that has super-insulated walls and is air-tight.[10] The design principles also focus on optimized window performance, optimized solar and internal gains, and balanced heat and moisture recovery ventilation. The Passive House design principles are intended to lower peak heating and peak cooling load and result in minimized mechanical systems for heating and cooling.[11] Occupant comfort is a primary driver behind the design principles, as the building is designed to maintain optimal interior temperature and moisture conditions.

As noted in the final 2019-2021 Energy Efficiency Plan Term Sheet,[12] the PAs will implement a new Passive House offering in 2019-2021 through both training efforts and new incentive offerings. These offerings could include incentives to mitigate soft costs to help provide financial certainty early in projects, including an early modeling subsidy, design team incentives, design charrette incentives, and a certification subsidy. Additionally, the PAs could provide a performance-based incentive calculated on a $/kWh and $/therm savings basis. The PAs and the Department of Energy Resources (DOER) are committed to changing the process by which savings are claimed to be a more whole building performance-based approach for the Passive House offer.

The Massachusetts 2019-2021 three-year plan indicates that the new Passive House offering could include a multi-faceted incentive structure, outlined in Table 7. The new Passive House offering suggests that participants may pursue certification with either Passive House Institute of the United States (PHIUS) or the Passive House Institute (PHI), which was founded in Germany. The certification requirements for PHIUS are based off of the German PHI certification system, but it should be noted that the certification requirements differ between the two institutes.[13,14] The differences are primarily due to PHIUS applying U.S.-specific data for energy costs, construction costs, and climate data.

[10] This concept is not to be confused with passive solar design, which focuses on large southerly facing glazing. Passive solar did not take off as a building design concept due to net negative windows and large temperature swings from the heavy focus on southerly glazing.
[11] Passive House certification requires peak and annual loads to be under a specified threshold. The standard is different depending on whether Passive House Institute (PHI) or Passive House Institute-US (PHIUS) is pursued.
[12] http://ma-eeac.org/wordpress/wp-content/uploads/Term-Sheet-10-19-18-Final.pdf
[13] PHIUS+ 2015 climate specific requirements: http://www.phius.org/phius-2015-new-passive-building-standard-summary. Beginning in April, PHIUS will move to PHIUS+ 2018.
[14] PHI requirements: https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm

**Table 7: Potential Passive House Incentive Structure (based on 3-year plan)**

| Incentive Structure | Recipient | Details |
|---|---|---|
| Modeling Subsidy | Owner | Cost of Warme Und Feuchte Instationar (WUFI) or Passive House Planning Package (PHPP) modeling |
| Design Team Incentive | Architect, Design Team | $/kWh and $/therm incentives for projects achieving precertification and certification (if applicable) |
| Design Charrette | Architect, Design Team | Sustainability charrette incentive in either Programming and Schematic or Design Development design phases, directed to design team lead |
| Certification Subsidy | Owner | Adder per multifamily unit for achieving PHIUS or PHI certification |
| Performance Incentive | Owner | $/kwh and $/therm incentives for savings where projects are performing more efficient than the User Defined Reference Home for the residential portion and Mass Save baseline for the commercial spaces. |

## 1.2 Passive House Background and Certifications

There are two certification organizations for Passive House structures in the U.S., PHI and PHIUS.

The certification process for PHI is a pass/fail standard based on a limited set of criteria, with the primary metric being a threshold value for the modeled heating and cooling demand. The project team submits various project-specific documentation to be reviewed by a PHI Certifier to determine whether the project meets PHI standards. PHI recommends involving a certifier early in the planning process to help inform design decisions. However, projects may achieve certification without taking this step. The specific details on certification submittals are presented in the PHI building criteria.[15] PHI has three separate criteria: Passive House, EnerPHit (retrofits), and Low Energy Building Standard (for projects that are not able to meet the Passive House standards).

The PHIUS+ 2018 is also a pass/fail certification system. The certification process includes prescriptive quality assurance requirements adopted from the following U.S. government building programs: ENERGY STAR, Zero Energy Ready Home, and EPA Indoor airPLUS. PHIUS certification requirements include meeting space conditioning requirements, annual source-energy thresholds, and achieving an airtight envelope. The certification process requires the project team submit the required project documentation and meet various QA/QC protocols, which may vary slightly by building type.[16] The project certification process begins with pre-certification, a process used to verify that the energy model matches plans and specifications. The final

[15] https://passivehouse.com/downloads/03_building_criteria_en.pdf
[16] PHIUS. February 2019. “PHIUS+ 2018 Passive Building Standard Certification Guidebook Version 2.0.”

certification verifies that the finished building matches plans and specifications and is conducted by a PHIUS-certified independent Rater or Verifier.

More details on the Passive House certifications and their specific requirements can be found in the literature review that was delivered by NMR in early May of 2019.[17]

## 1.3 Evaluation Approach

The Team conducted five key tasks for the final report:

- A detailed model comparison for a sample of MFHR Passive House projects.
- A review of 2018 MFHR program participant data and a potential savings assessment.
- A detailed model comparison for a sample of MFLR and single-family Passive House projects.
- A review of low-rise program participant data.
- IDI's with market actors to understand the opportunities, barriers, incremental costs, and potential incentives associated with Passive House and the new offering.

Together these tasks are intended to inform the new program offerings. Details on the specific evaluation methods and the corresponding results can be found in the remaining report sections.

[17] http://ma-eeac.org/wordpress/wp-content/uploads/MA19R05_PassiveHouse_LitReview_Final_2019.07.17.pdf

# Section 2 Multifamily High-Rise Modeling

The primary purpose of the modeling task was to assess the capabilities of different modeling tools and determine the extent to which they can be used to model baseline conditions for Passive House projects. In particular, the Team assessed how the various models considered in this study handle proposed Passive House designs and how they handle modeling the baseline conditions outlined in the MFHR UDRH. The results of the MFHR modeling comparison are the same as presented in the interim report. The results of the modeling comparison were used to inform the program design, determine which modeling tools should be allowed to calculate program savings, and to determine what steps are required to ensure that models reflect the actual features of these projects (see Table 6 for details on the current MFHR Passive House offering).

The Team worked collaboratively with ICF, the RNC program's implementation contractor, PHIUS, and Steven Winter Associates to execute the MFHR modeling task. Working with our team members, we collectively identified five multifamily projects that were built or designed using Passive House design principles to assess the capabilities of three separate modeling tools. The modeling tools that are compared in this report are detailed in Table 8.

**Table 8: MFHR Modeling Tools**

| Modeling Tool | Details |
|---|---|
| ICF's Multifamily High-Rise Tool | The tool currently used to model savings for the Multifamily High Rise (MFHR) New Construction Program. This tool is run on an EnergyPlus platform using OpenStudio and a custom API. |
| Warme Und Feuchte Instationar (WUFI) Passive | The Passive House modeling tool used to certify projects under the Passive House Institute U.S. (PHIUS) certification body. |
| Passive House Planning Package (PHPP) | The Passive House modeling tool used to certify projects under the Passive House International (PHI) certification body. |

Each tool was used to model the five projects under two different scenarios:

1. The proposed design scenario that represents the projects as they were designed incorporating Passive House design principles.
2. The baseline scenario that represents the same projects modeled to reflect the current MFHR UDRH assumptions.

The Team coordinated with ICF, PHIUS, and Steven Winter Associates to ensure consistency across the modeling tools in terms of model inputs and assumptions. For example, the Team worked to align assumptions surrounding square footage, lighting, and air infiltration across the tools. More details on the assumptions that were made to maintain consistency between the tools can be found in Section 2.2 and in Appendix B.

## 2.1 MFHR Methods and Processes

Currently, program savings for MFHR program participants are calculated by comparing the MFHR UDRH to the proposed building using ICFs multifamily modeling tool. The Team conducted a comparison of modeled outputs between WUFI Passive, PHPP, and the ICF modeling tool to assist in the determination of the best way to claim savings for mid-rise and high-rise multifamily projects in the new Passive House offering.

The Team obtained energy models and additional project documentation for five multifamily Passive House projects that had met pre-certification or final certification requirements.[18] The Team provided a $500 incentive to project teams that agreed to participate. Due to the limited number of certified multifamily Passive House projects in Massachusetts, the Team looked to surrounding states to fill the sample quota. One of the five projects is based in Massachusetts while the other four are in New York. The energy modeling team collaborated on the recruitment and procurement of the project participants. Recruitment emails were sent out to a sample of potential participants that detailed the study and the incentive amount. Potential participants were strategically selected so that the Team could procure files for a variety of project sizes. Participants provided energy models and any additional project files that were essential for developing models in the three software packages that were included in the model comparison effort.

Some summary information about the projects can be found in Table 9 and Table 10.

[18] Note that the MFHR projects that agreed to participate achieved or are pursuing certification through PHIUS.

**Table 9: MFHR Sampled Projects – Project Details**

| Site ID | Climate Location | Gross Square Footage | # of Res Stories | # of Units | Heating Type[19] | DHW Type | Ventilation Type[20] |
|---|---|---|---|---|---|---|---|
| Site 1 | Boston | 33,500 | 4 | 28 | DMS | Central Boiler | ERV |
| Site 2 | NY - JFK | 110,185 | 7 | 101 | Central VRF -w/heat recovery | Central Boiler | ERV |
| Site 3 | NY - LaGuardia | 156,940 | 14 | 154 | Central VRF -w/heat recovery | Central Boiler | ERV |
| Site 4 | NY - LaGuardia | 234,958 | 11 | 249 | Central VRF -w/heat recovery | Instantaneous system - electric | ERV |
| Site 5 | NY - LaGuardia | 261,260 | 26 | 277 | Central VRF -w/heat recovery | Central Boiler | ERV |
| Baseline Scenario (MFHR UDRH) | Same as reference building | Same as reference building | Same as reference building | Same as reference building | Same type – efficiency adjusted | Same type – efficiency adjusted | Same as reference building |

**Table 10: MFHR Sampled Projects – Efficiency Details**

| Site ID | Wall R-value | Roof R-value | Window U-factor | Window SHGC | Infiltration Rate (ACH50) | Infiltration Rate ($CFM50/ft^2$) |
|---|---|---|---|---|---|---|
| Site 1 | R-32 | R-100 | 0.138 | 0.61 | 0.56 | 0.076 |
| Site 2 | R-24 | R-33 | 0.276 | 0.36 | 0.50 | 0.068 |
| Site 3 | R-26 | R-31 | 0.202 | 0.26 | 0.21 | 0.034 |
| Site 4 | R-22 | R-50 | 0.339 | 0.34 | 0.42 | 0.070 |
| Site 5 | R-19 | R-30 | 0.314 | 0.25 | 0.35 | 0.047 |
| Baseline Scenario (MFHR UDRH) | R-14.84 (Mass Wall) | R-30.34 | 0.38 | 0.40 | Variable by project volume | 0.31 |

Due to the limited number of Passive House projects used for this study, it should be noted that the results are not statistically robust, but instead are intended to inform the program design surrounding savings calculations.

[19] Ductless mini-split (DMS) heat pump systems use inverter-driven compressor technology and can be installed in split or multi-split configurations. A common configuration is to install one or more wall-mounted indoor evaporator units that are connected to one outdoor condenser. Variable Refrigerant Flow (VRF) heat pump systems are similar

## 2.2 MFHR Assumptions

Once the study participants agreed and project files were provided, the energy modeling team collaborated to develop energy models in the various software packages that aligned with the proposed buildings conditions. The energy modeling team then worked to develop the baseline models, which applied the MFHR UDRH assumptions that are currently used to calculate program savings. This process required the Team to conduct baseline energy consumption calculations that also led to adjustments in the proposed models. Once both the baseline and proposed models were completed in all three software packages, the energy modeling team set up several follow-up collaboration sessions to clarify that correct adjustments were made between the software packages and to discuss the most appropriate way to handle the fundamental differences between the tools. Certain model inputs, such as square footage and occupancy, were adjusted in both the proposed and baseline models while others, such as insulation levels and mechanical equipment efficiencies, only impacted the baseline model. A list of the assumptions is provided in Appendix B and the MFHR UDRH assumptions are provided in Appendix D.

The modeling and coordination effort between the energy modeling teams required significant input from all involved. The energy modeling teams were also pressed for time, which added a layer of complexity to the process. The flexibility in the Passive House tools allowed the modeling team to align inputs that were more challenging to adjust in the ICF tool based on the information available to the energy modeling team. Lighting inputs were aligned between the models, interior equipment consumption remained at equivalent levels between the proposed and baseline models, and pumps were attributed to either heating, cooling, and domestic hot water end-uses when possible.[21]

## 2.3 MFHR Summary Results

The summary of site energy use intensity (EUI) results for all projects are displayed in Table 11. This is not a comparison between the PHI and PHIUS certifications, rather it is meant to inform the program on the most appropriate method for claiming savings over the baseline scenario. The Team has not only considered the outputs but also the implications on:

- Ease of use for program administrators, implementors, HERS raters, and participants.
- Transparency of methodology and approach.
- Ability to incorporate appropriate measures and baseline metrics.
- The need to characterize whole building savings by end-use.

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to multi-split heat pumps, but they are often larger and more complex. VRF systems have the ability to simultaneously heat and cool, while recovering heat from one zone to another.

[20] Energy Recovery Ventilators (ERVs) are mechanical ventilation systems have heat exchanger that transmits some amount of water vapor along with the heat energy, this differs from a Heat Recovery Ventilator (HRV), whereas only heat is transferred.

[21] Consumption for pump end-uses remain aggregated in the PHPP end-use category due to complexities and time constraints distributing the specific pump use into hot water, heating, and cooling end-use categories.

The results of the energy modeling indicate that while there are subtle differences between WUFI and PHPP, each model produces similar results when assumptions are consistent between the two tools – though PHPP shows a higher level of savings. The ICF tool resulted in higher levels of overall average consumption for both the baseline and proposed cases, but the savings results indicate that the ICF tool has saving levels in line with the WUFI and PHPP results. After considering the level of effort to re-model the project from either of the Passive House tools to the ICF tool, the public availability of the Passive House tools[22], similar savings results, and the effort needed to adjust WUFI or PHPP default values to the baseline scenario – the Team concludes that either WUFI or PHPP are appropriate tools to calculate savings over the baseline when the assumptions are adjusted as recommended for the Passive House offering. Note, we are not recommending that both WUFI and PHPP be used for a single project. Rather, the Team is suggesting projects pursuing PHIUS certification use WUFI while projects pursuing PHI certification using PHPP.

Note that interpreting the accuracy of the modeled results is limited due to a lack of monitored billing data for Passive House projects. Determining the accuracy of the models requires comparisons to actual performance that were not available at the time of this study. Monitoring actual performance of future participants going through the program will provide insights on this question, as well as communicable information to the market, as described in the findings from the in-depth interviews (IDIs) with various market actors.

The average savings from all five projects were within 4% of each other for the three tools – the percentage savings over baseline site EUI consumption was 29% for the ICF tool, 31% for WUFI Passive, and 33% for PHPP. The ICF tool's overall average annual consumption results were higher for both the proposed and baseline case but resulted in the lowest percent savings. The total annual consumption results are provided in Table 41 of Appendix B.

[22] Note that both WUFI Passive and PHPP are publicly available at a cost. There is a free version of WUFI Passive that can be used for certification through PHIUS, but it has limited functionality. The ICF tool is used as an internal program tool for the MFHR program and is not publicly available.

Table 11: MFHR Summary Modeling Site EUI Results (kBtu/ft²/Year)

| Site ID | Baseline Results Site EUI (kBtu/ft²/yr) | | |
|---|---|---|---|
| | ICF | WUFI | PHPP |
| Site 1 | 40.8 | 46.9 | 45.4 |
| Site 2 | 37.7 | 36.8 | 35.5 |
| Site 3 | 36.6 | 38.2 | 37.7 |
| Site 4 | 40.3 | 34.8 | 34.2 |
| Site 5 | 39.5 | 33.4 | 33.6 |
| **Average Site EUI** | **39.0** | **38.0** | **37.3** |
| **Site ID** | **Proposed Results Site EUI (kBtu/ft²/yr)** | | |
| | **ICF** | **WUFI** | **PHPP** |
| Site 1 | 27.1 | 29.1 | 26.1 |
| Site 2 | 27.5 | 25.4 | 24.0 |
| Site 3 | 25.2 | 26.7 | 25.8 |
| Site 4 | 29.1 | 25.2 | 24.3 |
| Site 5 | 28.7 | 23.1 | 22.8 |
| **Average Site EUI** | **27.5** | **25.9** | **24.6** |
| **Site ID** | **Savings Results Site EUI (kBtu/ft²/yr)** | | |
| | **ICF** | **WUFI** | **PHPP** |
| Site 1 | 13.7 | 17.8 | 19.3 |
| Site 2 | 10.2 | 11.4 | 11.5 |
| Site 3 | 11.4 | 11.5 | 11.9 |
| Site 4 | 11.3 | 9.5 | 9.9 |
| Site 5 | 10.7 | 10.2 | 10.8 |
| **Average Site EUI** | **11.5** | **12.1** | **12.7** |
| **Site ID** | **% Savings Results Site EUI (kBtu/ft²/yr)** | | |
| | **ICF** | **WUFI** | **PHPP** |
| Site 1 | 33% | 38% | 43% |
| Site 2 | 27% | 31% | 32% |
| Site 3 | 31% | 30% | 32% |
| Site 4 | 28% | 27% | 29% |
| Site 5 | 27% | 31% | 32% |
| **Average Site EUI** | **29%** | **31%** | **33%** |

## 2.4 MFHR Proposed Models

The Team looked at the proposed site EUI by end-use to understand what differences existed between the models and what drivers may have caused these differences. In general, the Passive House tools were fairly aligned by end-use. The ICF tool outputs indicate some end-uses that are a fair amount higher than the Passive House tools (see Figure 5 and Table 12). The ICF tool output indicates a much higher consumption from cooling (~72% higher) and heating (~50% higher), than the Passive House models, though heating and cooling loads are a small contributor to the total site EUI. Overall, hot water and interior equipment end-uses drive a substantial proportion of the average site EUI for the proposed models.

The Passive House model outputs for hot water were higher than the ICF tool. The average site EUI for hot water was ~18% lower in the ICF tool. The differences in hot water consumption are likely driven by the Passive House tools factoring in transmission pipe losses.

**Figure 5: MFHR Average Proposed Model Site EUI by End-Use (kBtu/ft²/Year)**

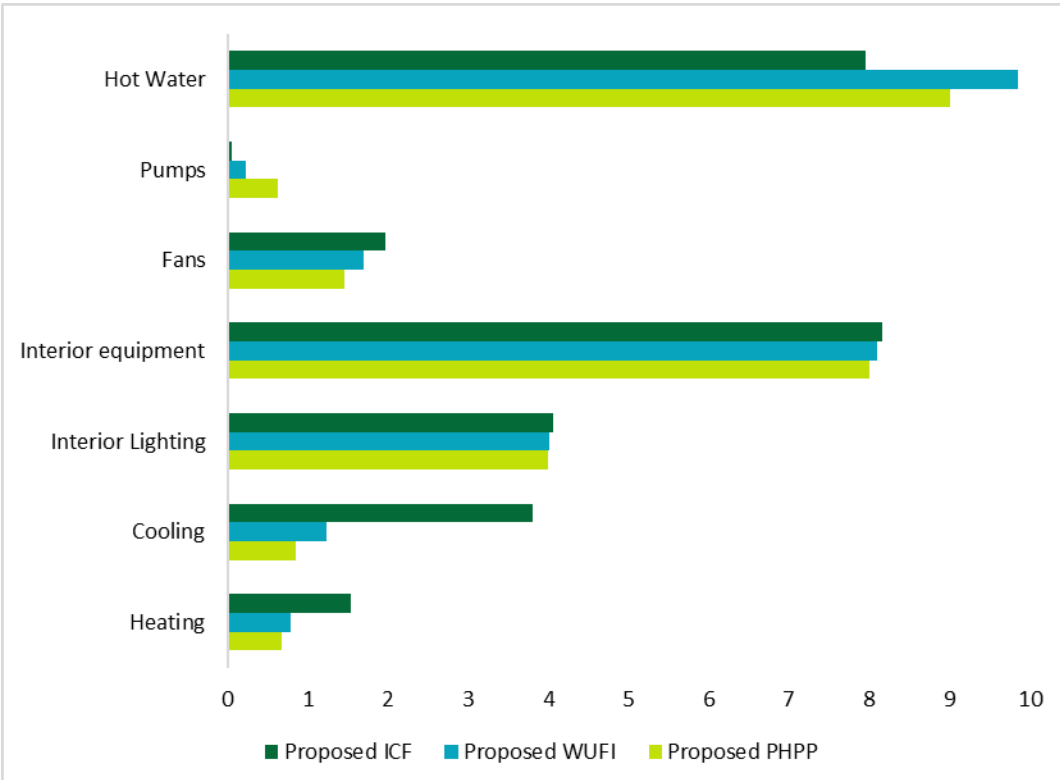


**Table 12: MFHR Average Proposed Model Site EUI by End-Use (kBtu/ft²/Year)**

| End-Use | ICF | WUFI | PHPP |
|---|---|---|---|
| Heating | 1.5 | 0.8 | 0.7 |
| Cooling | 3.8 | 1.2 | 0.9 |
| Interior lighting | 4.1 | 4.0 | 4.0 |
| Interior equipment | 8.2 | 8.1 | 8.0 |
| Fans | 2.0 | 1.7 | 1.5 |
| Pumps | 0.1 | 0.2 | 0.6 |
| Hot Water | 8.0 | 9.9 | 9.0 |
| **Total** | **27.5** | **25.9** | **24.6** |

## 2.5 MFHR Baseline Models

The baseline model scenarios were based on the current MFHR program UDRH and team modeling assumptions (described above, in Section 2.2, and in Table 40 of Appendix B). The Team found similar trends as in the proposed models when looking at the baseline site EUI model outputs by end-use. The Passive House tools were once again fairly aligned by end-use. The ICF tool results indicated higher baseline consumption for cooling (~64%), fans (46%), and heating (~8%) than the Passive House tools (see Figure 6 and Table 13). The ICF tool results were also lower for hot water (~23%) and pumps (~75%).

As described above, the current MFHR program baseline was applied to the baseline models. The Team identified that potential adjustments to the baseline scenario may be appropriate for the Passive House baseline. Passive House standards emphasize using electric heating and cooling methods – which appears to be primarily delivered to Passive House multifamily projects through inverter-driven compressors – either split or multi-split systems, or central variable refrigerant flow (VRF) systems. The current baseline provides efficiency adjustments for these measures. That said, after a review of the program tracking data, the Team found that only 8% of program participants actually applied VRF systems and another 6% used mini-split systems. The Team anticipates that future passive multifamily projects will primarily use central VRF systems and some smaller projects will continue to use the split systems. This would suggest potentially modeling a more common heating system, fuel, and efficiency for these projects – such as a central boiler or furnace for heating (these equipment types account for 70% of program heating systems) and central air-conditioners for cooling. Mechanical ventilation, occupancy calculations, infiltration, hot water consumption (gal/person), and design set point temperatures for heating, cooling, and DHW may also warrant an adjustment to the current baseline protocols for the new Passive House offering.

