MA19R05: Residential New Construction Passive House Assessment – Interim Report

Final Interim Report

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SUBMITTED TO:
The Massachusetts Electric and Gas Program Administrators

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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 interim report presents the results of a detailed modeling comparison for multifamily projects built to Passive House design principles. In addition, this report presents the results of a series of in-depth interviews (IDIs) with various market actors to understand the opportunities, barriers, incremental costs, and incentive issues associated with a new Passive House offering.

This preliminary report focuses on multifamily buildings four stories or greater in size as this will be the initial target market for the new program offering. Below we present the key findings of our research broken into the following categories:

- Model comparison
- Incentive suggestions and structure
- Incremental costs
- 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 Team conducted a detailed comparison of three energy modeling tools that are being considered to calculate savings for the new offering. The team conducted a detailed model comparison for five Multifamily High-Rise (MFHR) projects that incorporate Passive House design principles. The tools included in our assessment are listed in Table 1. The project-specific details are provided in Table 9 and Table 10 in the main body of the report.

Table 1: Modeling Tools

Modeling Tool	Details
ICF's Multifamily High-Rise Modeling 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.

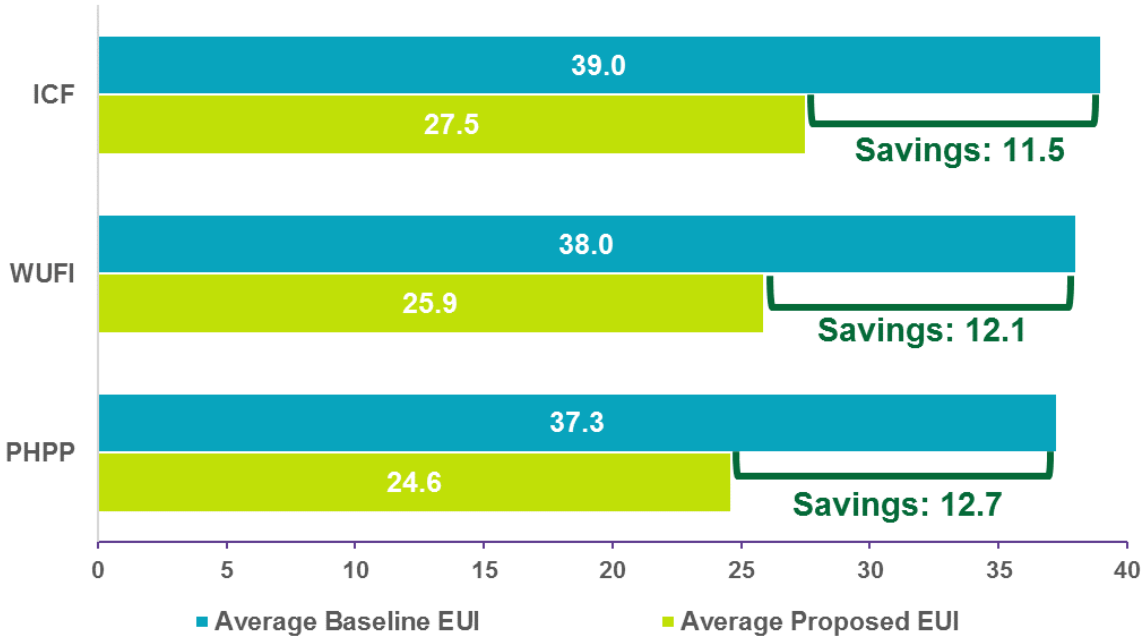
The primary objective of the model comparison was to determine the extent to which these tools can handle the inputs and detail associated with Passive House new construction and the extent to which they can be used to model the baseline conditions that will be used as the foundation to calculate program 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.

Energy Use Intensity (EUI) Savings

The three models used for this analysis (WUFI Passive, PHPP, and the ICF multifamily tool) were aligned closely in projecting average savings for the five Passive House projects used in this comparison (Figure 1). Model-estimated savings ranged from 11.5 to 12.7 kBtu/ft^2/yr – these represent savings between 29% and 33% over the baseline consumption EUIs. The three modeling tools were also closely aligned in their baseline and proposed EUIs, with the ICF tool predicting the highest baseline and proposed EUIs and the lowest average EUI savings. Note that the model assumptions used for this analysis were based on proposed model conditions and UDRH protocols. These differ from the default assumptions associated with PHIUS and PHI certifications. Had the certification default assumptions been used the model consumption estimates would be different than those presented here.[1]

Figure 1: Average EUI Comparisons Across Models (kBtu/ft^2/yr)

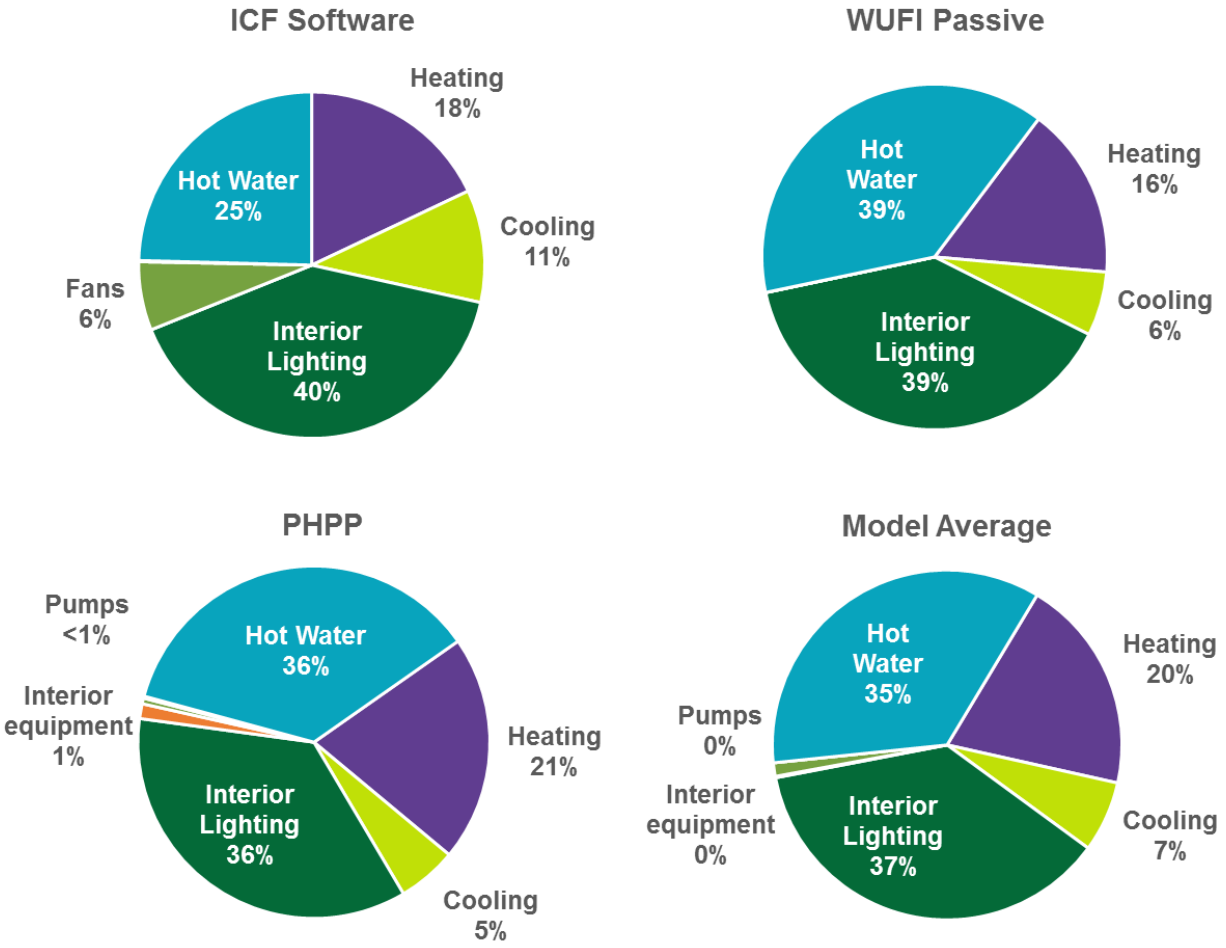


The energy models all suggested that interior lighting and domestic hot water were the main sources of energy savings over the baseline, accounting for 37% and 35% of EUI savings respectively, when averaged across the models (Figure 2). WUFI and PHPP attributed a much greater share of savings to domestic hot water than the ICF tool—39% for WUFI and 36% for PHPP, compared to 25% for ICF—while the ICF tool estimated slightly higher cooling and fan savings compared to the Passive House tools. Averaged across models, heating (20%) and

[1] The team conducted a literature review which found evidence that default assumptions applied in PHPP may lead to underestimating actual consumption especially for plug-load, lighting, and hot water end-uses. Different assumptions are used in WUFI for plug-loads and lighting, while hot water use is the same between the two models.

cooling (7%) make up a middle tier of savings sources after lighting and domestic hot water. WUFI and PHPP estimated that fan energy use would increase by 1-2% over the baseline while the ICF tool assumed fan energy *savings* of 6%.