Figure 6: MFHR Average Baseline Model Site EUI by End-Use (kBtu/ft²/Year)

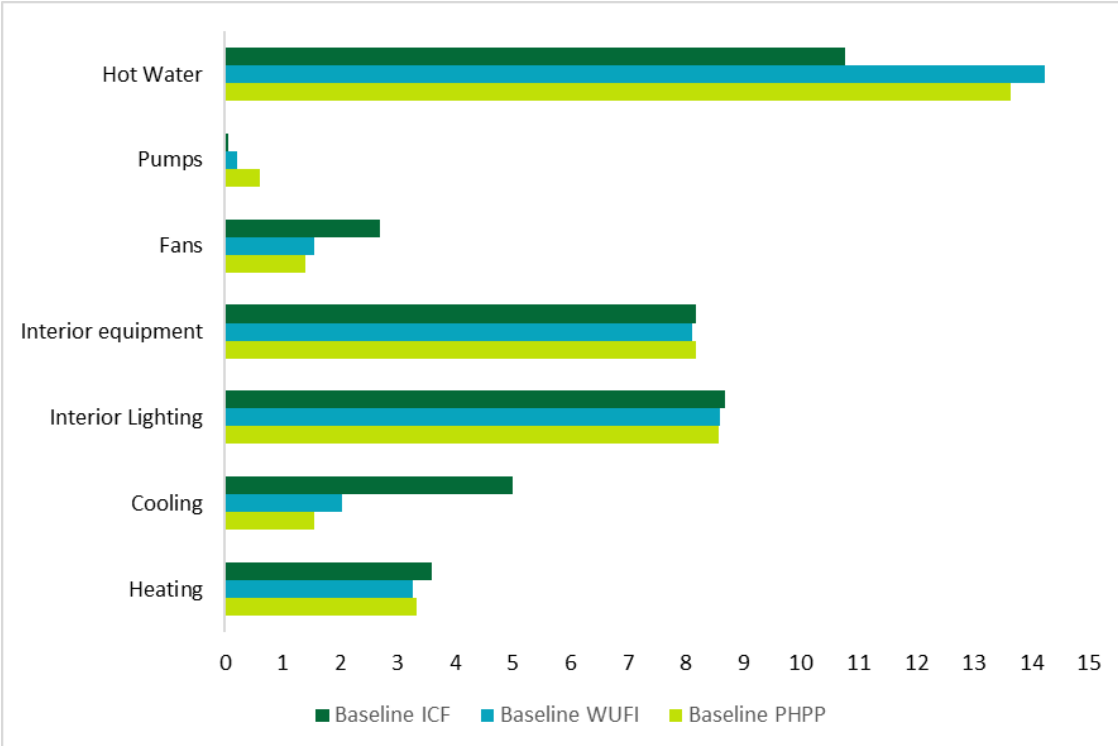


Table 13: MFHR Average Baseline Model Site EUI by End-Use (kBtu/ft²/Year)

| End-Use | ICF | WUFI | PHPP |
|---|---|---|---|
| Heating | 3.6 | 3.3 | 3.3 |
| Cooling | 5.0 | 2.0 | 1.6 |
| Interior lighting | 8.7 | 8.6 | 8.6 |
| Interior equipment | 8.2 | 8.1 | 8.2 |
| Fans | 2.7 | 1.5 | 1.4 |
| Pumps | 0.1 | 0.2 | 0.6 |
| Hot Water | 10.8 | 14.2 | 13.7 |
| **Total** | **39.0** | **38.0** | **37.3** |

## 2.6 MFHR End-Use Savings Results

The average savings by end-use for each of the three models are presented in Figure 7 and Table 14. The five modeled projects attribute a higher level of lighting end-use savings on average when compared to the average lighting savings from 62 actual MFHR program participants (4.6 kBtu/ft²/year vs. 3.2 kBtu/ft²/year). The higher lighting savings in the Passive House models compared to the program's average lighting savings may be attributed to the use of the certification protocols on calculating lighting consumption, which may overstate the amount of savings that would be derived with the use of project-specific detailed lighting schedules. However, it should be noted that the lighting end-use savings of the modeled Passive House projects fell within the program's range of lighting end-use savings (0.0 to 6.6 kBtu/ft²/year). The Team did not have detailed lighting schedules for the sampled projects and leveraged the certification's lighting calculator and assumptions (see Appendix B for details on modeling assumptions). However, even though lighting savings are potentially overstated using the certifications lighting protocol, the Team anticipates that lighting savings would be higher in Passive House projects than the average program participant lighting savings.

The average fan consumption for WUFI and PHPP resulted in negative savings. The Team attributes the negative fan savings to the UDRH baseline ventilation rate adjustment (which lowers the ventilation requirement in the baseline scenario compared to the proposed scenario).[23]

As expected, based on the proposed and baseline end-use results, the Passive House tools are closely aligned for most end-uses. Even though the ICF tool resulted in a lower site EUI, the overall site EUI savings were within 4% for all three models.[24] The average site EUI savings results indicate that Passive House tools are capable of modeling the baseline scenario, and the ICF tool is capable of modeling the proposed scenario. However, as mentioned above, the Team recommends the Passive House tools are used to model savings for the Passive House offering due to additional reasons such as the level of effort for remodeling in the ICF tool, Passive House tool flexibility, public availability, and comparable savings results.

**Figure 7: MFHR Average Site EUI Savings by End-Use (kBtu/ft$^2$/Year)**


[23] The energy modeling team also discussed that this may also be attributed to the fact that the proposed models assume ERVs while the baseline models don't assume ERVs. Introducing an ERV core into the ventilation air streams increase pressure drops that need to be made up with more fan energy consumption.

[24] Due to the small sample sizes, the Team was not able to determine if the differences were statistically significant.

**Table 14: MFHR Average Site EUI Savings by End-Use (kBtu/ft²/Year)**

| End-Use | ICF | WUFI | PHPP |
|---|---|---|---|
| Heating | 2.1 | 2.5 | 2.7 |
| Cooling | 1.2 | 0.8 | 0.7 |
| Interior lighting | 4.6 | 4.6 | 4.6 |
| Interior equipment | 0.0 | 0.0 | 0.2 |
| Fans | 0.7 | -0.2 | -0.1 |
| Pumps | 0.0 | 0.0 | 0.0 |
| Hot Water | 2.8 | 4.4 | 4.6 |
| **Total** | **11.5** | **12.1** | **12.7** |

## 2.7 Current MFHR Program Participant Savings Results by End-Use

Table 15 provides the average site EUI by end-use for the proposed and the baseline scenarios of 62 MFHR program participants. These values represent the proposed building conditions and the baseline building conditions (application of the MFHR UDRH) modeled in the ICF MFHR Tool. As with the five passive house projects, average site EUI savings are highest for lighting and water heating for the program models. Cooling is also a minor contributor to overall savings, behind lighting and water heating, while program homes do not see heating savings in the aggregate when comparing the proposed models to the UDRH baseline. The lack of heating savings is primarily attributed to the loss of internal gains from increased levels of high efficiency lighting in the proposed models.

While the sample size of the modeled results presented in Table 14 are limited, the results suggest sizable savings over the current MFHR participants. The results suggest the modeled Passive House projects achieve 74% to 92% higher savings (in site EUI) than the current program.

**Table 15: MFHR Proposed Savings over Baseline for Program Models 62 program participants by End-Use (kBtu/ft²/Year)**

| End-Use | Baseline | Proposed* | Savings* |
|---|---|---|---|
| Heating | 2.8 | 2.9 | -0.1 |
| Cooling | 3.0 | 2.3 | 0.8 |
| Interior lighting | 8.2 | 5.0 | 3.2 |
| Interior equipment | 8.5 | 8.5 | - |
| Fans | 1.1 | 1.0 | 0.2 |
| Pumps | 0.3 | 0.2 | <0.1 |
| Hot Water | 11.9 | 9.4 | 2.5 |
| Heat Rejection | 0.1 | 0.1 | <0.1 |
| **Total** | **35.9** | **29.2** | **6.6** |

*Totals may not sum due to rounding.

# Section 3 Multifamily Low-Rise Modeling

Currently, program savings for MFLR program participants are calculated by comparing the low-rise UDRH to the proposed building using Ekotrope, a cloud-based energy modeling tool.[25]

The modeling process for the MFLR sample was only conducted in REM/Rate and Ekotrope for two of the four sampled projects. The Team was not able to replicate the two largest sample projects in REM/Rate or Ekotrope due to time and budget constraints. Ekotrope and REM/Rate software are typically meant for individual-unit level modeling – whether that is single-family homes or individual apartment units. Alternatively, the Passive House tools are designed to model whole buildings. In order to replicate the two larger MFLR sample projects, the Team would have needed to develop up to 60 separate proposed unit models and 60 separate baseline models in REM/Rate or Ekotrope to compare to one whole-building model in either of the Passive House tools. In addition to the time and budget constraints, the Team believes that the comparison between only unit-level models and whole building models would likely be misleading – especially on the larger MFLR projects. That said, the Team was able to construct the unit-level models for the two smaller sampled MFLR projects (3-units and 30-units).[26]

The results below show only comparisons among the Passive House tools as those are the models where we were able to compare all four sample projects. A comparison across all four modeling tools for the two projects where this comparison was feasible is presented in Appendix C. This section of the report details the results from all four sample projects in WUFI and PHPP to maintain consistency with the MFHR and single-family sections of the report.

The Team worked collaboratively with PHIUS and Steven Winter Associates to execute the MFLR modeling task. Working with our team members, we collectively identified four multifamily projects that were built or designed using Passive House design principles to assess the capabilities of three separate modeling tools. The modeling tools that are compared in this report are detailed in Table 16.

[25] https://ekotrope.com/

[26] Please note that while the 3-unit project was included in the MFLR section, the program defines attached buildings with less than five units as single-family dwellings. For the purposes of this study the Team considered single-family as single-family detached buildings and buildings with multiple units as multifamily.

**Table 16: Low-Rise Modeling Tools**

| Modeling Tool | Details |
|---|---|
| Ekotrope | The HERS modeling tool currently used to model savings for the RNC Program. |
| REM/Rate | The HERS modeling tool formerly used to model savings for the RNC Program. |
| Warme Und Feuchte Instationar (WUFI) Passive | The Passive House modeling tool used to certify projects under the Passive House Institute U.S. (PHIUS) certification body. |
| Passive House Planning Package (PHPP) | The Passive House modeling tool used to certify projects under the Passive House International (PHI) certification body. |

Each modeling tool was used to model two sampled projects (results presented in Appendix C) and the Passive House tools were used to model all four projects (results presented in the subsections below) under two different scenarios:

1. The proposed design scenario that represents the projects as they were designed incorporating Passive House design principles.
2. The baseline scenario that represents the same projects modeled to reflect the current low-rise UDRH assumptions.

The Team coordinated with PHIUS and Steven Winter Associates to ensure consistency across the modeling tools in terms of model inputs and assumptions. For example, the Team worked to align assumptions surrounding square footage, air infiltration, and building component efficiencies across the tools.

## 3.1 MFLR Methods and Process

The Team obtained energy models and additional project documentation for four MFLR Passive House projects that had met pre-certification or final certification requirements. The Team provided a $300 incentive to project teams that agreed to participate. Due to no certified MFLR Passive House projects in Massachusetts at the time of recruitment, the Team looked to surrounding states to fill the sample quota. The four projects were located in separate states: CT, NY, PA, and VT. The energy modeling team collaborated on the recruitment and procurement of the project participants. Recruitment emails were sent out to a sample of potential participants that detailed the study and the incentive amount. Potential participants were strategically selected so that the Team could procure files for a variety of project sizes. Participants provided energy models and any additional project files that were essential for developing models in the four software packages that were included in the model comparison.

Some summary information about the projects can be found in Table 17 and Table 18.

**Table 17: MFLR Sampled Projects – Project Details**

| Site ID | Climate Location | iCFA[27] | # of Res Stories | # of Units | Heating Type | DHW Type | Ventilation Type |
|---|---|---|---|---|---|---|---|
| Site 1 | NY – Stewart Field | 2,354 | 3 | 3 | DMS | HPWH | HRV |
| Site 2 | VT - Burlington | 27,690 | 3 | 30 | DMS | Boiler - Gas | ERV |
| Site 3 | PA - Harrisburg | 45,235 | 3 | 49 | DMS | HPWH | ERV |
| Site 4 | CT - Hartford | 70,247 | 3 | 63 | DMS | Boiler - Gas | ERV |
| Baseline Scenario (Low-rise UDRH) | Same as reference building | Same as reference building | Same as reference building | Same as reference building | Same type – efficiency adjusted | Same type – efficiency adjusted | Same as reference building |

**Table 18: MFLR Sampled Projects – Efficiency Details**

| Site ID | Wall R-value | Roof R-value | Window U-factor | Window SHGC | Infiltration Rate (ACH50) |
|---|---|---|---|---|---|
| Site 1 | R-35 | R-64 | 0.192 | 0.53 | 0.96 |
| Site 2 | R-38 | R-70 | 0.136 | 0.34 | 0.53 |
| Site 3 | R-24 | R-67 | 0.303 | 0.31 | 0.45 |
| Site 4 | R-35 | R-41 | 0.139 | 0.43 | 0.42 |
| Baseline Scenario (Low-rise UDRH) | R-16.1 | Flat: R-33.3<br>Vault: R-26.3 | 0.30 | 0.30 | 3.57 |

## 3.2 MFLR Assumptions

Once the study participants agreed to participate and project files were provided, the energy modeling team collaborated to develop energy models in the various software packages that aligned with the proposed buildings' conditions. The energy modeling team then worked to develop the baseline models, which applied the low-rise UDRH assumptions that are currently used to calculate program savings.

The energy modeling team deviated slightly from the low-rise UDRH when applying window areas for the baseline models. The low-rise program UDRH states that window area is to be distributed equally in four cardinal directions. Due to some of the projects facing more or less than four cardinal directions, the Team distributed window area based on the proportion of window-to-wall

[27] Interior Conditioned Floor Area (iCFA) is any interior space at least 7' in height, drywall-to-drywall. This includes stairs, cabinets, interior walls, mechanical spaces, storage, etc. This excludes open-to-below areas and unconditioned spaces.

area for each orientation. This also aided in simplifying window redistribution for the three-dimensional models used in WUFI. The window area inputs were aligned between all models.

During the energy modeling team's quality control process, a discrepancy regarding the de-rating of heat pumps was found between the Passive House models and the traditional Ekotrope and REM/Rate models. Both of the Passive House certifications require heat pump efficiency levels to be de-rated based on performance in various temperature conditions and to account for interactive effects on space heating, whereas nominal efficiency values are generally applied to Ekotrope and REM/Rate.[28,29] The Team decided to apply the de-rated efficiency values to all of the models for consistency and a more conservative heat pump performance. Essentially, this means that heat pump efficiency values for water heating, space heating, and space cooling are discounted to reflect a more conservative equipment efficiency. The Team applied the de-rated values to both the proposed and baseline models. This resulted in higher consumption values in both the proposed and baseline conditions.

Lighting and appliances inputs were not changed between the proposed and baseline models, as the low-rise RNC program currently does not claim savings for these measures using energy modeled outputs.

## 3.3 MFLR Summary Results

As stated above, only two sampled projects were modeled in all four software packages. The results for the two projects are presented in Appendix C. The following subsections display the results for the four sampled projects that were modeled in WUFI and PHPP.

The summary site EUI results for all projects are displayed in Table 19. This is not a comparison between the PHI and PHIUS certifications, rather it is meant to inform the program on the most appropriate method for claiming savings over the baseline scenario. The Team has not only considered the outputs but also the implications on:

- Ease of use for program administrators, implementors, HERS raters, and participants.
- Transparency of methodology and approach.
- Ability to incorporate appropriate measures and baseline metrics.
- The need to characterize whole building savings by end-use.

Note that interpreting the accuracy of the modeled results is limited due to a lack of monitored billing data for Passive House projects. Determining the accuracy of the models requires comparisons to actual performance that were not available at the time of this study. Monitoring actual performance of future participants going through the program will provide insights on this question, as well as communicable information to the market, as described in the findings from the IDIs with various market actors.

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[28] PHIUS Heat Pump Protocol and Calculator: http://phius.org/Tools-Resources/Protocols-Calculators/Tech_Corner_9%20Heat_Pump.zip

[29] PHI calculates the de-rated heat pump performance directly in the PHPP model. PHI protocol differs from PHIUS in that the user inputs COP values for additional temperature test points – provided by manufacturer specification sheets.

The average savings from the four projects were similar between WUFI and PHPP when the inputs were aligned, with the percent difference between the proposed and baseline models both at 33%. Interestingly, the percent savings for the MFLR models were very similar to the percent savings for the MFHR projects. The total annual consumption results are provided in Table 42 of Appendix B.

### Table 19: MFLR Summary Modeling Site EUI Results (kBtu/iCFA/Year)

| Site ID | Baseline Results Site EUI (kBtu/iCFA/yr) | |
|---|---|---|
| | WUFI | PHPP |
| Site 1 | 40.4 | 43.6 |
| Site 2 | 42.0 | 44.8 |
| Site 3 | 29.8 | 28.9 |
| Site 4 | 32.8 | 32.9 |
| **Average Site EUI** | **36.2** | **37.6** |
| **Site ID** | **Proposed Results Site EUI (kBtu/iCFA/yr)** | |
| | **WUFI** | **PHPP** |
| Site 1 | 25.7 | 26.1 |
| Site 2 | 28.3 | 29.4 |
| Site 3 | 18.7 | 19.4 |
| Site 4 | 24.3 | 24.6 |
| **Average Site EUI** | **24.2** | **24.9** |
| **Site ID** | **Savings Results Site EUI (kBtu/iCFA/yr)** | |
| | **WUFI** | **PHPP** |
| Site 1 | 14.8 | 17.6 |
| Site 2 | 13.7 | 15.4 |
| Site 3 | 11.0 | 9.5 |
| Site 4 | 8.5 | 8.3 |
| **Average Site EUI** | **12.0** | **12.7** |
| **Site ID** | **% Savings Results Site EUI (kBtu/iCFA/yr)** | |
| | **WUFI** | **PHPP** |
| Site 1 | 37% | 40% |
| Site 2 | 33% | 34% |
| Site 3 | 37% | 33% |
| Site 4 | 26% | 25% |
| **Average Site EUI** | **33%** | **33%** |

## 3.4 MFLR Proposed Models

The Team looked at the proposed site EUI by end-use to understand what differences existed between the models and what drivers may have caused these differences. In general, the Passive House tools were fairly aligned by end-use, the largest difference was in lighting and appliances, followed by a small difference in heating end-use. (see Figure 8 and Table 20).

Figure 8: MFLR Average Proposed Model Site EUI by End-Use (kBtu/iCFA/Year)

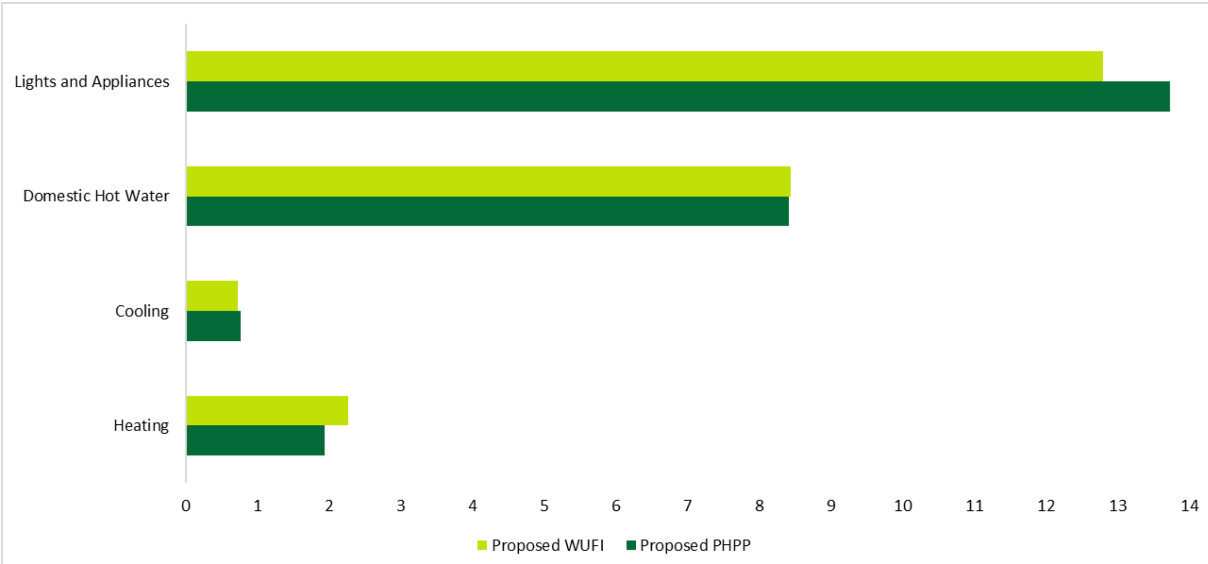



Table 20: MFLR Average Proposed Model Site EUI by End-Use (kBtu/iCFA/Year)

| End-Use | WUFI | PHPP |
|---|---|---|
| Heating | 2.3 | 1.9 |
| Cooling | 0.7 | 0.8 |
| Hot Water | 8.4 | 8.4 |
| Lighting and Appliances | 12.8 | 13.7 |
| **Total** | **24.2** | **24.9** |

## 3.5 MFLR Baseline Models

The Team found similar trends as in the proposed models when looking at the baseline site EUI model outputs by end-use. The Passive House tools were once again fairly aligned by end-use, with lighting and appliance end-uses seeing the largest difference between the two models, followed by heating (see Figure 9 and Table 21).

Figure 9: MFLR Average Baseline Model Site EUI by End-Use (kBtu/iCFA/Year)

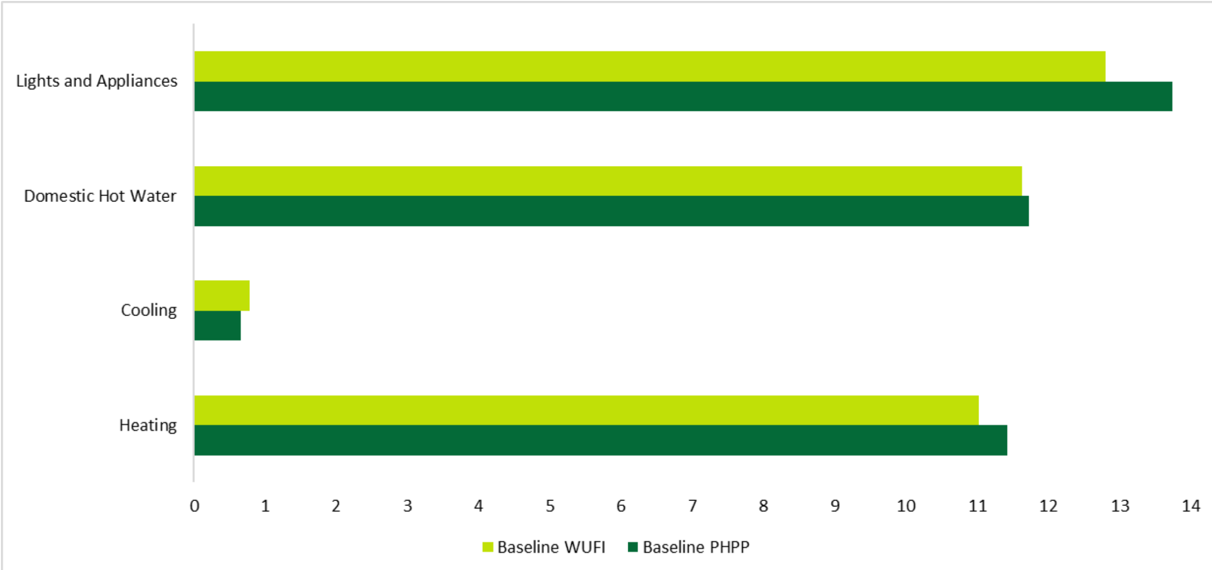



Table 21: MFLR Average Baseline Model Site EUI by End-Use (kBtu/iCFA/Year)

| End-Use | WUFI | PHPP |
|---|---|---|
| Heating | 11.0 | 11.4 |
| Cooling | 0.8 | 0.7 |
| Hot Water | 11.6 | 11.7 |
| Lighting and Appliances | 12.8 | 13.7 |
| **Total** | **36.2** | **37.6** |

## 3.6 MFLR End-Use Savings Results

The average savings by end-use for each of the three models are presented in Figure 10 and Table 22. The largest site EUI savings were from the heating end-use (9.5 for PHPP and 8.8 for WUFI, respectively) followed by hot water (3.3 for PHPP and 3.2 for WUFI). While average site EUI savings were similar, PHPP had a slightly higher site EUI savings on average compared to WUFI.