Figure 2: Proposed Savings Over Baseline by End-Use



INCENTIVE SUGGESTIONS AND STRUCTURE

The Team conducted 21 IDIs with various market actors that have been or are currently engaged in Passive House projects. The team selected individuals that had experience with Passive House as their perspective provided deeper Passive House insights and context for the program to draw upon. One of the objectives of the IDIs was to understand the incentives that may be required to promote Passive House design strategies into new construction projects. In addition, market actors were asked about the design and distribution of potential program incentives. In particular, market actors were asked when in the construction and/or Passive House certification process incentives would be most useful and who the incentive should be distributed to.

Table 2 presents a summary of market actor responses when asked about incentive amounts and timing (additional details can be found in Table 22). As shown, most market actors suggested an incentive amount falling somewhere between $4,000 and $10,000 per unit. Only two of five

developers (both working exclusively with market-rate projects) suggested an incentive level of $10,000 per unit. The rest of the market actors, including multiple affordable housing developers, suggested incentives of $4,000 or $5,000 per unit.

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.

Most market actors suggested distributing incentives at various stages. The most common suggestion 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 2: Incentive Structure Summary

Incentive Recipient	Incentive Timing	Incentive Amount
Primary response: Owner/Developer	**Primary response:** Initial modeling, pre-certification, 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:** $10,000 or more per unit

INCREMENTAL COSTS

Another component of the IDIs was focused on the incremental costs associated with building Passive House certified projects. Incremental costs are difficult to assess as market actors do not always have the same comparison point when considering such costs. For example, some consider the additional costs compared to a code-built project, while others consider the additional costs compared to their standard new construction projects. 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 3 presents a summary of the incremental costs associated with Passive House construction according to the market actors that were interviewed as part of this evaluation. As shown, incremental cost estimates for both soft and hard costs ranged from 2% to 10%. The most commonly cited incremental cost was estimated to be around 5% compared to typical new construction practices. Not surprisingly, builders indicated that the incremental costs associated with Passive House design are dependent on current building practices. If a builder or developer is already designing and building to a high-performance standard, then the incremental costs required to pursue Passive House certification will be lower. 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 3: Passive House Incremental Cost Estimates

Market Actor Group	Sample Size	Incremental Cost - Low Range	Incremental Cost – High Range
Architect/engineer	1	2%	2%
Builders	5	5%	10%
Industry Experts	5	5%	10%
Developers	5	3%	10%

There was agreement across industry experts, architects, and engineers 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 this.

Overall, respondents were unable to provide specific hard costs associated with measure-level upgrades. However, a couple of developers provided details on the actual costs for certification and the associated soft costs. Note that actual soft costs will range based on project size and specifications, consultants performing the service, and level of experience. The actual project estimates are provided in Table 4.

Table 4: 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) ➢ Between $10,000 - $20,000 for a 98-unit project and 108-unit project ($102.04-$204.08/unit) ➢ 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) ➢ $22,000 for a 135-unit project ($162.96/unit) ➢ $17,000 for a 98-unit project ($173.47/unit)

PRELIMINARY POTENTIAL SAVINGS

The Team compared a sample of 62 2018 MFHR participant projects to the source energy requirements for four separate Passive House certification options to estimate the potential

savings associated with Passive House projects. Specifically, the Team compared the proposed and baseline energy models, built in the ICF tool, to the source energy requirements in Table 5.[2]

Table 5: Passive House Source Requirements

Certification Option	Source Energy Requirements
PHIUS+ 2018	➢ Residential: 3,840 kWh/person/yr ➢ Commercial: 34.8 kBtu/ft2/yr ➢ Accounts for both on-site and off-site energy generation
PHIUS+ Core	➢ Residential: 5,500 kWh/person/yr ➢ Commercial: 38.0 kBtu/ft2/yr ➢ Accounts for only on-site energy generation
PHIUS+ 2015	➢ Residential: 6,200 kWh/person/yr ➢ Commercial: 38.0 kBtu/ft2/yr ➢ Account for only on-site energy generation
PHI	➢ All spaces: 38.0 kBtu/ft2/yr ➢ Accounts of on-site generation and new off-site generation

The Team converted these source requirements to a site consumption estimate using ratios from the MFHR models. More details on this methodology can be found in Section 3.

Table 6 presents a summary of the preliminary potential savings assessment. Specifically, the results presented here compare the average baseline and proposed model results from the 62 2018 MFHR program participant projects to the Passive House source energy criteria detailed above. These numbers are not meant to be exact, instead they are meant to provide a reference point that the PAs can use to estimate potential program savings when designing their initial program offering. As shown, the estimated site energy EUI savings range from 12.1 to 20.0 kBtu/ft^2/yr, depending on the certification being used, when compared to the baseline model results for these projects. These EUI savings represent savings between 33% and 55% over the modeled baseline consumption.

The PHIUS+ 2015 comparison is consistent with the findings from our model comparison. This is significant as the model comparison looked at projects that were primarily certified or pre-certified under PHIUS+ 2015. As a result, while acknowledging this is a high-level assessment, the Team believes the PAs can use these numbers as a starting point to estimate potential program savings for future participant projects. Note, any future program participant projects would be pursing PHIUS+ 2018, PHIUS+ Core, or PHI certification.

[2] 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.

Table 6: Preliminary Potential Savings Using Passive House Source Criteria

Certification Requirement	Savings Over Baseline	Savings Over Proposed
Modeled Site EUI in ICF Tool (kBtu/ft2/yr)	35.9	29.2
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%

RECOMMENDATIONS AND CONSIDERATIONS

Based on the findings presented above, the Team makes the following recommendations and considerations regarding the new program offering. Supplemental program considerations can be found throughout the body of the report.

Recommendation: The PAs should allow for the use of both the WUFI Passive and PHPP models to calculate savings for their new offering. 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. The model comparison shows that, with a few adjustments, the Passive House tools generate comparable consumption estimates (compared to each other) when the same modeling protocols are followed (see Appendix B for certification default values and 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.[3] Lastly, the Team believes that using these 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

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

program-specific modeling protocols and creating a comparative baseline model in the Passive House tools is likely to require less labor than creating brand new models in the ICF tool.

Recommendation: 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 developers into the program.

Consideration: The PAs should consider revisiting the current MFHR UDRH assumptions to ensure they are capturing all the savings opportunities associated with Passive House projects. The current version of the MFHR UDRH was developed to calculate savings associated with the MFHR New Construction Program. The Team suggests that the PAs consider working with evaluation, implementation, and Passive House experts (such as PHIUS and Steven Winter Associates) to revisit the current baseline assumptions and ensure they are appropriate for the new offering. 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 UDRH does 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 program is indeed driving more efficient practices.

Consideration: 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 PAs should consider offering initial overall incentives in the range of $5,000 to $10,000 per unit to attract immediate attention for the program.[4] The implementation contractor, ICF, provided details on the average incentive amount per-unit for 49 program participants ($630.16/unit). The program incentive offering that has been suggested from the IDIs is substantially higher than the current average program offering. As a result, the proposed incentive amount would allow the program flexibility to require additional information from Passive House program participants to validate current program assumptions on the energy savings, the project costs, and the non-energy benefits of Passive House projects in Massachusetts.

[4] 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.

Consideration: 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 design regarding certification. Market actors indicated that they would like to see incentives spread out over a few different project milestones. The PAs should consider offering incentives for design team charrettes and initial modeling, pre-certification, and final certification. 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.[5] Providing a proportion of the incentives prior to achieving final certification would provide some assurances to potential participants that incentives are available and will not be taken away if final certification is not achieved – though that scenario should result in any final certification incentives being held back.

Consideration: 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 offering, 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. The PAs should consider requiring initial participants to provide detailed cost information to better understand the incremental costs associated with Passive House certification and design techniques.

There may be an opportunity to align cost data collection efforts with the incremental cost reporting framework that the Massachusetts Clean Energy Center (CEC) requires for their Passive House Design Challenge incentive offering. This would require the PAs to collaborate with the Massachusetts 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.

[5] 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.

Section 1 Introduction and Approach

This interim report presents initial findings from the MA19R05 Passive House evaluation. The Team conducted a detailed model comparison for five Multifamily High-Rise (MFHR) projects that incorporate Passive House design principles. The model comparison included three different energy modeling tools: the ICF multifamily modeling tool, WUFI Passive, and PHPP. The focus of this interim report is on the mid-rise and high-rise market as this is the initial market that the PAs offering will focus on. A comparable review will be conducted for low-rise new construction projects for the full draft report.

In addition to the modeling comparison this report presents key findings from in-depth interviews (IDI's) with 21 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 results of these research tasks will be used by the PAs to inform their initial program offering for the mid-rise and high-rise multifamily new construction market.

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.[6] 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 lower peak heating and peak cooling load and result in minimized mechanical systems for heating and cooling.[7] 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,[8] 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.

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[6] 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.

[7] Passive House certification requires peak and annual loads to be under a specified threshold. The standard is different depending on whether Passive House Insistute (PHI) or Passive House Institute-US (PHIUS) is pursued.

[8] http://ma-eeac.org/wordpress/wp-content/uploads/Term-Sheet-10-19-18-Final.pdf

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.[9,10] The differences are primarily due to PHIUS applying U.S.-specific data for energy costs, construction costs, and climate data.

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 multi-family 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 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.[11] 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).

[9] 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.
[10] PHI requirements: https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm
[11] https://passivehouse.com/downloads/03_building_criteria_en.pdf

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.[12] The project certification process begins with pre-certification, a process used to verify that the energy model matches plans and specifications. The final 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.