**Figure 10: MFLR Average Savings by End-Use (kBtu/iCFA/Year)**

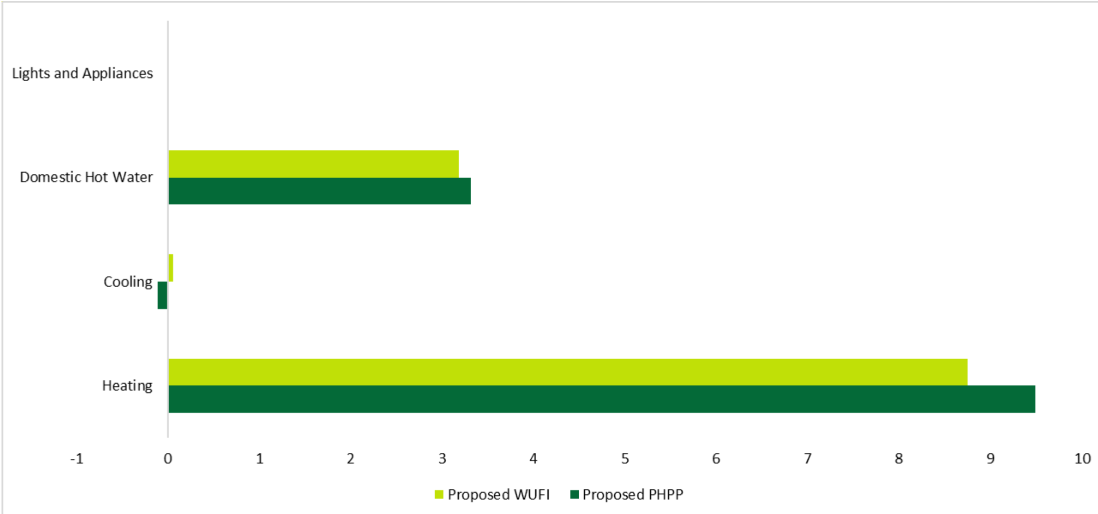



**Table 22: : MFLR Average Savings by End-Use (kBtu/iCFA/Year)**

| End-Use | WUFI | PHPP |
|---|---|---|
| Heating | 8.8 | 9.5 |
| Cooling | 0.1 | -0.1 |
| Hot Water | 3.2 | 3.3 |
| Lighting and Appliances | 0.0 | 0.0 |
| **Total** | **12.0** | **12.7** |

## 3.7 Current MFLR Program Participant Savings Results by End-Use

Table 23 provides average EUI savings values by end-use from 4,506 MFLR program participants. Savings data were provided by the program implementor, ICF; however, specific proposed and baseline values were not available at the time of the study. Please note that the site EUI values presented in the table are based on the conditioned floor area (CFA)[30], as opposed to the iCFA. The area measurements for iCFA are lower than CFA, generally between 5% and 10%. As a result, the values in this table are not direct comparisons to the site EUI per iCFA reported above. The low-rise UDRH outlines that lighting and appliances are set to have the same modeled values in both the proposed case and baseline case, resulting in no savings potential.[31]

Though the savings results from the Passive House models above (Table 22) are not directly comparable, and have a limited sample size. The results suggest MFLR projects built to passive standards may see much greater savings than is currently being captured by the traditional RNC program. The Passive House models, though not directly comparable, show 122%-135% higher

[30] Conditioned Floor Area (CFA) is defined as the floor area of the conditioned space volume within a building or dwelling unit, not including the floor area of attics, crawlspaces, and basements below air sealed and insulated floors. Additional details on CFA are provided in the link: ANSI/RESNET/ICC 301-2019 Standards.

[31] It should be noted that the PAs do claim lighting savings for MFLR projects, but those savings are calculated outside of energy modeling tools. Any lighting savings currently claimed by the MFLR program should be directly transferrable to a new Passive House initiative.

savings levels – though the Team anticipates that with an apples-to-apples comparison, the increased savings would be closer to the MFHR range.

### Table 23: MFLR Program Participant Average Modeled Site EUI (kBtu/ft$^2$/yr) Savings

| End-Use | MF Program Savings |
|---|---|
| Heating | 3.1 |
| Cooling | 0.1 |
| Hot Water | 1.5 |
| Lighting and Appliances | 0.0 |
| **Total** | **5.4** |

# Section 4 Single-Family Modeling

The Team used the same modeling tools and scenarios for the single-family modeling effort as those that are detailed in the beginning of Section 3 for the MFLR modeling process.

## 4.1 Single-Family Methods and Process

As described in Section 3, program savings for low-rise program participants are calculated by comparing the low-rise UDRH to the proposed building using Ekotrope. The Team conducted a comparison of modeled outputs between WUFI Passive, PHPP, Ekotrope, and REM/Rate to assist in the determination of the best way to claim savings for single-family projects in the new Passive House offering.

The Team obtained energy models and additional project documentation for five single-family Passive House projects that had met pre-certification or final certification requirements. The Team provided a $150 incentive to project teams that agreed to participate. Due to a limited number of certified and pre-certified single-family Passive House projects in Massachusetts, the Team looked to surrounding states to fill the sample quota. The five projects were located between Massachusetts and New York. The energy modeling team collaborated on the recruitment and procurement of the project participants. Recruitment emails were sent out to a sample of potential participants that detailed the study and the incentive amount. Participants provided energy models and any additional project files that were essential for developing models in the four software packages that were included in the model comparison.

Some summary information about the projects can be found in Table 24 and Table 25.

**Table 24: Single-Family Sampled Projects – Project Details**

| Site ID | Climate Location | iCFA | # of Bedrooms | Primary Heating Type | DHW Type | Ventilation Type |
|---|---|---|---|---|---|---|
| Site 1 | NY-Binghamton | 1,428 | 3 | DMS | HPWH | ERV |
| Site 2 | NY - Poughkeepsie | 3,245 | 4 | DMS | HPWH | ERV |
| Site 3 | MA – Boston | 3,366 | 6 | DMS | HPWH | ERV |
| Site 4 | NY – Stewart Field | 3,680 | 4 | DMS | HPWH | HRV |
| Site 5 | MA – Norwood Memorial | 5,635 | 3 | DMS | HPWH | ERV |
| Baseline Scenario (Low-rise UDRH) | Same as reference building | Same as reference building | Same as reference building | Same type – efficiency adjusted | Same type – efficiency adjusted | Same as reference building |

**Table 25: Single-Family Sampled Projects – Efficiency Details**

| Site ID | Wall R-value | Roof R-value | Slab R-value | Window U-factor | Window SHGC | Infiltration Rate (ACH50) |
|---|---|---|---|---|---|---|
| Site 1 | R-58 | R-98 | R-42 | 0.141 | 0.46 | 0.34 |
| Site 2 | R-55 | R-77 | R-51 | 0.161 | 0.50 | 0.37 |
| Site 3 | R-43 | R-61 | R-31 | 0.140 | 0.46 | 0.63 |
| Site 4 | R-43 | R-58 | R-50 | 0.151 | 0.52 | 0.46 |
| Site 5 | R-54 | R-120 | R-50 | 0.169 | 0.50 | 0.48 |
| Baseline Scenario (Low-rise UDRH) | R-16.1 | Flat: R-33.3 Vault: R-26.3 | Uninsulated (varies) | 0.30 | 0.30 | 3.57 |

## 4.2 Single-Family Assumptions

Once the study participants agreed and project files were provided, the energy modeling team collaborated to develop energy models in the various software packages that aligned with the proposed buildings conditions. The energy modeling team then worked to develop the baseline models, which applied the low-rise UDRH assumptions that are currently used to calculate program savings.

As was the case with the MFLR modeling effort, the Team deviated slightly from the UDRH protocols for the application of glazing distribution. Additionally, the Team de-rated heat pumps using the same process described for the MFLR modeling effort. Please see Section 3.2 for additional details.

Lighting and appliance inputs were not changed between the proposed and baseline models, as the low-rise RNC program currently does not claim savings for these measures using energy modeled outputs.

## 4.3 Single-Family Summary Results

The summary site EUI results for all projects are displayed in Table 26. Please note that the site EUI is derived from the projects' iCFA for the single-family projects, rather than gross square footage. This is not a comparison between the PHI and PHIUS certifications, rather it is meant to inform the program on the most appropriate method for claiming savings over the baseline scenario. The Team has not only considered the outputs but also the implications on:

- Ease of use for program administrators, implementors, HERS raters, and participants.
- Transparency of methodology and approach.
- Ability to incorporate appropriate measures and baseline metrics.
- The need to characterize whole building savings by end-use.

The results of the energy modeling indicate that while there are subtle differences between WUFI and PHPP, each model produces similar results when assumptions are consistent between the two tools – though PHPP shows a higher level of savings. Ekotrope and REM/Rate tools resulted in lower levels of overall average consumption for both the baseline and proposed cases and is reflected in the lower overall savings results. Similar to MFHR and MFLR, the Team concludes that either WUFI or PHPP are appropriate tools to calculate savings over the baseline when the certification modeling assumptions are adjusted to reflect more accurate model inputs. The Team notes that one challenge applying the low-rise program UDRH to the Passive House tools is manually adjusting the window area in the baseline case. Note that the low-rise program encompasses both MFLR and single-family projects. This issue is detailed in Section 3.2.

Note that interpreting the accuracy of the modeled results is limited due to a lack of monitored billing data for Passive House projects. Determining the accuracy of the models requires comparisons to actual performance that were not available at the time of this study. Monitoring actual performance of future participants going through the program will provide insights on this question, as well as communicable information to the market, as described in the findings from the IDIs with various market actors.

The average savings from all five projects were similar between WUFI, PHPP, and Ekotrope, within 3%; however, REM/Rate had a noticeably lower average savings – the percentage savings over baseline site EUI consumption was 48% for REM/Rate, 56% for Ekotrope, 57% for WUFI Passive, 59% for PHPP. The savings results for the single-family modeling were much higher than what was seen in both the MFHR and MFLR results. The increased potential for savings is likely due to energy consumption in smaller structures being more shell dominated, as opposed to balancing large amounts of internal and solar gains in multifamily buildings – meaning that the lower insulation and equipment efficiency levels have a larger impact on site energy consumption of smaller structures. The total annual consumption results are provided in Table 43 of Appendix B.

**Table 26: Single-Family Summary Modeling Site EUI Results (kBtu/iCFA/Year)**

| Site ID | Baseline Results Site EUI (kBtu/iCFA/yr) | | | |
|---|---|---|---|---|
| | WUFI | PHPP | Ekotrope | REM/Rate |
| Site 1 | 48.3 | 44.7 | 41.0 | 36.7 |
| Site 2 | 31.3 | 29.8 | 23.5 | 22.2 |
| Site 3 | 29.3 | 31.7 | 25.6 | 36.8 |
| Site 4 | 42.3 | 42.5 | 32.4 | 29.4 |
| Site 5 | 31.6 | 36.3 | 32.1 | 29.0 |
| **Average Site EUI** | **36.6** | **37.0** | **30.9** | **30.8** |
| **Site ID** | **Proposed Results Site EUI (kBtu/iCFA/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 19.4 | 19.4 | 19.9 | 18.4 |
| Site 2 | 14.9 | 13.8 | 11.3 | 12.7 |
| Site 3 | 14.7 | 13.9 | 12.8 | 18.6 |
| Site 4 | 15.8 | 16.1 | 12.8 | 15.9 |
| Site 5 | 12.8 | 12.6 | 11.5 | 13.5 |
| **Average Site EUI** | **15.5** | **15.2** | **13.6** | **15.8** |
| **Site ID** | **Savings Results Site EUI (kBtu/iCFA/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 28.9 | 25.3 | 21.2 | 18.2 |
| Site 2 | 16.3 | 16.0 | 12.2 | 9.5 |
| Site 3 | 14.6 | 17.8 | 12.8 | 18.2 |
| Site 4 | 26.4 | 26.4 | 19.6 | 13.5 |
| Site 5 | 18.8 | 23.7 | 20.7 | 15.5 |
| **Average Site EUI** | **21.0** | **21.8** | **17.3** | **15.0** |
| **Site ID** | **% Savings Results Site EUI (kBtu/iCFA/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 60% | 57% | 52% | 50% |
| Site 2 | 52% | 54% | 52% | 43% |
| Site 3 | 50% | 56% | 50% | 49% |
| Site 4 | 63% | 62% | 61% | 46% |
| Site 5 | 60% | 65% | 64% | 53% |
| **Average Site EUI** | **57%** | **59%** | **56%** | **48%** |

## 4.4 Single-Family Proposed Models

The Team looked at the proposed site EUI by end-use to understand what differences existed between the models and what drivers may have caused these differences. In general, the Passive House tools were fairly aligned by end-use. Ekotrope outputs were also fairly similar to the Passive House tools, except for domestic hot water, which was much lower. REM/Rate was higher for heating and cooling end-uses than all of the tools, and similar to Ekotrope for domestic hot water (see Figure 11 and Table 27). The increased hot water consumption is likely driven by the Passive House tools factoring in transmission pipe losses.

**Figure 11: Single-Family Average Proposed Model Site EUI by End-Use (kBtu/iCFA/Year)**

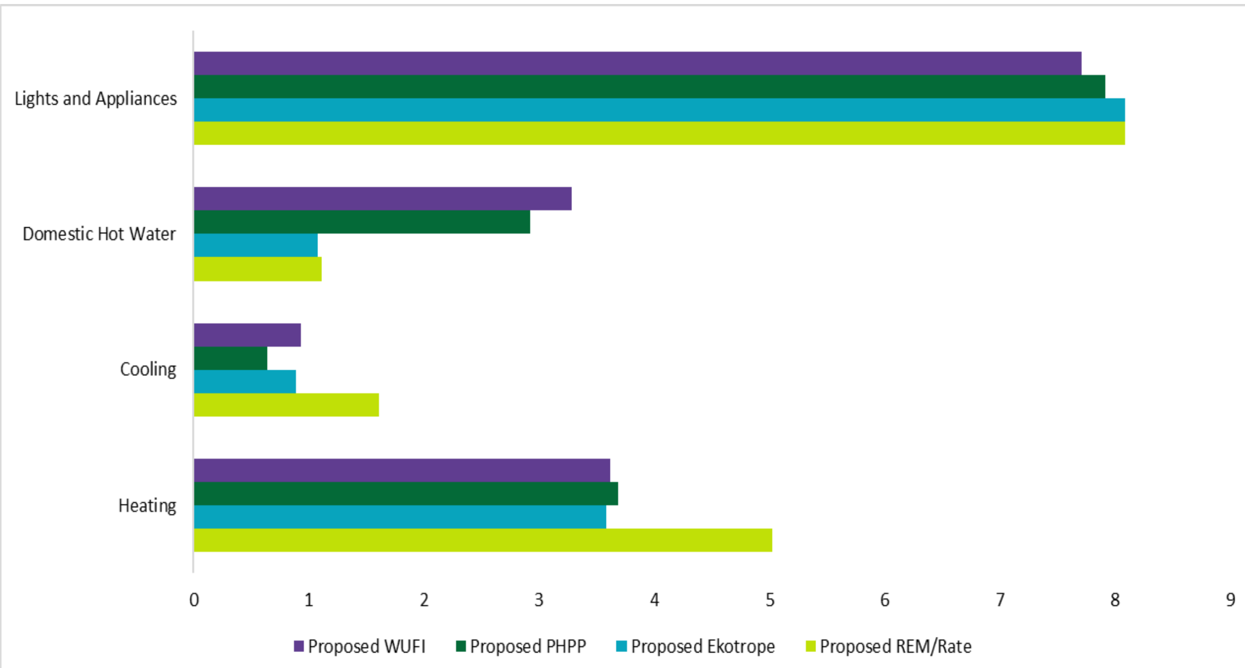



**Table 27: Single-Family Average Proposed Model Site EUI by End-Use (kBtu/iCFA/Year)**

| End-Use | WUFI | PHPP | Ekotrope | REM/Rate |
|---|---|---|---|---|
| Heating | 3.6 | 3.7 | 3.6 | 5.0 |
| Cooling | 0.9 | 0.6 | 0.9 | 1.6 |
| Hot Water | 3.3 | 2.9 | 1.1 | 1.1 |
| Lighting and Appliances | 7.7 | 7.9 | 8.1 | 8.1 |
| **Total** | **15.5** | **15.2** | **13.6** | **15.8** |

## 4.5 Single-Family Baseline Models

The Passive House tools were once again fairly aligned by end-use, while Ekotrope and REM/Rate were also fairly aligned by end-use. The Passive House tools had higher heating and hot water outputs compared to Ekotrope and REM/Rate (see Figure 12 and Table 28). The higher heating consumption values for the Passive House tools in the baseline cases, and the opposite scenario in the proposed cases, suggest that the Passive House tools' heating consumption outputs are impacted to a greater degree by building shell performance – such as insulation, infiltration, shading factors, and solar heat gains from windows when compared to Ekotrope and REM/Rate in single-family buildings.

As described above, the current low-rise program UDRH inputs were applied to the baseline models. The Team identified that potential adjustments to the baseline scenario may be appropriate for the Passive House baseline. Passive House standards emphasize using electric heating and cooling methods – which appears to be primarily delivered to Passive House single-family projects through mini-split systems. The current baseline provides efficiency adjustments for these measures; however, the Team anticipates that mini-split systems are used in only a subset of the baseline or program participant homes. The Team also anticipates that future Passive House projects will primarily use mini-split systems for space heating and cooling. This would suggest potentially modeling a more common space heating or cooling system, fuel, and efficiency for these projects in the baseline conditions. Due to limited availability of program data at the time of the final report and a baseline study taking place concurrently, this is just a hypothesis that should be further explored, along with other potential adjustments for the application of the low-rise UDRH on Passive House single-family projects.

**Figure 12: Single-Family Average Baseline Model Site EUI by End-Use (kBtu/iCFA/Year)**

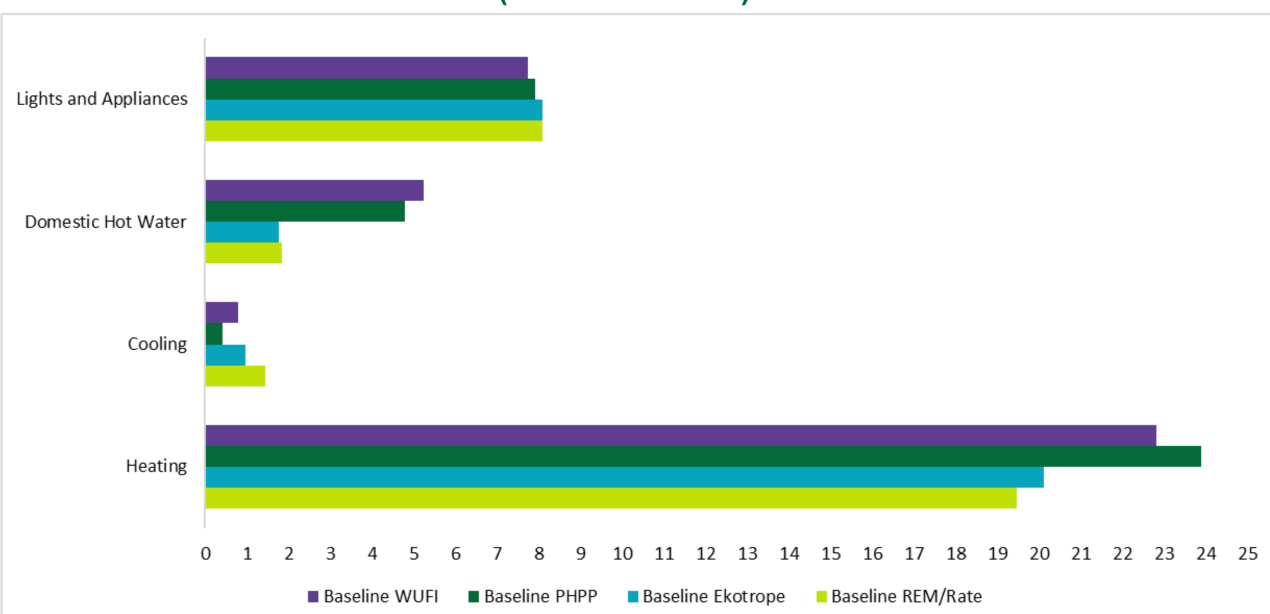


**Table 28: Single-Family Average Baseline Model Site EUI by End-Use (kBtu/iCFA/Year)**

| End-Use | WUFI | PHPP | Ekotrope | REM/Rate |
|---|---|---|---|---|
| Heating | 22.8 | 23.9 | 20.1 | 19.5 |
| Cooling | 0.8 | 0.4 | 1.0 | 1.4 |
| Hot Water | 5.2 | 4.8 | 1.8 | 1.8 |
| Lighting and Appliances | 7.7 | 7.9 | 8.1 | 8.1 |
| **Total** | **36.6** | **37.0** | **30.9** | **30.8** |

## 4.6 Single-Family End-Use Savings Results

The average savings by end-use for each of the four models are presented in Figure 13 and Table 29. Currently the low-rise program UDRH requires inputs for lighting and appliances to be the same as the proposed case, effectively eliminating the potential for savings in these categories based on modeled outputs.[32]

The average cooling consumption for WUFI, PHPP, and REM/Rate resulted in negative savings. Average cooling savings for Ekotrope were positive, but relatively negligible. The higher cooling consumption in the proposed cases is due to the increased internal gain load from the higher insulation levels and the air-tight construction of the passive houses. As expected, based on the proposed and baseline end-use results, the Passive House tools are closely aligned for savings on end-uses, with PHPP showing a slightly higher amount of savings attributed with heating end-uses. Ekotrope had average site EUI savings in between the Passive House tools and REM/Rate. The results from the five single-family projects that were modeled show that savings from heating were the dominant savings by end-use, followed by domestic hot water.

[32] It should be noted that the PAs do claim lighting savings for low-rise projects, but those savings are calculated outside of energy modeling tools. Any lighting savings currently claimed by the low-rise program should be directly transferrable to a new Passive House initiative.