1.3 Evaluation Approach

The Team conducted three key tasks for this interim report:

- A detailed model comparison for a sample of multifamily Passive House projects.
- A review of 2018 MFHR program participant data and a potential savings assessment.
- 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 offering, which will initially focus on mid-rise and high-rise multifamily buildings. Details on the specific evaluation methods and the corresponding results can be found in the remaining report sections.

[12] PHIUS. February 2019. "PHIUS+ 2018 Passive Building Standard Certification Guidebook Version 2.0."

Section 2 Preliminary 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 calculate savings 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 modeling comparison are intended to inform the program design and help the PAs determine which modeling tools are appropriate to calculate program savings and what steps are required to ensure any program savings are as accurate as possible.

To date, the modeling component of this study has focused on multifamily projects that are four stories or more in size. The Team worked collaboratively with ICF, the RNC program's implementation contractor, PHIUS, and Steven Winter Associates to execute this 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: 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 NMR 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 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.[13] 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.

Table 9: Sampled Projects – Project Details

Site ID	Climate Location	Gross	# of Res Stories	# of Units	Heating Type*	DHW Type
Site 1	Boston	33,500	4	28	DMS	Central Boiler
Site 2	NY - JFK	110,185	7	101	Central VRF -w/heat recovery	Central Boiler
Site 3	NY - LaGuardia	156,940	14	154	Central VRF -w/heat recovery	Central Boiler
Site 4	NY - LaGuardia	234,958	11	249	Central VRF -w/heat recovery	Instantaneous system - electric
Site 5	NY - LaGuardia	261,260	26	277	Central VRF -w/heat recovery	Central Boiler

*DMS is “Ductless Mini-Split” while VRF is “Variable Refrigerant Flow”.

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

Table 10: 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

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.

2.2 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 C.

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 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 when possible.[14]

2.3 Summary Results

The summary 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

[14] 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.

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.
- Accuracy of claimed savings.
- 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. 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[15], similar savings results, and the effort needed to adjust WUFI or PHPP default values with 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 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 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 26 of Appendix B.

[15] 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: Summary Modeling 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 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 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 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 EUI	**29%**	**31%**	**33%**

2.4 PROPOSED MODELS

The Team looked at the proposed 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 3 and Table 12). The ICF tool output is indicating a much higher consumption from cooling (~72% higher average EUI) and heating (~50% higher), than the Passive House models.

The Passive House model outputs for hot water average EUI were higher than the ICF tool. The 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 3: Average Proposed Model EUI by End-Use (kBtu/ft²/Year)

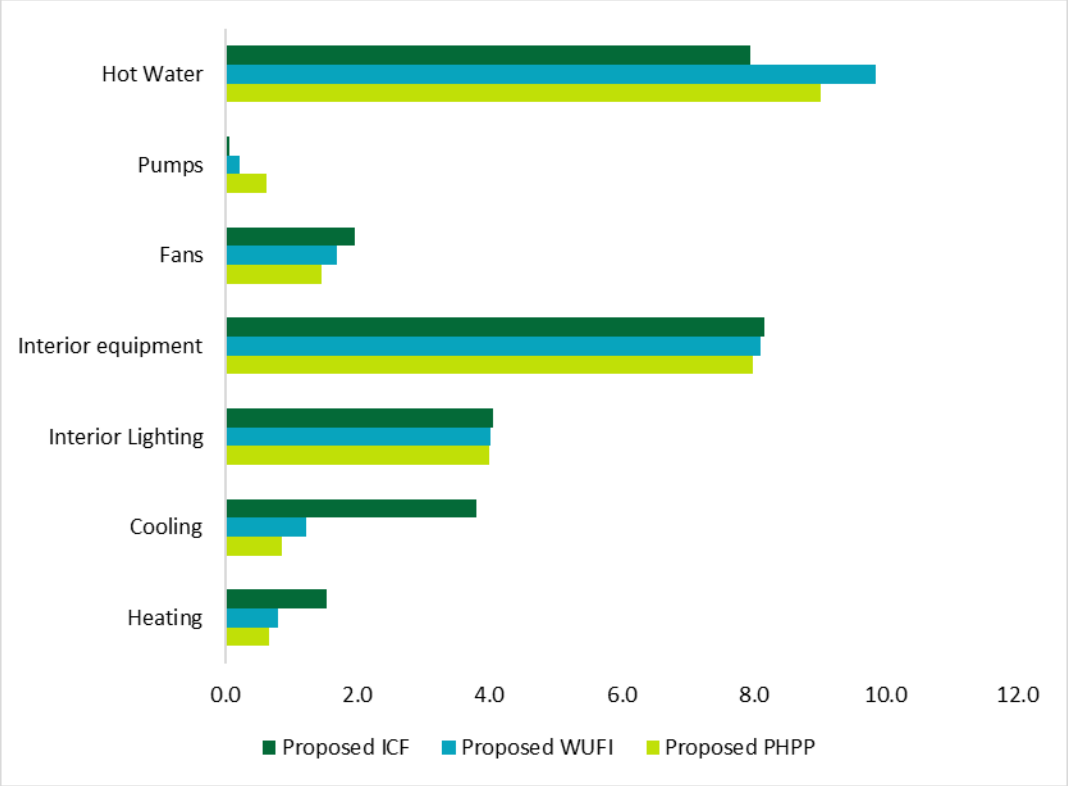


Table 12: Average Proposed Model EUI by End-Use (kBtu/ft²/Year)

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 Baseline Models

The Team found similar trends as in the proposed models when looking at the baseline 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 4 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 either mini-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 actual 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 will continue to use mini-splits. 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 4: Average Baseline Model EUI by End-Use (kBtu/ft^2/Year)

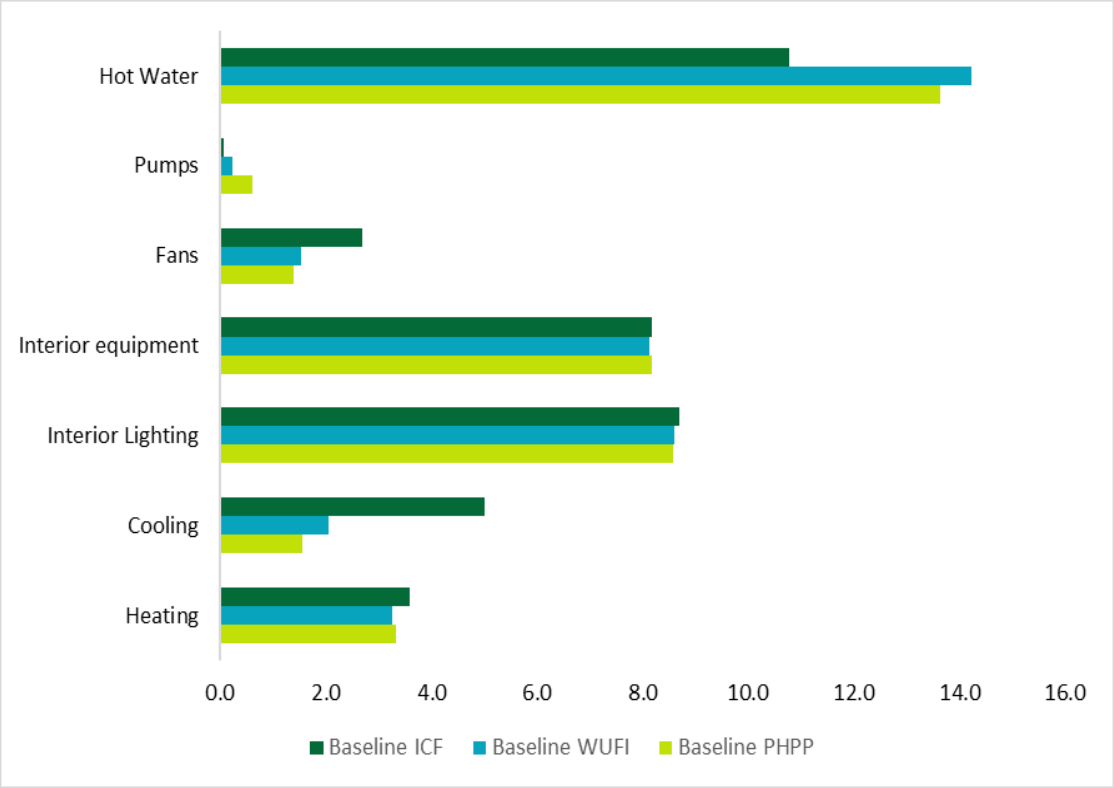


Table 13: Average Baseline Model EUI by End-Use (kBtu/ft²/Year)

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 End-Use Savings Results

The average savings by end-use for each of the three models are presented in Figure 5 and Table 14. The lighting savings may be attributed to the use of certification protocols to calculate lighting consumption. The Team did not have detailed lighting schedules for the acquired projects and leveraged the certification lighting calculators and assumptions (see Appendix B for details on modeling assumptions). 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 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).[16] 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 results were lower, the overall EUI savings were within 4% for all three models.

[16] 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.

Figure 5: Average EUI Savings by End-Use (kBtu/ft²/Year)

Table 14: Average 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**

Table 15 provides average end-use EUI comparisons between the proposed and baseline scenarios for the program models used in this study. These values are derived from the ICF modeling tool using the MFHR UDRH values and proposed conditions in the 62 sampled MFHR sites. As with the five passive house projects, average 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 due to the loss of internal gains from high efficiency lighting in the proposed models.

Table 15: Proposed Savings over Baseline for Program Models 62 program participants

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**	**29.3**	**6.6**

*Totals may not sum due to rounding.