Figure 13: Single-Family Average Savings by End-Use (kBtu/iCFA/Year)

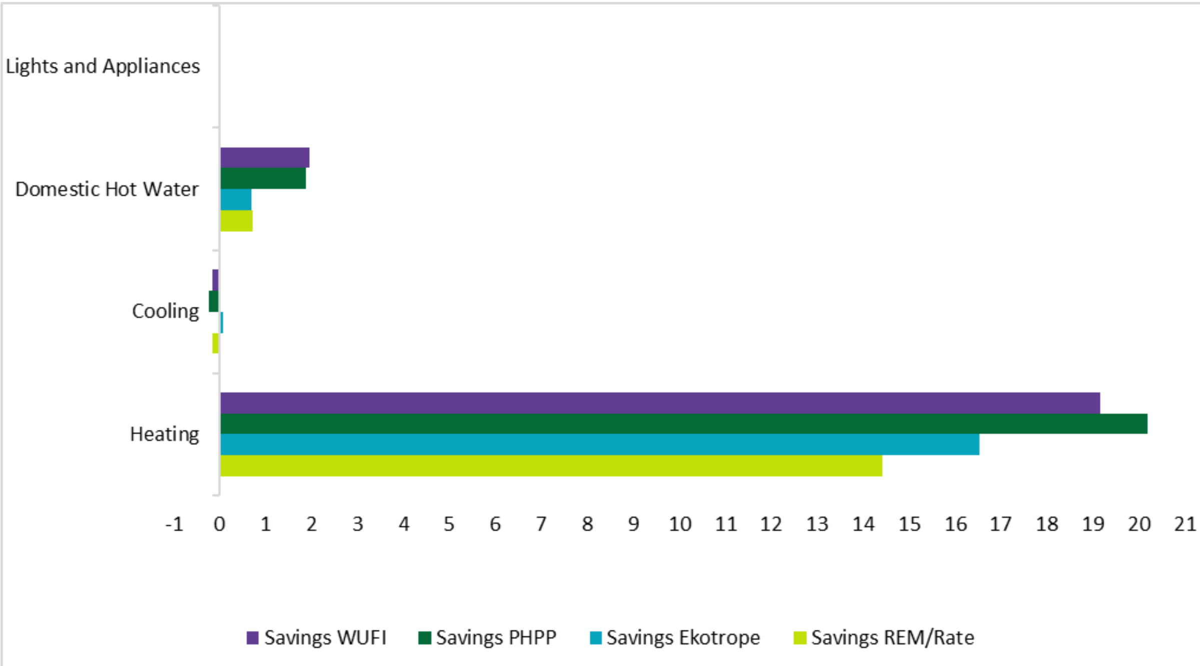



Table 29: Modeled Single-Family Average Savings by End-Use (kBtu/iCFA/Year)

| End-Use | WUFI | PHPP | Ekotrope | REM/Rate |
|---|---|---|---|---|
| Heating | 19.2 | 20.2 | 16.5 | 14.4 |
| Cooling | -0.2 | -0.2 | 0.1 | -0.2 |
| Hot Water | 2.0 | 1.9 | 0.7 | 0.7 |
| Lighting and Appliances | 0.0 | 0.0 | 0.0 | 0.0 |
| **Total** | **21.0** | **21.8** | **17.3** | **15.0** |

## 4.7 Current Single-Family Program Participant Savings Results by End-Use

Table 30 provides average end-use EUI savings values from 10,142 single-family program participants. Savings data was provided by the program implementor, ICF; however, specific proposed and baseline values were not available at the time of the study. Please note that the site EUI values presented in the table below are based on the CFA, as opposed to the iCFA. The area measurements for iCFA are lower than CFA, generally between 5% and 10%, so the values in this table are not direct comparisons to the site EUI per iCFA, reported above. The low-rise UDRH outlines that lighting and appliances are set to have the same consumption in both the proposed case and baseline case, resulting in no savings potential.

Though the savings results from the Passive House models above (Table 29) are not directly comparable and have a limited sample size. The results suggest single-family projects built to passive standards may see much greater savings than is currently being captured by the traditional RNC program. The Passive House models, though not directly comparable, show higher savings (ranging from 74% to 144% higher) over the current RNC program results – though the Team anticipates that with an apples-to-apples comparison, the higher savings would be a smaller margin. It should be noted that the Passive House modeled projects were constructed using an older certification standard and has since been updated. Note once again, that the modeled savings results should be interpreted with caution due to small sample sizes and modeling assumptions that were made to ensure consistency between modeling software.

**Table 30: Single-Family Program Participant Average Modeled Site EUI Savings**

| End-Use | SF Program Savings |
|---|---|
| Heating | 7.4 |
| Cooling | 0.1 |
| Hot Water | 2.2 |
| Lighting and Appliances | 0.0 |
| **Total** | **8.6** |

# Section 5 Program Data Review and Potential Savings Assessment

The Team reviewed a sample of 62 MFHR participant projects from 2018 to understand the energy consumption of the proposed and baseline conditions from recent MFHR participant projects. These projects were all modeled using the ICF multifamily tool. The Team explored whether applying baseline EUIs by various project sizes was a reasonable approach to estimating program savings. Based on the results of the model comparison, where the ICF tool was shown to estimate higher consumption values than the Passive House tools, the Team ultimately determined this may not be the best approach for estimating program savings from future Passive House participant projects.

As shown in Table 31, the average site EUI for proposed program participant buildings was 29.2 kBtu/ft$^2$/yr. The average baseline site EUI for these projects – where energy models are created without the incentivized energy conservation measures (ECMs) factored in – was 35.9 kBtu/ft$^2$/yr, suggesting that the program lowered the intensity of building energy use by almost 20% on a square foot basis. The Team also calculated source EUI values for each project using the national average conversion ratios from the ENERGY STAR Portfolio Manager.[33] Source energy aims to capture the total energy required to deliver both primary energy (raw fuel being burned for energy) and secondary energy (the energy product of raw fuel, such as grid-sourced electricity) to a building. Secondary fuels are adjusted to be given a higher energy impact to account for losses incurred in raw fuel combustion and energy transmission – for example the national source energy conversion ratio for grid electricity is 2.8. Natural gas, on the other hand, is a primary fuel and has a source energy ratio of just 1.05. Because of the distribution of energy consumption attributable to electricity versus natural gas in these projects, the average source to site energy ratio is about 2.0 for both baseline and proposed projects.[34]

Finally, the Team categorized projects by building size and the number of floors and compared average EUIs to determine if patterns emerged. Note that sample sizes were limited to 3 projects at 11 or more floors, while the distribution of buildings by square footage was more even.

[33] Source energy conversion values and additional background on source energy can be found here: https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf
[34] These calculations do not account for the presence of any on-site or off-site renewable energy generation as these factors are not included in the program energy models.

**Table 31: EUI Comparisons for Baseline and Proposed Program Sites**

| EUI by Project Size | Sample Size | Baseline | Proposed |
|---|---|---|---|
| **Overall Source EUI** | **62** | **78.0** | **63.3** |
| *By Building Height* | | | |
| Less than 4 floors | 11 | 73.9 | 58.1 |
| 4-10 floors | 48 | 78.5 | 63.6 |
| 11 floors or more | 3 | 85.7 | 78.1 |
| *By Building Size* | | | |
| Less than 50,000 sq. ft. | 20 | 80.6 | 64.0 |
| 50,000-100,000 sq. ft. | 25 | 75.9 | 60.5 |
| 100,000 sq. ft. or more | 17 | 78.0 | 66.5 |
| **Overall Site EUI** | | **35.9** | **29.2** |
| *By Building Height* | | | |
| Less than 4 floors | 11 | 34.5 | 27.7 |
| 4-10 floors | 48 | 36.0 | 29.2 |
| 11 floors or more | 3 | 38.6 | 35.2 |
| *By Building Size* | | | |
| Less than 50,000 sq. ft. | 20 | 36.3 | 29.5 |
| 50,000-100,000 sq. ft. | 25 | 35.2 | 28.0 |
| 100,000 sq. ft. or more | 17 | 36.3 | 30.7 |

## 5.1 MFHR Preliminary Potential Savings

In order to identify potential savings associated with the new program offering, the Team compared the energy use of 2018 MFHR program participant projects to a series of Passive House certification energy requirements. This analysis uses the source energy requirements associated with Passive House certification. The Team compared the program data to the source energy requirements in Table 32 to estimate the potential savings associated with the new offering.

**Table 32: Passive House Source Requirements**

| Certification Option | Source Energy Requirements |
|---|---|
| PHIUS+ 2018 | ➢ Residential: 3,840 kWh/person/yr<br>➢ Commercial: 34.8 kBtu/ft$^2$/yr<br>➢ Accounts for both on-site and off-site energy generation |
| PHIUS+ Core | ➢ Residential: 5,500 kWh/person/yr<br>➢ Commercial: 38.0 kBtu/ft$^2$/yr<br>➢ Accounts for only on-site energy generation |
| PHIUS+ 2015 | ➢ Residential: 6,200 kWh/person/yr<br>➢ Commercial: 38.0 kBtu/ft$^2$/yr<br>➢ Account for only on-site energy generation |
| PHI | ➢ All spaces: 38.0 kBtu/ft$^2$/yr<br>➢ Accounts of on-site generation and new off-site generation |

Specifically, the Team focused on comparing the source energy requirements from various Passive House certifications to the baseline and proposed model consumption estimates for 2018 MFHR program participant projects. To make this comparison, the Team applied the same source energy factors referenced above (from the ENERGY STAR portfolio manager site), to estimate a source energy associated with 2018 MFHR projects. The annual source energy estimates were then compared to the annual site energy consumption for the same projects to develop a site-to-source ratio factor. This factor was then multiplied by the Passive House source energy requirements – determined for each site using the residential and commercial square footage and occupancy values in the program data and the corresponding values in Table 32 – to estimate a Passive House annual site energy requirement.

For example, one baseline model projected to use roughly 483,000 kBtu of energy on site (site EUI of 36.1), which equates to about 915,000 kBtu of source energy (source EUI of 68.4) after applying the ENERGY STAR source energy conversions for gas (1.05) and electricity (2.8). The PHIUS+ 2018 Source Energy requirement for this building was calculated at about 461,000 kBtu (source EUI of 34.5) using the residential occupancy and commercial square footage energy requirements outlined in Table 32. This building had a site-to-source energy ratio of about 0.5 (483,000/915,000), which was applied to the PHIUS+ 2018 source EUI to get a site-level EUI for comparing to the baseline model. The result is a source to site (34.5 x 0.5) conversion of PHIUS+ 2018 that, when compared to the site EUI for the baseline model (36.1) yields a savings of about 50% over baseline. Using the same methodology, meeting the PHIUS+ 2018 source energy requirements would yield 38% savings over the as-built program model for this example site. The calculations used to identify savings over the baseline are presented in the algorithms below. Note that the same logic was applied to the other PHIUS and PHI certification requirements.

***Baseline Site Energy Calculation***

$$482{,}968\frac{kBtu}{yr} = (2{,}497\ therms \times 100) + (68{,}367\ kWh \times 3.412)$$

***Baseline Source Energy Calculation***

$$915{,}336\frac{kBtu}{yr} = (2{,}497\ therms \times 100 \times 1.05\ site\ to\ source\ gas\ conversion) + (68{,}367 \times 3.412 \times 2.8\ site\ to\ source\ electric\ conversion)$$

***Baseline Site to Source Ratio***

$$0.5 = \frac{482{,}968\ kBtu/yr}{915{,}336\ kBtu/yr}$$

***Baseline Total Site EUI***

$$36.1\frac{kBtu}{sq.ft.} = \frac{482{,}968\ kBtu/yr}{13{,}382\ sq.ft.}$$

***PHIUS+ 2018 Source EUI Requirement***

$$111{,}360\frac{kWh}{yr} = 29\ occupants \times \frac{3{,}840\frac{kWh}{person}}{yr}\ PHIUS\ kWh\ requirement$$

$$81{,}293\frac{kBtu}{yr} = 2{,}336\ commercial\ sq.ft. \times 34.8\ PHIUS\ kBtu\ requirement$$

$$461{,}253\frac{kBtu}{yr} = 81{,}293\frac{kBtu}{yr} + \left(111{,}360\frac{kWh}{yr} \times 3.412\right)$$

$$34.5\frac{kBtu}{sq.ft.} = \frac{461{,}253\ kBtu/yr}{13{,}382\ sq.ft.}$$

***Savings Over Baseline EUI***

$$17.9\frac{kBtu}{sq.ft.} = 36.1\frac{kBtu}{sq.ft.} - \left(34.5\frac{kBtu}{sq.ft.} \times 0.5\ site\ to\ source\ ratio\right)$$

$$50\%\ savings\ over\ baseline\ consumption = \frac{17.9\frac{kBtu}{sq.ft.}}{36.1\frac{kBtu}{sq.ft.}}$$

Table 33 displays the average calculated savings over baseline and proposed program models for each of the major Passive House certification bodies, expressed in site EUI. For PHIUS+ 2015, PHIUS+ Core, and PHIUS+ 2018, which require total occupancy to calculate source energy requirements, the Team estimated occupancy using an assumption that total occupancy is equivalent to the number of bedrooms plus one (on a per unit basis).[35]

As shown, the site savings for PHIUS+ 2015 are 33% when compared to the MFHR baseline consumption values. This aligns closely with the results in Section 2, Table 11, which show that the sampled MFHR Passive House projects from the modeling effort resulted in savings between 29% and 33% over baseline consumption. This is a reasonable comparison as most of the sampled projects for the modeling effort were built under the PHIUS+ 2015 certification requirements. This indicates that the potential savings values for PHIUS+ 2018 and PHI presented in Table 33 are a reasonable estimation of what savings might be under the new program as early program participants will be seeking certification under one of those two certification options.

PHIUS+ 2018 severely limits source energy consumption relative to the 2015 version, mainly through a more stringent kWh requirement per occupant – the PHIUS kWh allowance per occupant drops from 6,200/person/yr in 2015 down to 3,840/person/yr in 2018. The PHIUS+ Core requirement (5,500 kWh/person/yr) is right in the middle as it does not account for off-site renewable energy generation like the PHIUS+ 2018 requirement does. The analysis shows that PHIUS+ 2015 would have reduced site energy consumption by 16% on average compared with a program building, while this number jumps to 24% for PHIUS+ Core and 44% in the PHIUS+ 2018 scenario. Achieving PHI standards for source energy consumption, calculated as a function of 38 kBtu/ft$^2$/yr, would have provided 37% energy reductions compared with program buildings, on average. PHI reductions compared with program baseline and proposed models fall in between the PHIUS+ Core and PHIUS+ 2018 requirements for baseline and proposed scenarios

[35] This is consistent with the RESNET protocols for occupancy assumptions.

but align closer to the PHIUS+ 2018 savings source energy requirements. Compared to program baseline scenarios, performing to PHI requirements would cut energy consumption in half, while achieving PHIUS+ 2018 energy requirements would cut site consumption of baseline buildings by 55%.

It is worth noting that reductions in source energy consumption do not necessarily correlate with program claimable energy-efficiency savings. Passive House certification pathways allow developers to claim source-energy consumption reductions for renewable energy produced on-site (and, in some instances particular to PHIUS+2018, off-site). For this reason, the source-EUI standards for PHI and PHIUS do not necessarily directly correlate with the site-level energy consumption of a building and reductions in source-EUI requirements do not necessarily directly correlate with site-level program-claimable energy-efficiency savings.

**Table 33: Passive House EUI Savings versus Program Models**

| Program Consumption | Baseline Consumption | As-Built Consumption |
|---|---|---|
| *Site EUIs (in ICF Tool, kBtu/ft²/yr)* | *35.9* | *29.2* |
| **Certification Requirement** | **Savings Over Baseline** | **Savings Over As-Built** |
| **Site EUI Savings (kBtu/ft²/yr)** | | |
| PHIUS+ 2015 | 12.1 | 5.2 |
| PHIUS+ Core | 14.4 | 7.5 |
| PHIUS+ 2018 | 20.0 | 13.2 |
| Passive House Institute | 18.2 | 11.4 |
| **% EUI Savings** | | |
| PHIUS+ 2015 | 33% | 16% |
| PHIUS+ Core | 39% | 24% |
| PHIUS+ 2018 | 55% | 44% |
| Passive House Institute | 49% | 37% |

## 5.2 Multifamily Low-Rise and Single-Family Preliminary Potential Savings

At the time the final report was drafted, the Team did not have detailed low-rise or single-family program consumption data with which to perform a comparison of current program savings to Passive House requirements.

# Section 6 In-depth Interviews

This section presents the results of the 25 IDI's that were conducted for this project. The results include both the interviews that took place for the interim report and the four subsequent interviews that took place after the interim report. In order to keep this report concise and to-the-point, the Team presents key findings for all market actors together when there was a general consensus across the interview groups. The Team has called out specific market actor groups when their perspective was different from other market actors or warranted a detailed focus from key stakeholders in their review.

## 6.1 Recruitment

The recruitment effort for the IDI's was largely successful. The Team developed sample for the IDIs by drawing from professional Passive House databases (e.g., the PHIUS and PHI website's professional lists) and by coordinating with the PAs and PHIUS to identify specific contacts, both in Massachusetts and elsewhere, that are actively engaged in Passive House construction. Recruitment focused on market actors experienced with passive multifamily buildings, though given the limited number of market actors with this experience, some interviewees had worked only with single-family buildings. ICF, the RNC program's implementation contractor, supplied developer contacts and helped facilitate the Team's outreach to help the recruitment process for this hard to reach group. There was an overwhelming response from interview candidates, which resulted in fulfilling the quotas for certain market actor groups quickly. Interviewees were offered a $50 incentive for participating. Often the interviews lasted longer than the anticipated one-hour timeframe, due to interviewee willingness to discuss Passive House concepts and issues at length. Table 34 presents the sample targets and the number of interviews completed.

Note that interviewees all had some level of experience working on Passive House projects. The Team intentionally targeted market actors with experience in Passive House to better understand the specific challenges, benefits, training opportunities, incremental costs, and barriers associated with these projects. As Passive House is still an emerging and niche market in the construction industry, the Team looked to understand the perspective from those market actors with real-world experience. There were no interviewees that had incorporated Passive House design principles and actively did not pursue it anymore; however, all interviewees expressed there were incremental costs, challenges, and barriers to Passive House construction. And some interviewees expressed apprehension about a program requirement of certification may act as a barrier. The Team did not seek out interviewees that were advocates, rather targeted market actors with experience to provide the program insights regarding Passive House building.

**Table 34: In-depth Interview Sample**

| Market Actor Group | Target | Complete |
|---|---|---|
| Architect/engineer | 5 | 5 |
| Builders | 5 | 7 |
| Industry Experts | 4 | 5 |
| Occupants/Owners | 4 | 3 |
| Developers | 5 | 5 |
| **Total** | **25** | **25** |

*The Team opted to interview more single-family and small multifamily builders to get a better understanding of that market rather than continue pursuing non-passive house developers.

## 6.2 Barriers to Passive House Design and Construction

**Limited industry knowledge and experience with Passive House design and construction.**

Respondents reported that air sealing was the most difficult traditional building practice to overcome

All market actor groups are affected by this to some degree, but builders were the most frequent party mentioned by other interviewees. Specifically, builder experience with high-performance air sealing was mentioned as a key barrier to address within that group – builders need additional training to air seal to passive standards, and many builders fall prey to the misconception that buildings need to "breathe".[36] The need to work closely and foster strong collaboration with the builder and sub-contractors while they learn on the job was a key theme among architects and developers. Weekly meetings among project staff, signage (such as: no penetrations in the envelope posted in multiple languages), and on-site trainings were identified as best practices to keep designers, builders, and sub-contractors all on the same page to achieve the desired performance outcomes. One builder noted that if a developer has one bad experience with Passive House, they may never try it again.

**"We're really focused on trying to bring back the craft of building as something that's really real and recognizing that our contractors have to be our partners because execution is just as fundamental as design."**
**-Architect**

Developers look for architects, engineers, and builders with proven track records. Lack of experienced practitioners hinders a competitive bidding process for passive projects when only a limited set of market actors are available. The lack of certified Passive House buildings in Massachusetts is particularly noticeable for large MFHR buildings.[37] Limited awareness of passive design and building requirements among architects, engineers, and builders can be addressed through successful program intervention. The program can develop training resources

[36] Air-sealing buildings to Passive House standards requires mechanical ventilation to provide fresh indoor air for occupants; and is generally distributed through an energy recovery ventilator or heat recovery ventilator.
[37] There is currently one certified multifamily passive house building in Massachusetts. There are several additional multifamily projects currently in development; most are involved with the Massachusetts Clean Energy Center's grant program. There is another large mixed-use development in Boston, the Winthrop Center, that has indicated it will pursue building to Passive House standards. The Winthrop Center would be one of the largest Passive House buildings in the world.

or leverage existing third-party trainings that cater to each group.[38] Trainings for builders were recommended to include hands-on experience meeting air-tightness and other passive design requirements in the field, communicating project goals to sub-contractors, and understanding how to sequence construction steps to minimize mistakes that can hinder achieving passive performance standards.

**"50% of private developers are aware, of those 50%, 15-20% can talk about it, and 5% of those would be characterized as knowledgeable."**
**-Developer**

A planning official for a city in Massachusetts believed that awareness in the industry is increasing but that there is still a knowledge gap among private developers. Developer-specific sessions on Passive House that highlight the operational benefits of Passive House, lower utility bills and decreased maintenance costs, and the health and comfort benefits would go a long way toward boosting the position of Passive House in the market. Providing more data on energy consumption, funding, benefits, challenges, and incremental costs to developers will help to reduce financial uncertainty. Increasing awareness among members of design teams and a willingness to pitch passive buildings to multifamily owners and developers will likely remain an important piece of the puzzle until developer awareness grows.

**Lack of public awareness and demand for Passive House**. While awareness of Passive House has been increasing among industry actors over the past few years, awareness among the general public remains limited. The program may consider increasing awareness of Passive House with the general public to increase demand for passive buildings. This could include development of materials that clearly describe what a Passive House is and what benefits occupants may experience with this type of building.

**"If people measured the mold and people measured the air quality, the people who build buildings would get the message. The main thing wouldn't be granite countertops-they would say: "What is the quality [of the building]?"**
**-Developer**

Messaging and advertisements can focus on the financial benefits of reduced operating and maintenance costs, but every group interviewed for this study agreed that the health and comfort benefits are substantial and provide additional selling points. Additional messaging and advertisement angles may include energy conservation, resiliency, and carbon reduction potential to capture public interest – as several respondents cited these concepts as the initial inspiration to learn about Passive House. It was a largely shared belief that increased demand from renters and buyers in the market will help drive developer decisions to pursue building to Passive House standards.

**Estimated incremental costs of Passive House.** Cost premiums – both actual and perceived – were commonly cited barriers for the adoption of passive buildings in the market. When asked specifically about overall incremental costs of multifamily passive buildings relative to a code-compliant building, estimates ranged from 2% - 15% across interviewee groups. A few market actors suggested that building to Passive House standards does not have a cost premium – due

[38] One example would be the suite of certification courses offered by PHIUS, which include "Consultant," "Builder," and "Rater/Verifier" versions that are applicable to and used by each major market actor group involved in the design and construction of passive buildings – builders, architects, engineers, and energy raters.

to increasing code or baselines, increasing knowledge, more Passive House products on the market, and reductions in HVAC system costs.

Interviewed developers expressed that more robust data on incremental costs of varying project scales would be beneficial for influencing future projects to pursue Passive House standards. Several respondents indicated developers may dismiss Passive House due to a perceived cost increase that is not in line with reality. As one market actor put it, "most people view added performance as added cost." Market actors suggested the program may be able to help inform developers by sharing incremental cost data of projects going through the program, to help reduce financial uncertainty and move the market. Additional builder experience can play a role here as well – some interviewees believed that builders may artificially inflate prices when asked to bid on a passive project because they feel the project will take additional time, or that the client is simply willing to pay more. The findings from IDI responses on incremental costs and supplemental incremental cost data are presented in Section 7.

**Difficulty of achieving Passive House requirements increases as decisions are made later in project timeline.** Market actors agree that the decision to pursue Passive House at the onset of the initial planning phase is of central importance in reaching passive performance goals and minimizing cost premiums. Passive House performance considerations affect design and construction practices, the construction sequence, material selections, and many other aspects of the project. Once a project has begun, even if still in the schematic design phase, it will incur additional costs due to plan redesign, material considerations, and additional change orders. One architect mentioned that knowing you are going for Passive House in the beginning allows you to employ initial feasibility studies and early energy modeling, which can provide a myriad of benefits – it can inform and validate your design decisions and assist in value engineering, letting you know, for example, if the two inches of continuous insulation you planned for an assembly can actually be one inch. Several interviewees pointed out that deciding to go for Passive House certification during construction can be a non-starter because too many building components are in place to factor in the necessary air sealing, insulation, and thermal bridging considerations.