Section 3 Program Data Review and Potential Savings Assessment

3.1 Program Data Review

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 16, 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.[17] 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.[18]

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.

[17] Source energy conversion values and additional background on source energy can be found here: https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf

[18] 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 16: 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

3.2 PRELIMINARY POTENTIAL SAVINGS

In order to identify potential savings associated with the new program offering the Team compared the 2018 MFHR program participant projects to a series of Passive House certification 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 17 to estimate the potential savings associated with the new offering.

Table 17: Passive House Source Requirements

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

Specifically, the Team was focused on comparing the source energy requirements from these various Passive House certifications to the baseline and proposed modeled consumption estimates for the 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 requirements for the same projects to develop a site-to-source ratio factor. This factor was then multiplied by the Passive House source energy requirements for each site to estimate a Passive House annual site energy requirement.

Table 18 displays the calculated savings over baseline and proposed program models for each of the major Passive House certification bodies. In each case, the Passive House source energy value for each building was converted into a site EUI, using the site to source EUI ratio for each building, and the resulting value was compared to the actual 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).[19] The program also provided breakouts of residential and non-residential square footage, allowing the Team to create a consumption value for non-residential square footage according to the PHIUS requirements.

Source energy consumption requirements for PHIUS+ 2018 jump considerably over the 2015 version with the increased stringency of the updated kWh requirements—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 source 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 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 source consumption of baseline buildings by 55%.

It is worth noting that source energy consumption reductions 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.

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

Table 18: Passive House EUI Savings versus Program Models

Certification Requirement	Savings Over Baseline	Savings Over Proposed
Modeled Site EUI in ICF Tool (kBtu/ft^2/yr)	35.9	29.2
Site EUI Savings (kBtu/ft^2/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%

Section 4 In-depth Interviews

This section presents the results of the IDI's that have been conducted to date. In order to keep this interim 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.

4.1 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, several 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 19 presents the sample targets and the number of interviews completed at this time. The remaining four interviews will be completed prior to the final report.

Note that interviewees all had some level of experience working on Passive House projects.[20] 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 the program requirement for 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.

[20] With the exception of two interviews with developers that do not have Passive House experience. The team had not completed these two interviews, along with two of the occupant/owner interviews at the time of the interim report.

Table 19: In-depth Interview Sample

Market Actor Group	Target	Complete
Architect/engineer	5	5
Builders	5	5
Industry Experts	4	4
Occupants/Owners	4	2
Developers	5	5
Non-Passive House developers	2	0
Total	**25**	**21**

4.2 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". 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 might 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 actors are available. The lack of certified Passive House buildings in Massachusetts is particularly noticeable for large MFHR buildings.[21] 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 or leverage existing

[21] 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.

third-party trainings that cater to each group.[22] 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 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% - 10% across interviewee groups. A few market actors suggested that building to Passive House standards does not have a cost premium—due

[22] 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 5.

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 are in agreement on project outcomes and goals.

Code officials and permitting in certain municipalities may be a barrier. Developers noted that in some municipalities applying for variances on Passive House projects will 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. 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 reduction, occupant health, and resiliency—are likely to push their project to meet Passive House standards without incentives.

4.3 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, comfort, noise reduction, resilience, 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 which 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 in-depth interviews 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.

4.4 Material and Equipment Choices

4.4.1 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 state 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.

4.4.2 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 these 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.

4.5 Program Training Opportunities

Interview respondents identified lack of experienced builders as an obstacle and suggested the program support builder training

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 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.

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 5 Incremental Costs

5.1 Drivers of Increased Costs

5.1.1 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. 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 was 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.[23]

[23] 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.

5.2 INCREMENTAL COST ESTIMATES

5.2.1 In-Depth Interviews

Industry experts noted that cost could vary widely from project to project, but they agreed that the increased costs for multifamily buildings were in the range of 5-10%.[24] Developers similarly estimated that multifamily 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 5-10%. Among architects and engineers, the figures were more optimistic, for multifamily projects estimated 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 20: Passive House Incremental Cost Estimates

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

There was agreement across industry experts, architects, and engineers 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.

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 21.

[24] 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.

Table 21: 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) ➢ Between $10,000 - $20,000 for a 98-unit project and 108-unit project ($102.04-$204.08/unit) ➢ 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) ➢ $22,000 for a 135-unit project ($162.96/unit) ➢ $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.

5.2.2 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.

5.2.3 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.[25] The data included estimated project costs based on submitted applications to the program—which includes both Passive House and non-Passive House projects.[26] 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,

[25] Data was originally submitted to both the PAs and the Mass CEC from the Pennsylvania Housing Finance Agency (PHFA).
[26] 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.