Market actors suggested that planning to pursue Passive House standards at the on-set of a project sets a precedent for the whole team – from owner to subcontractors – to “get on board” and work together to achieve the performance goals. Design charrettes are effective at identifying cost-saving solutions and increasing overall building performance. Program intervention early in the initial planning stages, perhaps through holding design charrettes, is the most effective time to influence decision-making. An interesting phenomenon observed by a few respondents was the inclusion of Passive House requirements in project RFPs – setting expectations from the beginning and ensuring that all parties agree on project outcomes and goals.

**Code officials and permitting in certain municipalities may be a barrier**. Developers noted that in some municipalities specific criteria, such as achieving LEED Silver, is required – a different system than Passive House criteria and may require a variance if the code officials are unfamiliar with the criteria. This may cause delays in project timelines, which may have an impact on overall costs. In addition, code officials may not be very familiar with envelopes and air-barriers typical of Passive House construction. Builders mentioned that code officials can be wary of new Passive House materials or techniques because they are not explicitly captured in the code. Builders find that some code jurisdictions are focused on the past and are not progressive, causing the code officials to be a stumbling block in the building and certification process. One builder explained that they "had to add a product to the exterior of some of our buildings...even though the code official approved it, when we got on-site, he shut us down. We ended up adding a building wrap product to a product that did absolutely nothing for its fire safety other than it complied better to a T with what is in the code."

**Misalignment between market-rate developer goals and Passive House benefits.** Passive House has been gaining momentum among affordable multifamily developers due to incentives, operational savings, and non-energy impacts that are associated with Passive House buildings. For market-rate developers, the operational savings associated with Passive House are not realized when they choose to sell off the building asset. There are no studies that establish market values for Passive House buildings as compared to third party certifications like LEED, which has established measured market values.[39] In addition to uncertain market values, the lack of incremental cost data creates additional uncertainty for developers. The high demand for housing in the Boston metropolitan area, coupled with high rent prices, limit the marketability of utility savings; these developers are concerned that they will not be able to sell Passive House projects at a premium to cover incremental costs. Only committed market-rate developers – motivated by energy conservation, sustainability, greenhouse gas (GHG) reduction, occupant health, and resiliency – are likely to push their project to meet Passive House standards without incentives.

## 6.3 Passive House Benefits and Messaging

**Energy savings were considered a key benefit among market actors**. Interviewees agreed that energy and emissions reductions were realized in each of their passive projects and represent noteworthy benefits to passive design. Respondents indicated that occupant utility costs were significantly reduced compared to typical utility costs where data were available. However, the energy performance and billing data publicly available is typically one-off case studies with varying baseline conditions, which makes it difficult for market-rate developers to seriously consider. One developer suggested a report that details the project specs, costs, and corroborates the monitored performance of 20 passive projects would be a useful tool for convincing developers and investors. This emphasizes the importance of program intervention to acquire cost and energy performance data from passive projects and effectively communicate results to the market at large.

One developer actually lives in their Passive House development and claimed the overall usage for the building aligned with modeled results. They noted that their personal in-unit utility cost for both heating and cooling were $151 annually (set point temperature was indicated to be 73° F), and the total annual utility costs were $757. It should be noted that the building was not advertised to tenants as being Passive House, nor has there been an occupant education program in place. However, the owner indicated that they were working to start a tenant education program.

**Occupant comfort and health were often considered the primary benefit to Passive House buildings**. Across market actor groups, energy savings were mentioned as a key benefit, but just as common – and in many cases more emphasized – were considerations of indoor air quality,

[39] https://www.appraisalinstitute.org/assets/1/7/Green-Building-and-Property-Value.pdf

thermal comfort, noise reduction, resilience, ability to maintain temperature, reduced use of mechanical equipment – potential increase in equipment lifespan, and build quality. Passive house can be marketed to people with asthma, severe allergies, or other issues that can be assuaged with higher indoor air quality. One Passive House developer indicated people with asthma have reported no issues while in residence, but noticeable problems outside of residence. Industry experts also highlighted longevity and achieving the highest level of certification for energy efficiency as benefits.

> **"There are also huge comfort benefits, health benefits with continuously filtered fresh air. Resiliency benefits if you're weathering storms and blackouts—these buildings will hold temperature for days instead of hours and allow people to remain in their units. I think instead of talking about energy, for the market it's much more valuable to talk about comfort, health and resilience."-Architect**

**Passive House standards closely align with affordable housing interests**. Multiple architects and one non-profit builder highlighted the benefits of Passive House and how closely they aligned with the interests of affordable housing developers. The low operating costs, durability, and low maintenance inherent in passive design make it a natural fit with affordable housing goals. Market-rate developers may not plan to own or operate a building for very long, neutralizing some of the appeal of passive design. Affordable housing development differs in that the owner or developer will likely plan to operate the building for decades, and they cannot pass utility increases or other costs on to their tenants in the same way market-rate owners can.

**The variety of benefits offers options for shaping education and advertising campaigns**. Opinions were split on whether energy savings or non-energy benefits should be emphasized more when promoting Passive House, but respondents of all types were confident that the combination of benefits are an easy sell as education and awareness increase in the marketplace. As one interviewee suggested, messaging to high income customers could highlight that passive homes are the standard in build quality and comfort, while lower-income groups may be more receptive to the low operating and maintenance costs associated with passive design. Increased air quality and noise reduction can be emphasized in high-traffic urban areas.

> **"It feels better in here and they (occupants) feel happier in the building. In terms of that intangible, people just feel better." -Developer**

**State and local Passive House organizations can be a valuable resource for both practitioners and end-users**. Several respondents, including two Passive House occupants with no construction experience, were members of Passive House organizations that hold meetings and invite experts to give presentations, and they expressed an interest in expanding the footprint of similar activities as a means to build awareness. Members from the Team attended a discussion with board members of the Passive House Massachusetts chapter, which was followed up by a presentation by a local firm engaged in projects that are pursuing Passive House standards. The board members reiterated several of the high-level findings from IDIs with the various market actors, including:

- Incremental costs were considered to be approximately 3% more than baseline project costs but fell into a range from about 3-10%; typically, on the lower end for multifamily buildings.
- Incentive amounts should be high enough to off-set incremental cost of building to Passive House standards.
- The value of certification as a requirement is tied to the QA/QC procedures in place to achieve certification and the technical assistance provided during pre-certification.
- Potential barriers were lack of practical knowledge and experience in the industry – including developers, architects, engineers, and builders.
- Several attendees were habitants of Passive House buildings and described the benefits of living in a Passive House such as thermal comfort, health and wellness, indoor air quality, and reduced utility bills.
- Further education of the general public to the real costs and benefits will help drive the demand for buildings that meet Passive House standards.

## 6.4 Material and Equipment Choices

### 6.4.1 Strategic Electrification

Architects, engineers, and builders push for all electric systems in their passive projects for heating, cooling, ventilation, and domestic hot water, and this is typically how things play out in practice. The exception is domestic hot water in larger multifamily projects – some design team members have confidence in large-scale central heat pump systems for supplying hot water, but owners and developers remain apprehensive about deploying these central systems at a larger scale. High efficiency gas water heating is still predominant in larger residential passive buildings.

Industry experts also voiced similar concerns about the challenges of electrifying domestic hot water in large multifamily buildings, stating that equipment with the capability to do so is uncommon in the market, which makes gas options typically more cost-effective. A few market actors suggested the program should support the adoption of central heat pump hot water systems. One industry expert suggested that the program should lead a study on the best way to incorporate electric water heating systems into MFHR buildings. He suggested that costs in many large multifamily buildings could be kept close to non-Passive House levels, and electric water heating systems could be integrated successfully if the project was designed passive from the beginning. Combined with the already common use of electricity for HVAC, cooking, and laundry, this would remove the need for gas infrastructure to the project site, which helps offset the increased cost of the electric water heating system.

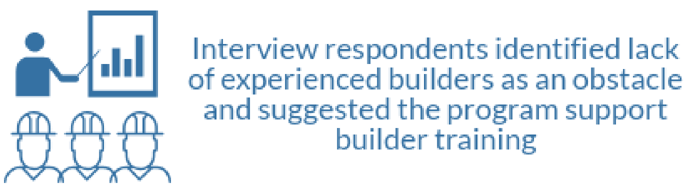
A local city building official expressed that strategic electrification aligns with their municipal goals for carbon reduction through eliminating fossil fuel usage. Carbon emissions and energy performance gains hold major value for municipalities with carbon reduction goals in the Commonwealth of Massachusetts. City and state officials are also influencing developers as Passive House performance standards have been identified as a “key strategy to reduce building sector energy consumption” to achieve 2050 carbon reduction goals for Massachusetts.

### 6.4.2 Embodied Energy (CO2 and CO2e) of Materials

The environmental impact of building materials is a common consideration among respondents. The consensus was to use low embodied carbon, or even carbon sequestering materials like dense-pack cellulose and wood fiber where possible, and only use foam products when alternatives are not realistic. Industry experts noted that since the PHIUS certification process does not consider the embodied energy of materials, some will continue to use carbon intensive products for as long as they are allowed, which may offset some of the benefits of Passive House. Materials that off-gas volatile organic compounds (VOCs) coupled with the stringent air-tightness requirements may contribute to a reduction in the indoor air quality of the building.

Paying mind to embodied energy and avoiding high impact materials can raise construction costs in some scenarios, which needs to be communicated when pushing these considerations to the wider market. Conversely, as widespread adoption of these types of materials increases, costs will fall. Some interviewees suggested that the program can raise awareness of embodied energy and provide educational and product references early in the design process on choosing low-embodied carbon materials while avoiding red-listed materials and materials that off-gas VOCs.

## 6.5 PROGRAM TRAINING OPPORTUNITIES




**Builders were most commonly cited as a group to target for additional training**. The construction demands of Passive House – a heavy focus on air sealing, highly insulated building envelopes, and eliminating thermal bridges – requires builders to execute at a higher level than in code-level construction, for example. At the same time, the schedule demands on contractors makes it difficult to step away from their work for several days for a certification training. An architect suggested that an effective approach for the program may be to develop smaller, bite-sized trainings for builders, each several hours long and touching on a specific aspect of passive construction. Industry experts made similar recommendations, saying that builders could learn Passive House techniques very quickly, but the training has to be available and they may need some incentive to participate.

The need for builders [and designers] with practical passive building experience was expressed by developers. However, with only a limited number of firms with this experience, there will be an issue with limited supply as the demand for Passive House projects increases. Another way the program may approach builder trainings is to deploy an experienced practitioner to conduct trainings on-site, before a specific phase of construction begins. The on-site trainings can be identified early in the planning phase and should revolve around potential pitfalls specific to Passive House construction. If multiple Passive House projects are being planned concurrently, the trainings could include multiple project teams.

**Leverage existing training and certification courses sponsored by PHIUS or PHI**. Multiple architects and engineers mentioned leveraging existing PHIUS or PHI certification courses as resources for training all market actors on passive design. Certification courses are available that cater to the training needs of architects, engineers, builders, and raters.

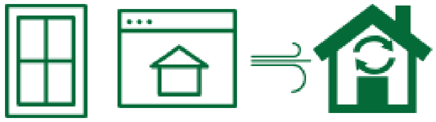
One engineer mentioned the tendency for mechanical systems designers to oversize HVAC systems – engineers are hesitant to size systems to meet the low load requirements of passive homes, and oversizing heat pumps can lead to short-cycling and high energy use. One industry expert mentioned that mechanical, electrical and plumbing (MEP) professionals are often overlooked in the Passive House process and that additional training or awareness for those parties could help projects go more smoothly. The Team observed this issue during an informational site visit for a multifamily project that achieved near Passive House standards. The project installed one ductless mini-split head for each apartment; however, the size of the head exceeded the requirements of the room size. The project team was concerned about potential short-cycling issues.

**Additional multifamily-specific training offerings**. One industry expert suggested that the program could offer additional training on Passive House in multifamily buildings, as the Passive House certification traditionally focuses on single-family. Another, speaking specifically about multifamily projects, suggested that the program could provide a framework to use throughout the integrated design process. One suggestion was a simple and effective tool that highlights when to involve builders, MEP professionals, and other actors.

# Section 7 Incremental Costs

## 7.1 Drivers of Increased Costs

### 7.1.1 In-Depth Interviews



Windows, modeling, and air sealing were the most commonly identified increased costs

**The building envelope.** The various building envelope upgrades – windows, insulation, higher quality air barriers and vapor barriers, designing and constructing thermal bridge free details, and air-sealing – all necessary components to meet passive design requirements were commonly-cited sources of incremental costs. Many stressed that the added time and materials necessary to perform air sealing to passive standard was a key cause of cost increases. Not only does it take more time to air seal to passive standards, but the complexity increases, necessitating additional training for the builder to become familiar with new products and construction techniques if they haven't previously built to passive standards. However, with proper training and QA/QC procedures in place for air sealing, the project schedule can remain intact. Architects and developers also mentioned added insulation as a source of increased costs. There was also a sense among some architects, engineers, and developers that builders and sub-contractors may inflate their prices when asked to bid out a passive project – assuming that the project will take longer and require more training or trial and error; or that they are dealing with a "premium" project and thus an owner or developer who is willing to pay more.

**Passive House certification and associated soft costs.** This includes the pre-certification and certification fees and additional soft costs such as: energy modeling, additional project coordination and meetings, Passive House consultants, and the rater fees. There was some disagreement on whether these processes actually led to incremental costs: one interviewee noted that modeling costs for large projects is extremely marginal to overall cost and can pay for itself with the information it provides to the project team, and another believed that early energy modeling could inform project decisions and allow for value engineering that leads to cost savings on materials and labor.

**Mechanical ventilation.** The added ventilation requirements of passive buildings were brought up by interviewees in most market actor groups as a source of increased costs. Continuous mechanical ventilation is needed in each passive design, and with this added up-front cost comes the need to make sure the ventilation system is sealed and properly integrated into the overall construction to avoid increased infiltration or other issues.[40]

[40] There seems to be some ambiguity among architects and engineers as to whether recent updates to the building code create a de facto code requirement for mechanical ventilation. Should this be the case now or in the near future, it would no longer be an incremental cost provided enforcement is consistent and the wider industry becomes aware of this.

## 7.2 Incremental Cost Estimates

### 7.2.1 In-Depth Interviews

Industry experts noted that cost could vary widely from project to project, but they agreed that the increased costs for MFHR buildings were in the range of 5-10%. Developers similarly estimated that MFHR incremental costs fell in a range of 3-10%; however, two indicated potential for little to no incremental cost for Passive House construction with proper planning or advances in industry experience. Builders noted that incremental costs are dependent on where you start from and whether you were previously building to high performance standards or to code and estimated incremental costs in the range of 3-15%. Builders responding specifically to MFHR Passive projects indicated a narrower range of 5-10%, while two MFLR and single-family builders provided the extremes of that range, estimating 3% and 12-15%. Industry experts suggested that incremental costs for single-family homes range from 5%-20%. Architects and engineers indicated the incremental costs were 10% for single-family. Architects and engineers were also more optimistic than other groups regarding high-rise projects, estimating a 2% cost increase. The most commonly cited incremental cost figure was estimated to be around 5%. Interviewees of all types believed that with proper planning and an evolution in approach, multifamily passive buildings could achieve cost parity with non-passive designs.

**Table 35: Passive House Incremental Cost Estimates**

| Market Actor Group | Incremental Cost - low range | Incremental cost – high range |
|---|---|---|
| Architect/engineer | 2% | 2% |
| Builders | 3% | 15% |
| Industry Experts | 5% | 10% |
| Developers | 3% | 10% |

Industry experts, architects, and engineers agreed that incremental costs, as a percent of project costs, decrease as the size of the building increases. Increasing surface to volume ratio (making it easier to achieve air leakage levels), increased internal gains (lowering insulation and heating load requirements), and decreasing marginal costs of modeling and certification fees as building size increases were all cited as explanations for decreased incremental costs (as a percentage of project costs) as size of building increases. The MFLR builder who pegged the incremental cost increase as 12-15% above their previous work (which they described as roughly code-level) pointed out that these could likely be higher for single-family homes. Two single-family occupants were interviewed for this study and both observed that they entered the process wanting to incorporate passive design strategies into their homes. As a result, these occupants did not price out an alternative option more akin to traditional new construction. Addressing higher incremental costs while winning over single-family participants with no preference for building to passive standards will be a major challenge for the single-family portion of the program moving forward. It is worth noting that as energy codes become more stringent and baseline construction practices advance, the cost disparity between passive and non-passive buildings will decrease.

Overall, respondents were unable to provide specific hard costs associated with measure-level upgrades. However, a couple developers provided details on the actual costs for certification and the associated soft costs. The actual project estimates are provided in Table 36.

**Table 36: Specific Cost Estimates Identified by Developers**

| Cost Category | Details |
|---|---|
| Initial Feasibility Modeling | ➢ Approximately 5,000 for initial feasibility modeling |
| Energy Modeling | ➢ $15,000 for 135-unit project ($111.11/unit)<br>➢ Between $10,000 - $20,000 for a 98-unit project and 108-unit project ($102.04-$204.08/unit)<br>➢ Between $30,000 - $50,000 for an early Passive House project that included multiple modeling entities ($1,071.43-$1,785.71/unit) |
| Rater Fees | ➢ $50,000 for a 135-unit project ($370.37/unit) |
| Certification Costs | ➢ $12,000 for a 28-unit project ($428.57/unit)<br>➢ $22,000 for a 135-unit project ($162.96/unit)<br>➢ $17,000 for a 98-unit project ($173.47/unit) |

One developer noted they had just begun a side-by-side schematic design cost comparison study of a non-Passive House and Passive House building, but results won't be available until later this year.

### 7.2.2 Literature Review

As mentioned in the literature review, published information on incremental costs was not easy to come by, and was characterized by moving baselines for comparisons and differing costing methodologies. Also, one-off case studies with cost data typically focused on single-family residences. Leaning heavily on a report done by the Pembina Institute in Canada that aggregated Passive House cost data, incremental costs were typically below 10% and averaged around 6%. This coincides well with estimates given by interviewees during IDIs for multifamily properties.

### 7.2.3 Pennsylvania Affordable Housing Cost Data

The PAs and Massachusetts Clean Energy Center (CEC) provided data of Pennsylvania affordable housing project costs, where they are working on integrating Passive House projects.[41] The data included estimated project costs based on submitted applications to the program – which includes both Passive House and non-Passive House projects.[42] The application costs are the estimated cost based on the proposed design, which are provided by project teams to the PHFA. For cost estimates at application, certified passive buildings went from a 3% premium over non-passive buildings per sq. ft. in 2015 up to 5% in 2016; however, by 2018 the cost per sq. ft. of a passive project was estimated to be 2% less than a non-passive building. On a per-unit basis,

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[41] Data was originally submitted to both the PAs and the Mass CEC from the Pennsylvania Housing Finance Agency (PHFA).

[42] The PHFA program awarded projects additional affordable housing credits for applicant projects that are designed to achieve Passive House standards.

costs for passive project applications were 3% lower in 2015, 1% higher in 2016, and almost 6% lower in 2018 compared to non-passive project applications.

The final construction costs were documented from 2015 – data for subsequent years were only available for application costs because projects were not fully completed. For 2015, the Team compared actual costs to estimated costs at application – passive buildings cost 5% more than estimated, compared to a 2% increase for non-passive buildings. An interesting finding was that overall construction costs in 2015 both by square footage and per-unit were lower for the Passive House projects. Note that sample sizes were limited, and one Passive House project was completed at a noticeably lower cost than others, driving the average down a fair amount. When the Team excluded that specific project the cost per sq. ft. was very similar to the non-passive projects; though the cost per unit still favored passive projects.

The Team was provided additional rationale from the MA CED on which factors drove down the costs for Passive House projects in Pennsylvania. Cost decreases were attributed to increased knowledge and practical experience of Passive House processes, and simplified aesthetic designs – essentially these projects are boxes. It should be noted that the data provided was for a handful of projects statewide – and sample sizes are limited, especially for Passive House projects on a per-year basis (under ten). However, this data does provide evidence that cost premiums for Passive House may fall as more projects break ground in Massachusetts. See Appendix A for additional details on costs per sq. ft. and per-unit.

## 7.3 Methods for Offsetting Incremental Costs

### 7.3.1 In-Depth Interviews

**Choose materials wisely, with focus on simplicity and familiarity.** Using pre-fabricated or standardized components to simplify construction and shrink construction timelines was one method suggested by several interviewees. A developer added that window installation can be included in these panelized systems, further decreasing on-site labor and simplifying air sealing. In addition, when there are opportunities to choose traditional materials that can meet passive building standards and that contractors are familiar with, this can be beneficial. If the contractors are familiar with the materials, they may be inclined to keep their labor costs closer to their standard prices, and the project can benefit from spending less on materials in general. It was also noted by builders that code officials are often resistant to approving builds utilizing new or unfamiliar materials – providing an additional benefit to the project team for considerations on material selection.

> **"It's about sticking with products you're familiar with. Zip sheathing can be used as an air-tight membrane and contractors are working with it. So, if you're taping seams you can get away with that, and contractors won't charge you extra because they know it."**
> **-Architect**

**Value engineering.** Early energy modeling was another method for keeping costs down by allowing for value engineering before materials are installed – you may be planning on installing

4" inches of continuous insulation, but modeling could demonstrate that reducing one inch is sufficient to maintain the performance of the assembly. Energy modeling can also help determine the quality of windows necessary to achieve desired performance – if a less expensive window type is tolerated by the model, one of the most commonly-cited large incremental costs can be lowered. Additionally, architects suggested they may compromise on the aesthetics to create better building envelopes, either externally or in the interior through less expensive interior finishes. An example of this is podium-style construction for mid-rise buildings – which allows parking for occupants but eliminates the need for substantial below grade foundation construction; this was also noted to increase resiliency of the building. Passive House design techniques include stacking kitchens and bathrooms, which reduce plumbing runs and simplifies overall design.

**Early and sustained communication and planning among project team.** Several interviewees mentioned the importance of sustained communication and collaboration among the project team as key to keeping costs down. One architect initiated weekly round tables with the entire project team to ensure that each member knew what was expected and that any questions were answered before moving forward with work. The general thought is to break down artificial barriers that limit knowledge sharing and planning among all parties to ensure each team member is supported and informed fully. Sequencing construction steps – including when certain materials arrive on-site was cited as having extra importance on passive projects, given the difficulty of maintaining continuous air- and thermal-barriers later in the construction process.

**Simplified heating and cooling systems.** Lower heating and cooling loads reduce the size and complexity of mechanical systems in Passive House buildings. There is still a challenge with getting properly sized mechanical equipment; however, there appears to be a trend to move to centralized VRF systems for heating and cooling, which also reduces potential maintenance costs of individual-unit systems. One developer mentioned that they were looking into a combined heating, cooling, and ventilation product that is projected to reduce total HVAC system costs by one-third, compared to their previous project.

# Section 8 Incentive Structure

The following sections present the IDI findings on the Passive House offering incentive structure, which includes incentive targets, requirements, timing, and amounts.

## 8.1 Incentive Structure – In-depth Interviews

Table 37 provides a summary of responses regarding incentive structure, mostly related to MFHR buildings, followed by a few entries specific to MFLR and single-family projects. As described earlier in the report, the MFHR incentive structure has been developed for the MFHR Passive House offering based on these results – which were provided in the interim report (see Table 6 for details on the incentive amounts and allocation points).

**Table 37: Incentive Structure Summary of IDI Responses**

| Market Actor Respondent | Incentive Recipient | Incentive Timing | Incentive Amount |
|---|---|---|---|
| ***High-Rise Incentives*** | | | |
| *Industry Expert Consensus* | *Owner/Developer & Builder* | *Partial at pre-certification, rest following completion* | *~$4,000 per unit* |
| Industry Expert | Owner/Developer | Initial Modeling | Modeling Cost |
| Industry Expert | Owner/Developer | Part 1) Pre-certification<br><br>Part 2) Following certification or based on a year's worth of data | $4,000 per unit, scaled down to $1,000 after a certain number of units |
| Industry Expert | Owner/Developer & Builder | Part 1) Pre-certification<br>Part 2) Majority following certification | Per unit incentive |
| Industry Expert | Owner/Developer & Builder | Initial Modeling | $4,000-$6,000 per unit |
| Architect/Engineer | Homeowner, Builder, & Architect | $5,000 ($3,000 to builder, $1,000 to homeowner, $1,000 to architect) | |
| Builder | Developer/Builder | Initial Modeling | Incremental cost of measure upgrades |
| Builder | Owner/Developer & Builder | Initial Modeling | Incremental cost of measure upgrades |
| *Developers Consensus* | *Owner/Developer* | *Phases (Pre-certification, Certification, and after a year of data)* | |
| Developers | Owner/Developer | Initial Modeling | $5,000 per unit |

| | | | |
|---|---|---|---|
| Developers | Owner/Developer | Part 1) Pre-certification<br>Part 2) Certification<br>Part 3) After a year's worth of data | $5,000 per unit ($2,000 pre-certification, $2,000 certification, $1,000 after billing data) |
| Developers | Owner/Developer | Part 1) Initial modeling<br>Part 2) Certification | $4,000 per unit |
| Developers | Owner/Developer | Part 1) Certification<br>Part 2) Performance | $10,000+ per unit |
| Developers | Owner/Developer | Design/pre-certification | $10,000 per unit |
| ***Low-rise and single-family incentives*** | | | |
| Builder/Designer | Owner/Architect | Certification | $7,000+ per unit |
| Builder | Builder | Certification | $5,000 per unit |
| Owner/occupant | Owner | Post-construction | Per unit incentive |
| Owner/occupant/industry expert | Owner/developer, builder, design team | Part 1) Design charrette<br>Part 2) Modeling<br>Part 3) Certification | $4,000 per unit |

### 8.1.1 Incentive Targets

Industry experts proposed an incentive structure aimed mostly at the owner or developer. Some also suggested that the builder should receive part of the incentive as they were the most difficult party to get on board, while one preferred a combination incentive to all involved (owner/developer, builder, architect). Architects, engineers, and builders were largely in favor of a combination incentive that paid out to the owner/developer, the builder, and the design team. One architect believed that targeting all funds to the owner/developer was most important to overcome resistance to the incremental costs of going passive over other design options. One Passive House owner/occupant, who pursued Passive House despite the cost increases, asserted that the owner/developer would need to be targeted with the bulk of the incentive directly, rather than some current construction incentive programs where the money goes to the builder. They did, however, suggest rewarding the builder; either financially or by awarding them certifications for successfully completing a passive construction process. The two MFLR and single-family builders interviewed were split on the preferred incentive target, with one saying the bulk should go to the owner and the other saying it should be a builder incentive.

Developer consensus was that incentives should be distributed to owner/developer because they are on the hook financially. They believed the program could support designers and builders through training offerings, educational resources, and subsidies for third party trainings.

### 8.1.2 Incentive Requirements

Developers had mixed opinions on incentive requirements-some believed that certification should be the program requirement, others mentioned a certification requirement may be a potential barrier for market adoption – especially if incentives are dependent on achieving certification. This may be a barrier for two reasons: one being uncertainty, for example the project meets pre-certification requirements but narrowly misses certification; the second being that some developers believe the market will pay the same whether certified or designed to certification standards, for example with LEED Gold buildings. As mentioned earlier, there is uncertainty about the market value to being certified; investors or developers may opt against pursuing certification because they think they are getting the performance benefits of the design without certification. One suggestion was to administratively align the program requirements with the certification requirements to make the project teams decision to pursue final certification as seamless as possible – but to leave it to the project team or market to make a final certification decision.

One of the key values of Passive House certification is assistance throughout the project – pre-certification, trained professionals on the project, and the QA/QC that comes with third party verification. Third party verification includes having a trained rater on the project team who verifies that the constructed building matches the proposed design and energy model.

Developers cited programs in other states, and the Massachusetts CEC grant that requires reporting on costs – specifically including component upgrade costs. Additionally, requirements on providing actual performance data were mentioned. The cost and consumption data were presented to provide the program a reciprocating value for the program incentives, which is providing data to communicate to the market at large.

### 8.1.3 Incentive Timing

Industry experts largely agreed on splitting the incentive, with part provided after energy modeling to help offset those initial costs, and additional payment after completing the project and attaining certification. Some supported awarding additional incentive based on real world performance after collecting data. “Real world performance is the ultimate goal, so we should base the incentive on that,” said one respondent. Another suggested that since it would cost money to monitor energy use, the program could pay for monitoring equipment and could benefit from the data collected, which is largely missing in the Passive House space.

Early incentives awarded alongside modeling or pre-certification can help ease incremental costs. Many advocated for an additional incentive following certification or based on performance data.

Architects and engineers generally stressed the importance of making incentives available early in the process. Echoing sentiments expressed by industry experts, they pointed to the need to cover the early costs of energy modeling, but also using the certainty of incentives to motivate the entire team to coalesce around the idea of building to Passive House standards as early as possible. One respondent pointed to the Massachusetts CEC Passive House Design Challenge as a good template because they make some incentive available earlier in the process, rather than waiting until construction is complete. A consistent theme throughout interviews was the importance of deciding to build passive as early as possible, and there was a belief among respondents that making at least some of the incentive available early can jump start the decision to pay for early modeling and consulting and thus increase the possibility that the project will hit the milestones needed to achieve certification. Four of five builders suggested incentives should be based on measured performance, largely because models cannot predict occupant behavior.

Most developers think a phased incentive approach would work best: early design charrette, pre-certification, completion, and potentially an additional incentive based on measured performance. Incentives and additional program support should come into play early in the project to impact design decisions. Incentives distributed at the pre-certification stage (essentially design meets specs) can directly impact construction loan interest rates. While developers recognized performance as critical, tying up incentives potentially years after project completion is not recommended.

For single-family and small multifamily projects, the incentive allocation may be simplified between pre-certification and certification stages. Though providing small incentives early in the design stage may encourage a larger uptick in single-family and small multifamily projects participating in the Passive House offering.

### 8.1.4 Incentive Amounts

**"I think if we can get a few of these projects under our belts, we won't have to incentivize it." -Developer**

In the multifamily space, the most common suggested incentive structure was a set amount based on the number of units, which ranged from $4,000 - $10,000+. One developer suggested higher incentives, especially if the incentive pool is limited, for projects with larger aggregate carbon reduction impacts – considering an anticipated increase in electric vehicles and the impact on the grid if occupants are required to travel extensive distances for basic living amenities. For large projects, incentives have to be large enough to be impactful. Scaling the incentive down over time was recommended by several respondents, the thought was a larger incentive over the next few years will accelerate market transformation of Passive House projects. As practical experience increases, costs will likely fall (as suggested from results of the Pennsylvania affordable multifamily market) and allow the program to taper off incentives. The incentive amount would be reduced as costs reduced, allowing the market to continue with less program support in later years.

The primary focus during the IDIs was for incentive amounts geared towards MFHR building; however, the Team was able to procure a few responses geared specifically for small multifamily and single-family projects. Market actors in all categories suggested that incremental costs for smaller Passive House projects are higher, indicating the need for a larger incentive to help reduce the cost burden. One builder with experience on MFLR passive buildings suggested an incentive of $7,000 per unit would be appropriate. He added that this would likely need to be higher for a single-family home, where incremental costs would be the highest. Another builder in the MFLR and single-family space thought $5,000 would be sufficient, more in line with the numbers provided by MFHR respondents. Please note that there were only a few responses specific to small-scale projects; however, the incentive range suggested is likely high enough to gain market traction but may not entirely offset incremental costs.

# Section 9 Program Recommendations and Considerations

Based on the findings presented above, the Team makes the following recommendations and considerations regarding the new program offerings. Various study activities such as a literature review, speaking with market actors during in-depth interviews, and attending building and design conferences have brought to light other considerations for the Passive House offering. Note that the Team will be conducting an additional task to develop a PTLM that focuses on the ability of the Passive House offering to generate market effects.

## 9.1 Program Recommendations

The Team presents the following program recommendations to the PAs and implementation contractor for the Passive House offering.

### 9.1.1 Modeling Tools for Savings Calculations

**The PAs should allow for the use of both the WUFI Passive and PHPP models to calculate savings for their new offerings.** The Team recommends using these tools to model both the proposed case and the baseline case to ensure consistency in the modeling of program savings. Specifically, the Team recommends using one modeling tool per project to assess savings; projects pursuing PHIUS certification should use WUFI Passive models, while projects pursuing PHI certification should use PHPP models. The model comparison shows that, with a few adjustments, the Passive House tools generate comparable consumption estimates when the same modeling protocols are followed (see Appendix B for certification default values and MFHR modeling assumptions). The PAs should be sure to incorporate specific modeling protocols to adjust the certification models and ensure that the assumptions used for items such as plug loads, lighting, and hot water usage reflect the most realistic values available.

The Team, working with PHIUS and Steven Winter Associates, was able to develop a worksheet that can be used to convert the MFHR User Defined Reference Home (UDRH) into WUFI Passive or PHPP. The modeling comparison highlighted that these tools can be used to model the MFHR UDRH scenario and that they include more detailed inputs specific to Passive House design than the ICF tool.[43] The current low-rise UDRH was easier to apply to the Passive House tools than the MFHR UDRH; however, one main challenge was the re-distribution of window area by orientation in the three-dimensional models for the baseline cases. The Team believes that using Passive House tools to calculate program savings will generate some efficiencies as future participants will already be building proposed models in either WUFI Passive of PHPP as part of the certification process. Adjusting these models to reflect program-specific modeling protocols and creating a comparative baseline model in the Passive House tools is likely to require less labor than creating new models in either the ICF MFHR tool or Ekotrope.

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[43] The ICF MFHR tool API was built to meet the PA needs for cost-effective energy modeling.

### 9.1.2 Performance Monitoring

**The PAs should monitor the performance of early program participants.** As part of the new program offering, the PAs should monitor the overall electric and gas consumption of early program participants. The PAs should also monitor any on-site renewable energy generation for these projects. The combination of these data points will allow the PAs to assess the accuracy of the Passive House modeling tools. While end-use metering could be valuable, the Team does not believe it is necessary to assess the overall accuracy of the modeling tools. Monitored performance data could also prove to be a useful marketing tool for the program moving forward. As part of the IDIs, developers indicated that they would be more likely to build to Passive House standards if they had proof that the buildings perform as efficiently as the modeling tools indicate they should. As a result, having monitored performance data from early participants may help recruit additional builders and developers into the programs.

## 9.2 Program Considerations

The Team has provided additional program suggestions and opportunities for the PAs and implementation contractor to consider for the Passive House offering.

### 9.2.1 Revisit UDRH Assumptions

**The PAs should consider revisiting the current UDRH assumptions for both the MFHR and low-rise programs to ensure they are capturing all the savings opportunities associated with Passive House projects.** The current versions of UDRH inputs were developed to calculate savings associated with the traditional new construction programs. The Team suggests that stakeholders, including evaluation, implementation, and Passive House experts (such as PHIUS and Steven Winter Associates), revisit the current baseline assumptions and ensure they are appropriate for the new offerings. As part of the modeling comparison, the Team identified certain savings opportunities that are not currently part of the UDRH. For example, the current MFHR and low-rise UDRH inputs do not account for the efficiency of ventilation units. Passive House promotes high-efficiency ventilation units that are likely to generate savings over typical ventilation units. The PAs should claim those savings if the programs are indeed driving more efficient practices. Another example is that Passive House projects are likely to use electric heating and cooling systems, rather than more traditional heating systems, and may warrant an exploration on whether fuel switching should be applied to the Passive House offering participants.

### 9.2.2 Further Research on the Accuracy of Modeling Baseline Conditions

**The PAs should consider additional research that explores the accuracy of the modeling tools compared to actual billing data.** The question regarding which modeling software is more reliable and accurate can be further explored by leveraging non-program energy models from previous baseline studies that now have a few years of post-occupancy billing data available. The Team suggests that the PAs consider a study that compares each of the low-rise modeling tools included in this study to billing data to assess the accuracy of the modeling tools. The Team has all the schematics and energy models needed to conduct this assessment for low-rise non-program homes that participated in the 2015 baseline study.[44] A comparable effort could also be completed for the small number of buildings that participated in the most recent MFHR baseline study.[45] This study, coupled with the requirement to monitor energy consumption in participant projects, should answer most questions about the accuracy of the modeling tools discussed in this report.

### 9.2.3 Incentive Amounts

**The PAs should consider offering an incentive that provides a reasonable amount of financial certainty for initial participants and is substantial enough to grab the attention of the market.** Developers indicated that there is a fair amount of uncertainty when it comes to building Passive House projects given the nascent nature of the market. As a result, they indicated that financial certainty in the form of incentives would be beneficial for generating interest in the new offering. In addition, developers and other market actors indicated that substantial incentives will be necessary to move the needle in the multifamily new construction market given the overall costs associated with these projects. The implementation contractor, ICF, provided details on the current average incentive amount per-unit for MFHR participants ($630/unit), MFLR participants ($964/unit), and single-family participants ($1,876/unit) in the traditional new construction programs. The program incentive levels that have been suggested from the IDIs are substantially higher than the current average program offerings.[46]

The Team proposed a MFHR incentive range for the PAs to consider in the interim report, which led to the development of the current MFHR Passive House offering (Table 1). The current PH offering is substantially larger than the traditional MFHR RNC program incentives (see average incentive values above). The current MFHR Passive House incentive structure should be considered for all multifamily projects over five units. This consideration is in regard to the incentive amount and allocation points rather than an alternative UDRH to calculate savings. This is due to market actors' recommendations to keep the incentive structure easy to interpret, similarities in modeled savings results between MFHR and MFLR projects, and the indicated lower incremental costs as project size increases. Note that smaller multifamily projects will likely see a larger incremental cost as a percentage of overall costs initially in the program.

Projects that are five units or less and single-family projects should receive an incentive that is larger than the MFHR incentive on a per-unit basis, between $5,000 and $7,000 per unit. This is to account for the higher incremental costs associated with small-scale projects.

### 9.2.4 Incentive Allocation Points

**The PAs should consider spreading incentives out across various stages in order to provide upfront incentives to market actors and to provide some flexibility in the program**

[44] http://ma-eeac.org/wordpress/wp-content/uploads/Single-Family-Code-Compliance-Baseline-Study-Volume-2.pdf
[45] http://ma-eeac.org/wordpress/wp-content/uploads/MA-Multifamily-High-Rise-Baseline-Study-Report.pdf
[46] The current Passive House Design Challenge offering from the Massachusetts Clean Energy Center for affordable multifamily buildings that achieve Passive House certification is up to $4,000/unit.

**design regarding certification.** Market actors indicated that they would like to see incentives spread out over a few different project milestones.

One of the concerns among market actors was tying incentives to certification and missing out on incentives for a project that uses Passive House design principles but just misses the final certification requirements. Conversely, the value proposition that market actors provided for including certification as part of the program requirements is the QA/QC verification process required for final certification that verifies that the design matches what has been constructed.[47] The Team considered the impact of participation in the program without the requirement of certification, but responses from market actors, the additional QA/QC, and the design support that certification provided throughout the project is a valuable resource for the program to leverage.

Providing a proportion of the incentives prior to achieving final certification would supply some assurances to potential participants that incentives are available and will not be taken away if final certification is not achieved. It should be noted that the MFHR offering includes a contingency for projects that achieve pre-certification but do not achieve or pursue final certification – which is an incentive based on savings performance, through the Net Performance Bonus (Table 1).

For multifamily projects, the PAs should consider offering incentives for design team charrettes and initial modeling, pre-certification, and final certification – as outlined in the current MFHR incentive structure.

The PAs should consider applying the same incentive amount and allocation points to all multifamily projects that are over five units.

Single-family projects and multifamily projects five units or less likely do not require as many incentive allocation points as projects are smaller in scope. The PAs should consider offering incentives at pre-certification and at final certification (pre-certification and Net Performance bonus if final certification is not achieved).

### 9.2.5 Bonus Incentives to Early Participants

**The PAs should consider providing bonus incentives to early participants for additional data to inform programmatic decisions.** The PAs should consider additional project incentives to early program participants that provide detailed cost information to better understand the incremental costs associated with Passive House design, construction, and certification. Additional incentives may also be provided to project teams that share monitored energy consumption by end-use or measure specific non-energy impacts with the program. As a result, the additional incentives would help validate current program assumptions on the energy savings, project costs, and non-energy impacts of Passive House projects in Massachusetts.

There may be an opportunity to align data collection of project costs with the incremental cost reporting framework that the Massachusetts CEC requires for their Passive House Design Challenge incentive offering. This would require the PAs to collaborate with the Massachusetts

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[47] Note that PHI and PHIUS have different verification protocols for final certification. The PHI certification requires air infiltration testing and commissioning ventilation systems. The PHIUS verification process includes both air infiltration testing and ventilation commissioning, along with a multitude of additional verification activities that must be completed by a certified rater. This link to the PHIUS MF rater checklist provides the reader additional context.

CEC to understand their design framework and determine whether it will meet the needs of the program – aligning how information is gathered would provide both entities with more data on Passive House project costs. This may provide both entities synergies, efficiencies, and consistency in program development and communication of the incremental costs to the market at large.

Note that certain information, such as project costs, are typically very sensitive and the program should provide memos of understanding or confidentiality agreements to project teams to assure their data will only be reported in aggregate if published.

### 9.2.6 Program Collaboration and Flexibility

The PAs should work closely with initial program participants in order to monitor the program design and allow for flexibility in programmatic changes when more information is available. While the Team believes the research presented in this report provides valuable data to inform the initial program offerings, there is still a need for more information regarding incentive amounts, incentive structure, and incremental costs. The Team recommends that the PAs work closely with initial participants to determine the extent to which the initial incentive amounts and incentive structure motivate potential market actors and cover the incremental costs associated with Passive House certification. For example, the program may monitor how many projects initially set out to participate in the offering and how many projects complete each incentive allocation point, to ensure early incentive allocation is effective for achieving the program goals.

Close collaboration with participants can also inform the development of a best practice guide for cost-effective project solutions – aimed at helping project teams achieve cost parity with non-passive house projects. Passive house experts have suggested incremental costs can be significantly reduced or eliminated with proper planning, experience, and training.

### 9.2.7 Training Opportunities

**The PAs should consider trainings specific to Passive House design and construction.** Market actors suggested several aspects where the program should intervene to encourage training, build experience, and expedite the advancement of construction practices to Passive House levels in Massachusetts. Trainings the program can emphasize include, but are not limited to, proper HVAC sizing, air-sealing, avoiding thermal bridges, material selection, energy modeling, Passive House inspections/ratings, designer-specific training, and developer-specific trainings.

The topic of proper HVAC sizing and Passive House design came up in the in-depth interviews as an area for future education and training for contractors. Contractors who are more likely to rely on rules of thumb for sizing HVAC equipment, or are less familiar with the energy performance of Passive House projects, may be more likely to oversize HVAC equipment in passive construction. In the case of some heat pumps, this can cause consistent short-cycling that never allows the heat pump to operate at peak efficiency and can cause much higher energy use than anticipated. Much of the energy benefit of passive design can be undone by a poorly designed HVAC system. This issue was corroborated, incidentally, by the Team during an educational tour of a multifamily building, which had employed in-unit ductless mini-splits that were oversized for the highly insulated, tightly air-sealed building – causing concern for potential short-cycling. The

PA's Passive House offering will likely benefit from additional training for HVAC contractors to understand how to size equipment appropriately in a high-performance Passive House project. This will require HVAC contractors to overcome what may seem like a counterintuitive practice of installing very low-capacity systems.

High performance air-sealing was cited by many market actors as a barrier to achieving Passive House standards. The program can leverage existing training, develop a best practices guide, and provide hands-on training. Air-sealing best practices should be documented from early project participants to help future participants overcome challenges in the most cost-effective way. For example, setting up a QA/QC procedure before construction starts, posting signs about reducing envelope penetrations in multiple languages, and testing air-infiltration early (especially in multifamily buildings).

The program should leverage existing training opportunities, especially for energy modeling, inspections or ratings, thermal bridging, and material selection – especially early in program development. Providing training incentives to early project participants will help advance baseline knowledge and bridge the experience gap in Passive House construction that currently exists in Massachusetts.

The program can also develop Passive House trainings specifically for developer audiences. These trainings should look to spread awareness to the developer community about Passive House construction, including the reduced energy consumption, additional occupant benefits, and costs associated with these projects. If the program leverages the considerations above, the offering will be well positioned to communicate participant results to the developer community at large, and will aide in the transformation of the new construction market to Passive House levels.

### 9.2.8 Rater Checklist Requirements

**The PAs should consider leveraging the PHIUS certification rater checklist and project verification procedure on all project participants.** The Passive House offering allows program participants to choose pursuing either PHIUS or PHI certification. While the two certification bodies share similar design principles, they have different performance requirements, as well as different verification requirements to achieve certification. PHI requires that an air infiltration test is conducted, and the ventilation system is tested and commissioned. PHIUS requires that a PHIUS certified rater is a part of the project team and completes an extensive verification checklist.[48] For single-family and small attached homes, the checklist also satisfies certification requirements for the Environmental Protection Agency's (EPA) ENERGY STAR New Homes (ESTAR), Department of Energy's Zero-Energy Ready Homes (ZERH), and the EPA Indoor airPLUS (IAP) programs. The multifamily-specific checklist certifies projects for the EPA ESTAR or EPA ENERGY STAR Multifamily New Construction Program (MFNC), and the DOE ZERH if eligible. If projects are not eligible, they still must demonstrate meeting the criteria on the checklist.[49] To verify that modeled inputs match the final construction, the program should consider requiring the PHIUS verification checklist or a similar checklist for all projects, regardless of which certification body is pursued. Note that this would cause an increase in cost for PHI

[48] https://www.phius.org/phius-certification-for-buildings-products/project-certification/documents-for-download
[49] https://www.phius.org/PHIUS+2018/PHIUS+%20Certification%20Guidebook%20v2.0_final.pdf

projects; however, project verification checklists are a valuable tool for the program to confirm that the actual construction matches the modeled building. The checklist should be completed by a certified individual and provided to the program and implementation staff for program documentation.

#### 9.2.9 Occupant Education Plans

**The PAs should consider working with multifamily project teams to develop occupant education plans aimed to reduce overall energy consumption.** The Team reported on an issue in the Passive House literature review that occupant behavior has a substantial impact on energy use in Passive House projects.[50] When an energy model is developed based on a proposed or even constructed building, there are factors that are beyond the control of the architect, builder, engineer, or developer, such as the occupants that inhabit the building. Inputs such as the amount of hot water used, the number of plugged-in devices, or hours of use for lighting are based on federal standards, certification assumptions, or even the energy modelers assumptions. In addition, there are unpredictable behaviors like opening the windows during the winter to clear out kitchen smells or to cool the building because the thermostat was set too high. This can be exacerbated in multifamily buildings, especially as the number of occupants increase. When utilizing energy models to predict energy usage or claim program savings, occupant behavior can throw off the desired energy performance of the building. The program has an opportunity to aid participants in the development of occupant education plans that aim to reduce the impact of these variables, especially in larger multifamily buildings. The program could work with initial project teams to develop pilot occupant education plans to compare the actual performance of those buildings to similar buildings that have not administered an occupant education plan.

### 9.3 Future Program Considerations

The Team has provided some additional future considerations for the PAs and implementation contractor as the Passive House offering progresses.

#### 9.3.1 Passive Building Material Selection and Embodied Carbon

Beyond traditional building energy-efficiency concerns, there is growing conversation and concern around the idea of construction materials and embodied energy (carbon dioxide and carbon dioxide equivalent). Embodied energy in the construction industry refers to the amount of greenhouse gasses (GHGs) released into the atmosphere as a result of the extraction and manufacturing process of building components. This holistic view of buildings and energy emissions reorients the discussion to focus more heavily on material choice and procurement practices and how that interplays with building performance. For example, a high performing building from an efficiency standpoint that uses closed-cell spray foam (CCSF, high levels of embodied energy) for insulation has created far more emissions than a code compliant building

[50] http://ma-eeac.org/wordpress/wp-content/uploads/MA19R05_PassiveHouse_LitReview_Final_2019.07.17.pdf

that is insulated with cellulose.[51] Addressing embodied energy in new construction and retrofits represents the next, more comprehensive step in realizing true emissions reductions in the sector, and can be implemented on a parallel track with more traditional efforts to increase building efficiency.

During in-depth interviews, Passive House market actors often indicated that they consider embodied carbon in their day to day practice – choosing dense-pack cellulose over CCSF, for example. Because of the air sealing and R-value requirements that come with Passive Design, a major concern moving forward is that the uptake of high-embodied energy spray foams and rigid foam board will increase in speed and scale as building energy performance is pushed forward. Numerous options exist or are being developed that, rather than causing a net carbon increase through their extraction and production, are sourced from organic materials, such as plant and wood fibers, and actually act as net carbon sinks. These include hempcrete, straw-based SIPS, and timber waste materials that, when used at scale, create a building that holds more carbon than was used to construct it.

Through our research, it is clear that the Passive House design industry has demonstrated an awareness of these issues and can be a resource to the program and the PAs should they want to fold these considerations into program education and awareness efforts in the future.[52] There are now tools for whole-building life cycle assessments that can aid in the design of low-embodied energy projects, such as EC3, a free embodied carbon construction calculator, or Tally, a plug-in for Revit (a common software used by designers).[53,54] The range of options the program can implement to support projects spans from spreading awareness on embodied energy and low-impact materials, to offering bonus incentives in the future to projects that demonstrate the lowest embodied energy impacts.

### 9.3.2 Passive Buildings and Non-Energy Impacts

As mentioned in Section 6, the non-energy benefits of Passive House design are mentioned by proponents almost as often as the energy savings advantages. Benefits include, but are not limited to, the following:

- Indoor air quality
- Thermal comfort
- Resilience
- Ability to maintain temperature during severe weather
- Noise reduction
- Potential increased lifespan of mechanical equipment
- Building quality (attention to moisture and condensation issues in building components)

[51] The Keynote Session at the 2019 NESEA BuildingEnergy Boston Conference centered on embodied carbon in the building industry, and provides a useful breakdown of these issues: http://nesea.org/session/carbon-drawdown-now-turning-buildings-carbon-sinks

[52] Additional resources have been made available for designers and builders to make better, more informed material choices. Examples of free databases that the program can immediately leverage during initial design charrettes include Circular Ecology's Inventory of Carbon and Energy (ICE) database and Quartz.

[53] https://buildingtransparency.org/

[54] https://choosetally.com/

Quantifying these benefits can be challenging, particularly in new construction, but this is a topic that is worth considering in the future. Non-energy benefits provide a selling point for Passive House. Program educational materials can highlight the non-energy and energy benefits to help increase participation. Depending on the customer and their value judgements, these benefits may contribute to bridging the incremental cost gaps that this evaluation has indicated are currently present between Passive House and more traditional design and construction techniques. Future work on quantifying these benefits for the program could add another dimension to the impact that the program is having in the marketplace. Occupant surveys for initial projects going through the Passive House offering may provide the PAs additional insights on the potential non-energy benefits of passive buildings, especially if compared with standard RNC program participants and baseline occupant responses.

### 9.3.3 Development of Baseline Modeling Protocols

Currently, the Passive House tools need to have proposed models converted into baseline models manually. The development of baseline UDRH modeling protocols using Passive House tools would help streamline the conversion from proposed to baseline models. A set of protocols for both high-rise and low-rise projects would allow project teams to project savings levels during the design phase. In addition, developing guidelines on converting the proposed models into the baseline scenario would allow project teams to submit both the proposed and the baseline models, along with any supplemental calculation spreadsheets, should those be necessary. In this scenario, the program implementors would need to verify correct calculations were made and transcribed into Passive House tool rather than develop a new model. The baseline modeling protocols should be developed after the UDRH for both high-rise and low-rise are revisited for the Passive House offering to maximize efficiency.

# Appendix A Detailed Incremental Cost Data

Based on a comparison of low-income multifamily projects in Pennsylvania that either; (1) achieved Passive House certification, (2) attempted certification but were unsuccessful, or (3) did not attempt Passive House certification, we compared the application costs per square foot to assess the incremental costs associated with Passive House design (Table 38). The application costs are the estimated costs based on the proposed design, which are provided by project teams to the Pennsylvania Housing Finance Agency (PHFA). In 2015, costs were higher per square foot in Passive House projects, as certified Passive Houses cost roughly 3% more per square foot than those that did not attempt certification. In 2016, the difference increased slightly to 5% between certified Passive House projects and those that did not attempt certification. Some of these differences may be due to differences in location throughout the state. Looking only at Philadelphia county, costs tended to be more similar between the groups. Regardless of location, by 2018 the cost per square foot of a certified Passive House project was less than that of a project that did not attempt to build to passive standards. A comparison of per-unit costs was also conducted (Table 39).

While many of these projects have not yet been completed, the Team was able to compare the 2015 projects final construction costs to the application costs for certified Passive House projects and those that did not build to passive standards. The average price per square foot at construction completion was greater for both certified passive and non-passive projects; however, the percent change was slightly greater for passive projects (5%) compared to non-passive (3%). It is interesting to note that final construction costs reported to the PHFA were lower for the Passive House projects compared to the non-Passive House projects. Reasons for the lower costs were described to be increasing experience of practitioners and simple aesthetic designs. Detailing to Passive House standards becomes much more expensive the more geometric features a building has. It is recommended to view these data with caution due to small sample sizes, different market forces and labor rates in Pennsylvania, and limited details on specifications of the buildings.

**Table 38: Square Footage Cost Comparison for PH and Non-PH Low-Income Multifamily Projects in Pennsylvania**

| | | Statewide | | Philadelphia County | | Design to Construction Difference (Statewide) | | |
|---|---|---|---|---|---|---|---|---|
| Year | Type | Average Sq.Ft Application Cost | % Above not PH | Average Sq.Ft Cost (Application) | % Above not PH | Average Sq.Ft Application Cost | Average Sq.Ft Construction Cost | % Change |
| 2015 | PH Certified | $160.57 | 3.0% | $213.06 | 0.2% | $160.57 | $168.29 | 5% |
| | PH Not Certified | $178.20 | 12.5% | $212.57 | 0.0% | - | - | - |
| | Not PH | $155.81 | - | $212.61 | - | $169.91* | $175.09 | 3% |
| 2016 | PH Certified | $186.25 | 5.2% | $248.37 | 8.28% | - | - | - |
| | PH Not Certified | $185.94 | 5.0% | $227.60 | -0.1% | - | - | - |
| | Not PH | $176.63 | - | $227.81 | - | - | - | - |
| 2018 | PH Certified | $182.89 | -1.8% | $234.87 | -7.0% | - | - | - |
| | PH Not Certified | $184.87 | -0.7% | $236.37 | -6.4% | - | - | - |
| | Not PH | $186.22 | | $252.43 | | - | - | - |

*Only 13 of 23 projects with final construction costs were provided. The average application cost only reflects these 13 projects.

## Table 39: Per-unit Cost Comparison for PH and Non-PH Low-Income Multifamily Projects in Pennsylvania

| | | Statewide | | Philadelphia County | | Design to Construction Difference (Statewide) | | |
|---|---|---|---|---|---|---|---|---|
| Year | Type | Average Per-unit Application Cost | % Above not PH | Average Per-unit cost (App) | % Above not PH | Average Per-unit Application Cost | Average Per-unit construction cost | % Change |
| 2015 | PH Certified | $175,148 | -3.3% | $220,930 | 6.0% | $175,148 | $183,540 | 5% |
| | PH Not Certified | $184,850 | 2.2% | $208,952 | 0.8% | -- | -- | -- |
| | Not PH | $180,842 | -- | $207,239 | -- | $204,721* | $212,980 | 4% |
| 2016 | PH Certified | $196,091 | 1.0% | $234,683 | 3.2% | -- | -- | -- |
| | PH Not Certified | $193,220 | 0.5% | $223,916 | -1.4% | -- | -- | -- |
| | Not PH | $194,108 | -- | $227,085 | -- | -- | -- | -- |
| 2018 | PH Certified | $191,115 | -5.7% | $225,416 | -14.2% | -- | -- | -- |
| | PH Not Certified | $202,344 | -0.2% | $240,089 | -7.2% | -- | -- | -- |
| | Not PH | $201,934 | -- | $257,427 | -- | -- | -- | -- |

*Only 13 of 23 projects with final construction costs were provided. The average application cost only reflects these 13 projects.

# B

# Appendix B Additional Modeling Details

## B.1 MFHR Model Assumptions

Table 40 describes the default values in PHPP, WUFI, and for the MFHR UDRH baseline. The PHPP adjustment column provides detail on the adjustments that were made to the PHPP assumptions to match the proposed model in the WUFI tool. Some baseline adjustments were applied to the proposed models to maintain consistency, which are highlighted in green (and are reflected in all three software packages). The energy modeling team calculated baseline adjustment values in an Excel spreadsheet and updated both PHPP and WUFI models based on the results. The overall consensus was that adjustments to both the PHPP and WUFI model to reflect baseline consideration required minimal time once the baseline adjustment calculator was compiled. Additional refinement of the baseline calculator would increase the efficiency of adjustments required to meet baseline specifications. It should be noted that there are additional steps required to pull out the site energy consumption usage from PHPP and that the energy modeling team developed a way to do this during the modeling comparison process.

**Table 40: PHPP Default, WUFI Default, Proposed Model, and Baseline Model Input Values**

| Measure | Default PHPP Value | Default WUFI Value | Adjustments for Proposed | MFHR UDRH Baseline Value |
|---|---|---|---|---|
| ***General*** | | | | |
| Project square footage | TFA[55] | iCFA[56] | Gross Square Footage | Gross Square Footage |
| Occupancy | ~377 sf/person | Bedrooms + 1 (RESNET Standard) | UDRH protocol: 0.002630 people/Res Sq.t | UDRH protocol: 0.002630 people/Res Sq.t |
| Interior Temp - Winter | 68°F | 68°F | UDRH Protocol: 71.3 | UDRH Protocol: 71.3 |
| Interior Temp - Summer | 77°F | 77°F | UDRH Protocol: 78.5 | UDRH Protocol: 78.5 |
| Internal Heat Gains - Winter | Proposed: 1.43 Baseline: 1.96 (Btu/hr.Gross sf) [57] | Proposed: 1.32 | -- | -- |

[55] Treated Floor Area (TFA) is the floor area of the rooms within the building that are conditioned. It excludes areas of internal partitions, doors, stairs, and unconditioned space.
[56] Interior Conditioned Floor Area (iCFA) is any interior space at least 7' in height, drywall-to-drywall. This includes stairs, cabinets, interior walls, mechanical spaces, storage, etc. This excludes open-to-below areas and unconditioned spaces.
[57] Calculation based on a function of TFA, occupant density, and number of units for each project. Presented average values from the modeling activities for the proposed and the baseline case.

| | | | | |
|---|---|---|---|---|
| | | Baseline: 1.904 (Btu/hr.gross.sf) [58] | | |
| Internal Heat Gains - Summer | Proposed: 1.53 Baseline: 2.06 (Btu/hr.Gross sf) | Proposed: 1.32 Baseline: 1.904 (Btu/hr.gross.sf) | *(default)* | -- |
| Electricity Site to Source Factor | 2.6 | 2.8 (2018 PHIUS); 3.16 (2015 PHIUS) | N/A – Source Energy not analyzed | 3.16 (Site 1) 3.10 (all other models) |
| ***DHW*** | | | | |
| DHW demand | 6.6 gal/person.day (@ 140 °F) | 6.6 gal/person.day (@ 140 °F) | UDRH protocol (~14.3 gal/person/day @ 140 °F) | UDRH protocol (17.87 gal/person/day @ 140 °F) |
| Tap openings per person per day | 6 | 3 | 3 | -- |
| ***Appliances / Plugs*** | | | | |
| Common Area Lighting | Included in lighting – residential [59] | Project specific or Reference: Building America "B10 Analysis – New Construction 2011-01-26" | Used Project File (the PHIUS MF Calculator) provided values. [60] | UDRH Protocol: for calculating Common Area Lighting load |
| Common Area Plugs | Included in plug loads – residential [61] | See above. | UDRH Protocol: for calculating Common Area Equipment load | UDRH Protocol: for calculating Common Area Equipment load |
| Exterior Lighting | none | 80% RESNET Assumptions | N/A: Exterior lighting not included in Analysis | N/A: Exterior lighting not included in Analysis |
| Lighting - Residential | LEDs @ 7-11 Watts per person (input is in lumens per watt). Lights on | 80% RESNET Assumptions | Used Project File (the PHIUS MF | UDRH Protocol: for calculating lighting load in residential space |

[58] Calculated varies based on project file specific inputs. Presented average values from the modeling activities for the proposed and the baseline case.
[59] The Energy Modeling Team manually entered common area lighting (kWh/yr) from UDRH calculations in addition to residential lighting.
[60] Note that the ICF tool lighting input required the both of the Passive House tools to slightly adjust the proposed usage derived from the certification assumptions due to not having the detailed lighting schedule assumptions typically used to calculate the input used in the ICF Tool.
[61] The Energy Modeling Team manually entered common area plug loads (kWh/yr) from UDRH calculations in addition to residential lighting.

| | | | | |
|---|---|---|---|---|
| | for 2,900 hr/yr on avg. [62] | | Calculator) provided values. [63] | |
| Plug Loads - Residential | 80 Watts per person, on for 2,900 hr/yr on avg PLUS 50 kWh/yr per person for small appliances. | 80% RESNET Assumptions | UDRH Protocol: for calculating residential equipment load. [64,65] | UDRH Protocol: for calculating lighting load for residential equipment load |
| ***Envelope and HVAC equipment*** | | | | |
| Envelope (insulation and air-sealing | Based on Project Files[66] | Based on Project Files[67] | Matched proposed input for insulation and air infiltration (converted to CFM75/S.F. for ICF tool) | UDRH Protocol: Adjusted air-infiltration rate and insulation levels |
| Heating, cooling, and DHW | Based on Project Files | Based on Project Files | Matched Mechanical equipment type, fuel, efficiency | UDRH Protocol: Adjusted mechanical system efficiencies. |
| Mechanical Ventilation Rates | Based on Project Files and PHI Certification protocols for mechanical ventilation systems | Based on Project Files | Aligned model's ventilation systems and usage | UDRH Protocol: 7.5 CFM/person + 0.03 CFM/SF |

[62] Lights on for 8,760 hours/yr. Adjusted lumens per watt input to get total dwelling unit lighting energy to match PHIUS MF Calculator for the proposed model and UDRH lighting calculations for the baseline model.
[63] Note that the ICF tool lighting input required the both of the Passive House tools to slightly adjust the proposed usage derived from the certification assumptions due to not having the detailed lighting schedule assumptions typically used to calculate the input used in the ICF Tool.
[64] For PHPP plugs on for 1,400 hours/yr. Adjusted Watts per unit input to get total dwelling unit plug load energy to match UDRH input. Zeroed out small appliances kWh/yr.
[65] For WUFI used UDRH calculations and entered the consumption difference from appliance specific-loads into a miscellaneous electric load input to match the UDRH calculated value.
[66] Air infiltration testing procedures are located in the Multifamily Certification guidebook: http://www.phius.org/PHIUSPlus2015docs/PHIUS-Plus_Multifamily-Certification-Standard-v2.1.pdf
[67] PHI air infiltration testing procedures: https://passivehouse.com/03_certification/02_certification_buildings/06_process/06_process.html

## B.2 MFHR Total Consumption Results

The body of this report focuses on EUI comparisons across the models that were considered for our model comparison analysis. Table 41 presents the overall consumption estimates, by site, for each of the MFHR models included in our assessment. Note that the annual consumption values presented below exclude exterior lighting and on-site photovoltaic generation.

**Table 41: MFHR Model Summary – Total Consumption (kBtu/Year)**

| Site ID | Baseline Results Total Consumption (kBtu/yr/) | | |
|---|---|---|---|
| | ICF | WUFI | PHPP |
| Site 1 | 1,366,781 | 1,569,613 | 1,520,049 |
| Site 2 | 4,159,410 | 4,058,531 | 3,911,734 |
| Site 3 | 5,746,634 | 6,001,387 | 5,922,766 |
| Site 4 | 9,475,878 | 8,170,589 | 8,036,329 |
| Site 5 | 10,310,649 | 8,717,472 | 8,782,872 |
| **Average Consumption** | **6,211,870** | **5,703,518** | **5,634,750** |
| **Site ID** | **Proposed Results Total Consumption (kBtu/yr/)** | | |
| | **ICF** | **WUFI** | **PHPP** |
| Site 1 | 909,288 | 973,264 | 873,771 |
| Site 2 | 3,033,499 | 2,799,691 | 2,644,608 |
| Site 3 | 3,957,620 | 4,193,271 | 4,050,389 |
| Site 4 | 6,826,491 | 5,931,692 | 5,719,063 |
| Site 5 | 7,508,626 | 6,044,540 | 5,961,419 |
| **Average Consumption** | **4,447,105** | **3,988,492** | **3,849,850** |
| **Site ID** | **Savings Results Total Consumption (kBtu/yr/)** | | |
| | **ICF** | **WUFI** | **PHPP** |
| Site 1 | 457,493 | 596,349 | 646,278 |
| Site 2 | 1,125,911 | 1,258,840 | 1,267,126 |
| Site 3 | 1,789,014 | 1,808,116 | 1,872,377 |
| Site 4 | 2,649,387 | 2,238,897 | 2,317,266 |
| Site 5 | 2,802,023 | 2,672,931 | 2,821,453 |
| **Average Consumption** | **1,764,766** | **1,715,027** | **1,784,900** |
| **Site ID** | **% Savings Results Total Consumption (kBtu/yr/)** | | |
| | **ICF** | **WUFI** | **PHPP** |
| Site 1 | 33% | 38% | 43% |
| Site 2 | 27% | 31% | 32% |
| Site 3 | 31% | 30% | 32% |
| Site 4 | 28% | 27% | 29% |
| Site 5 | 27% | 31% | 32% |
| **Average Consumption** | **29%** | **31%** | **33%** |

## B.3 MFHR Average Modeled EUI and Savings by Fuel

The average MFHR EUI for the proposed models, baseline models, and savings by fuel type are presented for each of the three software in Figure 14. As noted in the main body of the report, Passive House projects emphasize electrification but there are still challenges when it comes to electrifying hot water in multifamily buildings. Results from the IDIs suggest that while electric water heating equipment is technically feasible in MFHR buildings, it is not yet cost-effective compared to gas-fueled systems.

Figure 14: Average Modeled EUI and Savings by Fuel Type (kBtu/ft2/yr)


## B.4 MFLR Total Consumption Results

The body of this report focuses on EUI comparisons across the models that were considered for our model comparison analysis. Table 42 presents the overall consumption estimates, by site, for each of the MFLR models included in our assessment. Note that the annual consumption values presented below exclude on-site photovoltaic generation. The Team did not conduct a fuel specific break-out for the MFLR models.

**Table 42: MFLR Model Summary – Total Consumption (kBtu/Year)**

| Site ID | Baseline Results Total Consumption (kBtu/yr) | |
|---|---|---|
| | WUFI | PHPP |
| Site 1 | 95,185 | 102,701 |
| Site 2 | 1,161,768 | 1,239,440 |
| Site 3 | 1,346,262 | 1,307,178 |
| Site 4 | 2,304,195 | 2,312,678 |
| **Average Consumption** | **1,226,852** | **1,240,499** |
| **Site ID** | **Proposed Results Total Consumption (kBtu/yr)** | |
| | **WUFI** | **PHPP** |
| Site 1 | 60,431 | 61,367 |
| Site 2 | 783,542 | 813,746 |
| Site 3 | 847,044 | 879,077 |
| Site 4 | 1,706,905 | 1,726,371 |
| **Average Consumption** | **849,481** | **870,140** |
| **Site ID** | **Savings Results Total Consumption (kBtu/yr)** | |
| | **WUFI** | **PHPP** |
| Site 1 | 34,753 | 41,334 |
| Site 2 | 378,226 | 425,694 |
| Site 3 | 499,218 | 428,101 |
| Site 4 | 597,290 | 586,307 |
| **Average Consumption** | **377,372** | **370,359** |
| **Site ID** | **% Savings Results Total Consumption (kBtu/yr)** | |
| | **WUFI** | **PHPP** |
| Site 1 | 37% | 40% |
| Site 2 | 33% | 34% |
| Site 3 | 37% | 33% |
| Site 4 | 26% | 25% |
| **Average Consumption** | **33%** | **33%** |

## B.5 Single-Family Total Consumption Results

The body of this report focuses on EUI comparisons across the models that were considered for our model comparison analysis. Table 43 presents the overall consumption estimates, by site, for each of the single-family models included in our assessment. Note that the annual consumption values presented below exclude on-site photovoltaic generation. The Team did not conduct a fuel specific break-out for the single-family models due to electricity being the primary fuel used for all end-uses.[68]

[68] Two projects had wood stoves present for supplemental heating.

**Table 43: Single-Family Model Summary - Total Consumption (kBtu/Year)**

| Site ID | Baseline Results Total Consumption (kBtu/yr) | | | |
|---|---|---|---|---|
| | WUFI | PHPP | Ekotrope | REM/Rate |
| Site 1 | 68,988 | 63,866 | 58,590 | 52,345 |
| Site 2 | 101,421 | 96,540 | 76,320 | 71,956 |
| Site 3 | 98,535 | 106,618 | 86,130 | 123,923 |
| Site 4 | 155,590 | 156,445 | 119,260 | 108,178 |
| Site 5 | 178,241 | 204,694 | 181,110 | 163,477 |
| **Average Consumption** | **120,555** | **125,633** | **104,282** | **103,976** |
| **Site ID** | **Proposed Results Total Consumption (kBtu/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 27,769 | 27,741 | 28,350 | 26,325 |
| Site 2 | 48,496 | 44,639 | 36,650 | 41,264 |
| Site 3 | 49,443 | 46,771 | 43,050 | 62,727 |
| Site 4 | 58,285 | 59,261 | 47,050 | 58,411 |
| Site 5 | 72,182 | 71,092 | 64,550 | 76,185 |
| **Average Consumption** | **51,235** | **49,901** | **43,930** | **52,982** |
| **Site ID** | **Savings Results Total Consumption (kBtu/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 41,220 | 36,125 | 30,240 | 26,021 |
| Site 2 | 52,926 | 51,901 | 39,670 | 30,692 |
| Site 3 | 49,092 | 59,847 | 43,080 | 61,195 |
| Site 4 | 97,305 | 97,184 | 72,210 | 49,767 |
| Site 5 | 106,059 | 133,602 | 116,560 | 87,292 |
| **Average Consumption** | **69,320** | **75,732** | **60,352** | **50,993** |
| **Site ID** | **% Savings Results Total Consumption (kBtu/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 60% | 57% | 52% | 50% |
| Site 2 | 52% | 54% | 52% | 43% |
| Site 3 | 50% | 56% | 50% | 49% |
| Site 4 | 63% | 62% | 61% | 46% |
| Site 5 | 60% | 65% | 64% | 53% |
| **Average Consumption** | **57%** | **59%** | **56%** | **48%** |

# Appendix C Additional MFLR Modeling Results

The Team conducted a comparison of modeled outputs between WUFI Passive, PHPP, Ekotrope, and REM/Rate to assist in the determination of the best way to claim savings for MFLR projects in the new Passive House offering. This analysis includes the two MFLR sampled projects that were modeled in all four modeling tools.

Note that interpreting the accuracy of the modeled results is limited due to a lack of monitored billing data for Passive House projects. Determining the accuracy of the models requires comparisons to actual performance that were not available at the time of this study. Monitoring actual performance of future participants going through the program will provide insights on this question, as well as communicable information to the market, as described in the findings from the IDIs with various market actors.

It should be noted that both Ekotrope and REM/Rate modeling tools are used at the unit-level, while WUFI and PHPP are whole-building models. This means that usage associated with spaces such as hallways, mechanical rooms, entry ways, and amenities are not directly captured in Ekotrope or REM/Rate. Due to these differences, it may not be useful to make a direct comparison between the tools; however, it does provide insights on what the pros and cons are between using the traditional program modeling tools and using the passive house tools for MFLR Passive House projects. Table 44 presents the average EUI based on the iCFA of the two projects, Table 45 presents the annual consumption for the two projects, and Table 46 presents the average consumption per unit for the two projects.

**Table 44: MFLR Summary Modeling EUI Results (kBtu/iCFA/Year) – All Models**

| Site ID | Baseline Results EUI (kBtu/iCFA/yr) | | | |
|---|---|---|---|---|
| | WUFI | PHPP | Ekotrope | REM/Rate |
| Site 1 | 40.4 | 43.6 | 28.7 | 28.3 |
| Site 2 | 42.0 | 44.8 | 34.4 | 33.7 |
| **Average EUI** | **41.2** | **44.2** | **31.6** | **31.0** |
| **Site ID** | **Proposed Results EUI (kBtu/iCFA/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 25.7 | 26.1 | 20.8 | 22.6 |
| Site 2 | 28.3 | 29.4 | 24.4 | 25.9 |
| **Average EUI** | **27.0** | **27.7** | **22.6** | **24.3** |
| **Site ID** | **Savings Results EUI (kBtu/iCFA/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 14.8 | 17.6 | 7.9 | 5.7 |
| Site 2 | 13.7 | 15.4 | 10.0 | 7.8 |
| **Average EUI** | **14.2** | **16.5** | **8.9** | **6.8** |
| **Site ID** | **% Savings Results EUI (kBtu/iCFA/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 37% | 40% | 27% | 20% |
| Site 2 | 33% | 34% | 29% | 23% |
| **Average EUI** | **35%** | **37%** | **28%** | **22%** |

### Table 45: MFLR Model Summary - Total Consumption (kBtu/Year) – All Models

| Site ID | Baseline Results Total Consumption (kBtu/yr) | | | |
|---|---|---|---|---|
| | WUFI | PHPP | Ekotrope | REM/Rate |
| Site 1 | 95,185 | 102,701 | 67,540 | 66,705 |
| Site 2 | 1,161,768 | 1,239,440 | 952,780 | 934,125 |
| **Average Consumption** | **628,476** | **671,071** | **510,160** | **500,415** |
| **Site ID** | **Proposed Results Total Consumption (kBtu/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 60,431 | 61,367 | 49,060 | 53,202 |
| Site 2 | 783,542 | 813,746 | 676,470 | 718,134 |
| **Average Consumption** | **421,987** | **437,557** | **362,765** | **385,668** |
| **Site ID** | **Savings Results Total Consumption (kBtu/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 34,753 | 41,334 | 18,480 | 13,503 |
| Site 2 | 378,226 | 425,694 | 276,310 | 215,991 |
| **Average Consumption** | **206,490** | **233,514** | **147,395** | **114,747** |
| **Site ID** | **% Savings Results Total Consumption (kBtu/yr)** | | | |
| | **WUFI** | **PHPP** | **Ekotrope** | **REM/Rate** |
| Site 1 | 37% | 40% | 27% | 20% |
| Site 2 | 33% | 34% | 29% | 23% |
| **Average Consumption** | **35%** | **37%** | **28%** | **22%** |

### Table 46: MFLR – Total Consumption (kBtu/yr) Per Unit – All Models

| Site ID | Total Consumption Per Unit (kBtu/yr/unit) | | | |
|---|---|---|---|---|
| | WUFI | PHPP | REM/Rate | Ekotrope |
| Site 1 - Baseline | 31,728 | 34,234 | 22,235 | 22,513 |
| Site 1 - Proposed | 20,144 | 20,456 | 17,734 | 16,353 |
| **Site 1 - Savings per Unit** | **11,584** | **13,778** | **4,501** | **6,160** |
| **Site ID** | **Total Consumption Per Unit (kBtu/yr/unit)** | | | |
| | **WUFI** | **PHPP** | **REM/Rate** | **Ekotrope** |
| Site 2 - Baseline | 38,726 | 41,315 | 31,138 | 31,759 |
| Site 2 - Proposed | 26,118 | 27,125 | 23,938 | 22,549 |
| **Site 2 - Savings per Unit** | **12,608** | **14,190** | **7,200** | **9,210** |

# Appendix D Massachusetts UDRH Inputs

## D.1 MFHR UDRH Inputs

The current baseline assumptions for the Massachusetts MFHR program are provided below to provide additional context on how the baseline models were developed.

**Software Versions**

OpenStudio: 2.1.0

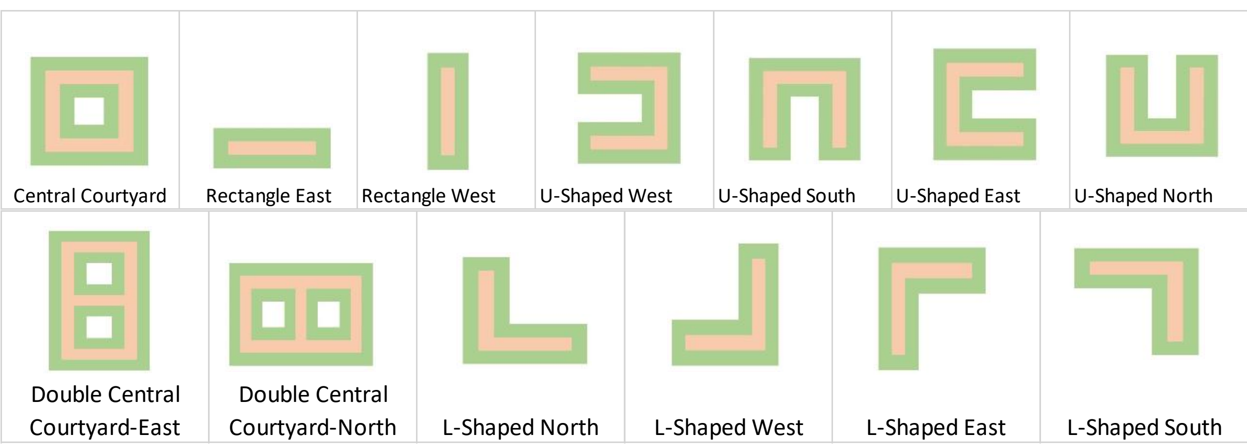
EnergyPlus: 8.7.0

**Geometry**

The tool uses the following standard library of seed geometries to generate models programmatically:

- Rectangle
- L-Shaped
- U-Shaped
- H-Shaped
- E-Shaped
- Central Courtyard
- Double Central Courtyards

**Figure 15: Seed Geometries**




Note that all geometries other than rectangular assume a 15 meter width across the geometry, which accounts for an apartment unit on each side of a corridor. The seed geometry shape is used as a starting point for the building geometry, which is adjusted based on several user inputs including:

- Number of residential floors

- Total residential floor area
- Total common floor area
- Average floor plate corridor area percentage
- Floor to floor height
- Breakout of first floor common area by space type
- Building shape
- Building orientation
- Building aspect ratio

The tool calculates the total floor area as the sum of the residential floor area and the common floor area, then determines the floor plate area (assumed to be the same on every floor) by dividing the total floor area by the number of residential floors. The tool then uses the average corridor area percentage to determine the floor area on each of the upper floors that are allocated to the building core (includes corridors and stairs). The space is allocated such that the depth from the building exterior to the core space is the same on all facades. The remainder of the common floor area is allocated as a standard common area on the first floor. The remainder of the first floor is assumed to be residential floor area.

The building floor plate is automatically sized based on the user-input building shape, floor areas, and aspect ratio. The spaces and thermal zones on each floor are automatically generated in a perimeter/core zone configuration for each floor type. The building model is then rotated a set number of degrees from north based on the user-input orientation, which can be entered at 45-degree increments. The model creates a distinct first and top floor with a multiplier applied to a representative middle floor.

The first floor common area is created by applying multipliers to standard space types with associated occupancy, plug, and lighting loads. The multipliers applied are based on the percentage breakouts of the space types on the first floor from the user (Lobby, Office, Fitness, Recreation, Storage, and Corridor).

**Spaces and Thermal Zones**

The final model has three distinct space types representing the different usage areas within the building. The residential space type is used in all apartment units. On upper floors, all residential units with a given orientation on a specific floor are grouped into a single space and therefore a single thermal zone. The Common space type is used for all core areas on the upper floors, which is assumed to include corridor and stair areas. Finally, the First Floor Common space type is used for the common area on the first floor, which represents all common areas traditionally found in a multifamily building, such as office, laundry, fitness, multi-purpose rooms, etc. Each space is also assigned to its own thermal zone with its own thermostat.

**Residential Space Type**

The Residential space type has the following baseline loads with an associated fractional schedule that determines what portion of the load to apply throughout the day:

- Occupancy Load: 0.002630 people/SF
- Lighting Load: 0.75 W/SF
- Equipment Load: Calculated based on appliances (see below)

- Ventilation Requirement: 7.5 CFM/person + 0.03 CFM/SF
- Infiltration: 0.045 CFM/exterior SF at natural conditions (equivalent to 0.40 CFM/SF at 75 Pa)

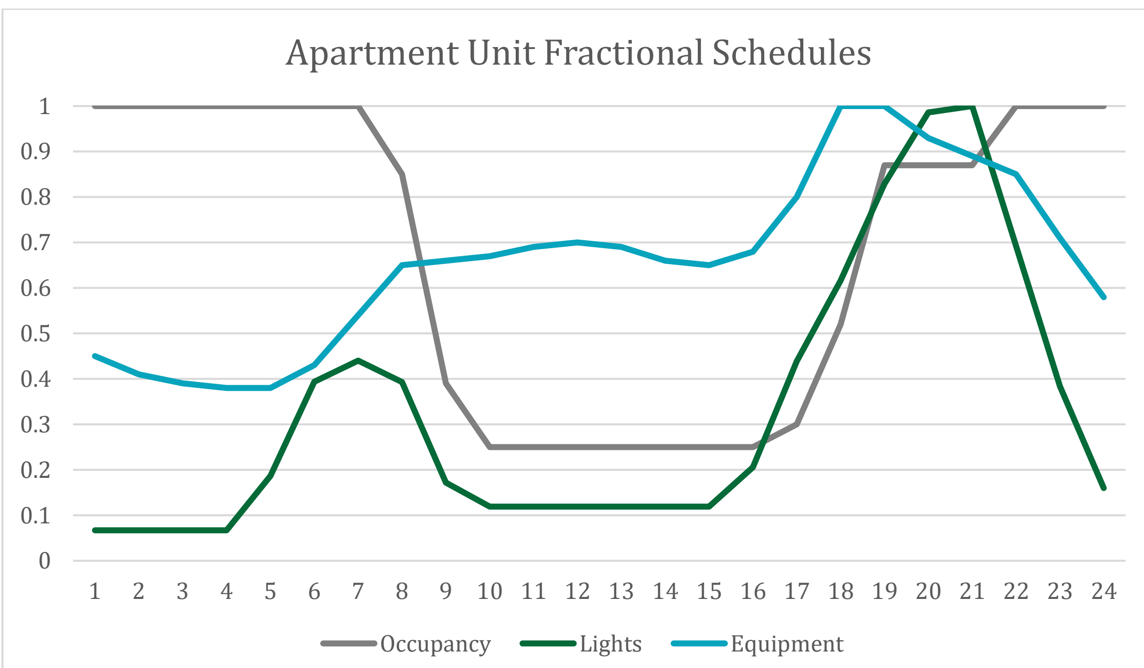
The loads in the residential units follow a fractional schedule as outlined below. This schedule is constant for every day of the year. Note that ventilation is not listed because it has a constant 1.0 fractional schedule; however, the ventilation requirement varies with the current occupancy in the space. Infiltration also has a constant 1.0 fractional schedule.

The equipment load for each residential unit is calculated as the sum of the individual loads for each appliance in the unit, calculated according to the below equation, and an assumed plug load of 1.05 kWh/year-SF.

$$Appliance\ Load\ \left(\frac{W}{SF}\right) = \frac{NumUnits \times Consumption\ \left[\frac{kWh}{year}\right] * 1000}{ResArea\ \times 365 \times 15.79[EFLH]}$$

Consumption values for various appliances, from ENERGY STAR MFHR calculator:

- Refrigerator: 423 kWh/year
- Stove (assumed electric): 604 kWh/year
- Dishwasher: 164 kWh/year
- Washer: 57 kWh/year
- Dryer: 418 + (139 x *Average Bedrooms*) kWh/year



### Common Space Type

The Common space type has the following baseline loads with an associated fractional schedule that determines what portion of the load to apply:

- Occupancy Load: 0.0 people/SF
- Lighting Load: 0.51 W/SF (PY2016) or 0.59 W/SF (PY2017 – PY2018)
- Equipment Load: 0.2 W/SF
- Ventilation Requirement: 7.5 CFM/person + 0.03 CFM/SF

The loads in the Common space (upper floor corridors) all follow a 1.0 fractional schedule and are therefore always assumed to be at their full load value.

### First Floor Common Space Type

The First Floor Common space type has the following baseline loads that are calculated based on the mix of space types within the first floor common area:

- Occupancy Load
    - Office: 0.00714 people/SF
    - Fitness: 0.03 people/SF
    - Recreation: 0.00427 people/SF
    - Lobby: 0.00427 people/SF
- Lighting Load
    - Office: 0.8 W/SF (PY2016) or 0.99 W/SF (PY2017 – PY2018)
    - Storage: 0.58 W/SF (PY2016) or 0.57 W/SF (PY2017 – PY2018)
    - Corridor: 0.51 W/SF (PY2016) or 0.59 W/SF (PY2017 – PY2018)
    - Fitness: 0.66 W/SF (PY2016) or 0.65 W/SF (PY2017 – PY2018)
    - Recreation: 0.58 W/SF (PY2016) or 0.66 W/SF (PY2017 – PY2018)
    - Lobby: 0.8 W/SF (PY2016) or 0.81 W/SF (PY2017 – PY2018)
- Equipment Load
    - Office: 0.61 W/SF
    - Fitness: 0.55 W/SF
    - Recreation: 0.67 W/SF
    - Lobby: 0.760476 W/SF
- Ventilation Requirement: 7.5 CFM/person + 0.03 CFM/SF
- Infiltration: 0.045 CFM/exterior SF

The loads in the First Common space all follow fractional schedules that vary by underlying space type.

### Wall Constructions

The tool allows selection of the following default wall constructions. They are each listed with the material layers that make up their construction. All are based on ASHRAE 90.1-**2013** standard constructions. These constructions are applied to the entire building façade. The values below account for thermal bridging when computing cavity R-values.

- Wood Stud (R-19.19)
    - Wood Siding – R-0.52

  - Insulation – R-18.22
  - ½ in. Gypsum – R-0.45
- Metal Stud (R-14.55)
  - Metal Siding – R-0
  - Insulation – R-14.10
  - ½ in. Gypsum – R-0.45
- Mass (R-14.84)
  - 1 in. Stucco – R-0.21
  - 8 in. Concrete – R-0.88
  - Insulation – R-13.3
  - ½ in. Gypsum – R-0.45
- Steel Frame (R-15.07)
  - Wood Siding – R-0.52
  - Insulation – R-14.10
  - ½ in. Gypsum – R-0.45

**Roof Constructions**

The tool allows selection of the following default roof constructions. They are each listed with the material layers that make up their construction. All are based on ASHRAE 90.1-**2013** standard constructions. These constructions are applied to the entire building roof.

- Flat Roof Insulation Above Deck (R-25.34 or 30.34)
  - Roof Membrane – R-0.34
  - Insulation – R-25 (PY2016) or R-30 (PY2017 – PY2018)
  - Metal Decking – R-0
- Flat Roof Insulation Below Deck (R-26.31 or 31.31)
  - Roof Membrane – R-0.34
  - Metal Decking – R-0
  - Air Gap – R-0.97
  - Ceiling Insulation – R-25 (PY2016) or R-30 (PY2017 – PY2018)
- Pitched Roof with Encapsulated Attic (R-49.34)
  - Roof Membrane – R-0.34
  - Metal Decking – R-0
  - Insulation – R-49
- Pitched Roof without Encapsulated Attic (R-49.9)
  - ½ in. Gypsum – R-0.45
  - Insulation – R-49
  - ½ in. Gypsum – R-0.45

**Fenestration**

The user selects a window-to-wall ratio for each facade. The windows are modeled as strips across each floor of the façade at a height of 2.5 feet above the floor. The user selects the window type, which impacts the baseline window characteristics as follows:

- Nonmetal Framing
  - U-Value: 0.38 (PY2016) or 0.38 (PY2017 – PY2018)

    - SHGC: 0.40
    - Visual Transmittance: 0.31
- Metal Framing - Fixed
    - U-Value: 0.38 (PY2016) or 0.38 (PY2017 – PY2018)
    - SHGC: 0.40
    - Visual Transmittance: 0.31
- Metal Framing - Operable
    - U-Value: 0.45 (PY2016) or 0.45 (PY2017 – PY2018)
    - SHGC: 0.40
    - Visual Transmittance: 0.31

**HVAC System**

The user selects an HVAC system for the residential units, an HVAC system for the first-floor common area, and a heating and cooling method for the corridor ventilation air. The corridors are assumed to be heated and cooled by a dedicated outdoor air system. For each of the HVAC systems an individual piece of zone equipment is added to each thermal zone. The zone equipment is responsible for providing outdoor air to the residential units and first-floor common area. The following thermostat set points are used for each space type:

- Residential: 78°F cooling; 68°F heating
- First Floor Common: 85°F cooling at night, 75°F during the day; 64°F heating at night, 71°F heating during the day
- Corridors: 80°F cooling; 65°F heating

The possible HVAC system types that can be selected for the residential units and the first-floor common area, along with their baseline efficiencies are listed below:

- Furnace with Central A/C – modeled as Packaged Terminal Air Conditioner with the following components:
    - 0.82 TE Gas-Fired heating coil
    - 3.28 COP cooling coil (PY2016 - PY2018) (equivalent to 13 SEER)
- Hydronic Heating with Central A/C - modeled as Packaged Terminal Air Conditioner with the following components:
    - Water heating coil connected to hot water loop to simulate individual hot water heaters providing heating
    - 3.28 COP cooling coil (PY2016 - PY2018) (equivalent to 13 SEER)
- Ductless Mini-Split Heat Pumps – modeled as Packaged Terminal Heat Pump with the following components:
    - 2.41 COP cooling coil (PY2016 - PY2018) (equivalent to 8.2 HSPF)
    - 3.53 COP cooling coil (PY2016 - PY2018) (equivalent to 14.5 SEER/12 EER)
- Water Source Heat Pumps – modeled as Water-to-Air Heat Pump units in individual thermal zones connected to WSHP circulating loop
    - 4.2 COP heating coil (PY2016) or 4.3 COP heating coil (PY2017 – PY2018)
    - 3.517 COP cooling coil (PY2016) (equivalent to 12.0 EER) or 3.81 COP cooling coil (PY2017 – PY2018) (equivalent to 13.0 EER)

- Ground Source Heat Pumps – modeled as Water-to-Air Heat Pump units in individual thermal zones connected to GSHP circulating loop
  - 3.1 COP heating coil (PY2016) or 3.2 COP heating coil (PY2017 – PY2018)
  - 3.927 COP cooling coil (PY2016) (equivalent to 13.4 EER) or 4.132 COP cooling coil (PY2017 – PY2018) (equivalent to 14.1 EER)
- VRF - Air-Cooled – modeled as VRF system in OS with heat recovery turned on. One outdoor unit serves the common area, and another serves all apartment units.
  - 3.2 COP (@ 47°F) heating coil (PY2016 - PY2018)
  - 3.107 COP cooling coil (PY2016 - PY2018) (equivalent to 10.6 EER)
- VRF - Air-Cooled with Heat Recovery – modeled as VRF system in OS with heat recovery turned on. One outdoor unit serves the common area, and another serves all apartment units.
  - 3.2 COP (@ 47°F) heating coil (PY2016 - PY2018)
  - 3.048 COP cooling coil (PY2016 - PY2018) (equivalent to 10.4 EER)
- Hydronic Baseboard with Through-Wall A/C – modeled as Packaged Terminal Air Conditioner with no heating and a separate baseboard.
  - 3.095 COP cooling coil (PY2016 - PY2018) (equivalent to 12.0 SEER)

The conversions used to convert to COP are as follows:

$$COP = EER/3.412$$

$$EER = (1.12 \times SEER) - (0.02 \times SEER^2)$$

$$COP = HSPF \times 0.294$$

### DHW System

The water use in residential units is based on ENERGY STAR MFHR Simulation Guidelines Hot Water Demand for medium use case (25 gal/person/day) according to the following equation:

$$\text{DHW Demand (gallons)} = Occupants \times 25 \frac{\frac{gal}{person}}{day} \times (0.36 + \left(0.54 \times \frac{Flowrate_{shower}}{2.5}\right) + (0.1 \times \frac{Flowrate_{kitchen} + Flowrate_{lav}}{2 \times 2.5}))$$

DHW Demand per person / occupancy assumptions:

- Occupancy is assumed to be one more person than number of bedrooms
- Baseline plumbing fixture flow rates:
  - Showerheads: 2.2 GPM (PY2016 - PY2018)
  - Kitchen Faucets: 2.2 GPM (PY2016 - PY2018)
  - Lavatory Faucets: 2.0 GPM (PY2016 - PY2018)
- Schedule assumes 6.5 Equivalent Full Load Hours (EFLH)

The possible DHW system types that can be selected for the residential units are as follows:

- In-Unit NG Storage Water Heater:
  - Efficiency: 0.5275 EF (PY2016) or 0.7427 EF (PY2017 – PY2018)
- In-Unit NG On-Demand Water Heater
  - Efficiency: 0.6181 EF (PY2016) or 0.8181 EF (PY2017 – PY2018)
- Whole Building Central Boiler
  - Efficiency: 0.5275 EF (PY2016) or 0.7427 EF (PY2017 – PY2018)
- In-Unit Electric Storage Water Heater
  - Efficiency: 0.871 EF (PY2016 - PY2018)
- In-Unit Electric On-Demand Water Heater
  - Efficiency: 0.9687 EF (PY2016) or 0.9287 EF (PY2017 – PY2018)
- In-Unit Electric Heat Pump Water Heater
  - Efficiency: 0.831 EF (PY2016) or 0.9375 EF (PY2017 – PY2018)

## D.2 Low-Rise UDRH

The attached spreadsheet details the current low-rise UDRH inputs.

2018 UDRH specs.xlsx