For the year 2015, final construction costs were documented--data for subsequent years were only available for application costs because projects were not fully completed. For 2015 the Team was able to compare actual costs to estimated costs at application—passive buildings costs 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.

Some rationale was provided to the Team on what was driving down the costs for Passive House projects in Pennsylvania which detailed increases in practical experience 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 10). 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.

5.3 Methods for Offsetting Incremental Costs

5.3.1 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. The impact of 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, however 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 which is projected to reduce total HVAC system costs by one-third, compared to their previous project.

Section 6 Incentive Structure

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

6.1 Incentive Structure – In-depth Interviews

Table 22 provides a summary of responses which are specifically related to multifamily buildings.

Table 22: Incentive Structure Summary of IDI Responses

Market Actor Respondent	Incentive Recipient	Incentive Timing	Incentive Amount
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 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 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 Part 2) Certification 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 Part 2) Certification	$4,000 per unit
Developers	Owner/Developer	Part 1) Certification Part 2) Performance	$10,000+ per unit
Developers	Owner/Developer	Design/pre-certification	$10,000 per unit

6.1.1 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.

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.

6.1.2 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.

6.1.3 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.

6.1.4 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.

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 23). The application costs are the estimated cost 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 24).

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 23: 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 24: 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.

Appendix B Additional Modeling Details

B.1 Model Assumptions

Table 25 describes the default values in PHPP, WUFI, and for the 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 25: PHPP Default, WUFI Default, Proposed Model, and Baseline Model Input Values

Measure	Default PHPP Value	Default WUFI Value	Adjustments for Proposed	UDRH Baseline Value
General				
Project square footage	TFA[27]	iCFA[28]	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) [29]	Proposed: 1.32 Baseline: 1.904	--	--

[27] 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.
[28] 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.
[29] 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.

		(Btu/hr.gross. sf) [30]		
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 [31]	Project specific or Reference: Building America "B10 Analysis – New Construction 2011-01-26"	Used Project File (the PHIUS MF Calculator) provided values. [32]	UDRH Protocol: for calculating Common Area Lighting load
Common Area Plugs	Included in plug loads – residential [33]	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

[30] Calculated varies based on project file specific inputs. Presented average values from the modeling activities for the proposed and the baseline case.
[31] The Energy Modeling Team manually entered common area lighting (kWh/yr) from UDRH calculations in addition to residential lighting.
[32] 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.
[33] The Energy Modeling Team manually entered common area plug loads (kWh/yr) from UDRH calculations in addition to residential lighting.

Lighting - Residential	LEDs @ 7-11 Watts per person (input is in lumens per watt). Lights on for 2,900 hr/yr on avg. [34]	80% RESNET Assumptions	Used Project File (the PHIUS MF Calculator) provided values. [35]	UDRH Protocol: for calculating lighting load in residential space
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. [36,37]	UDRH Protocol: for calculating lighting load for residential equipment load
Envelope and HVAC equipment				
Envelope (insulation and air-sealing	Based on Project Files	Based on Project Files	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

B.2 TOTAL CONSUMPTION RESULTS

The body of this report focuses on EUI comparisons across the models that were considered for our model comparison analysis. Table 26 presents the overall consumption estimates, by site, for each of the models included in our assessment. Note that the annual consumption values presented below exclude exterior lighting and on-site photovoltaic generation.

[34] 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.
[35] 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.
[36] For PHPP plugs on for 1,400 hrs/yr. Adjusted Watts per unit input to get total dwelling unit plug load energy to match UDRH input. Zeroed out small appliances kWh/yr.
[37] 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.

Table 26: 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 AVERAGE MODELED EUI AND SAVINGS BY FUEL

The average EUI for the proposed models, baseline models, and savings by fuel type are presented for each of the three software in Figure 6. 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 6: Average Modeled EUI and Savings by Fuel Type (kBtu/ft2/yr)

Appendix C Massachusetts 2018 MFHR UDRH

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 7: Seed Geometries

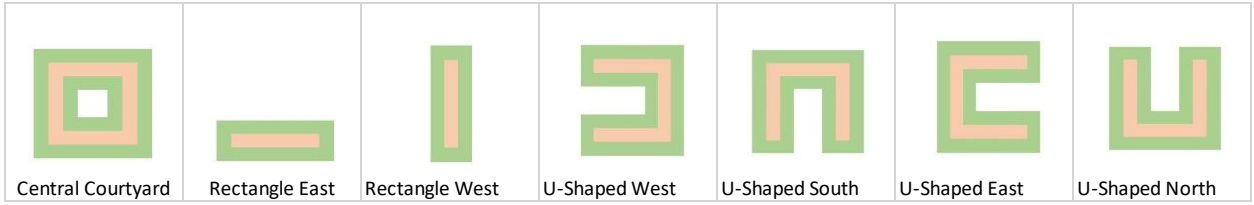
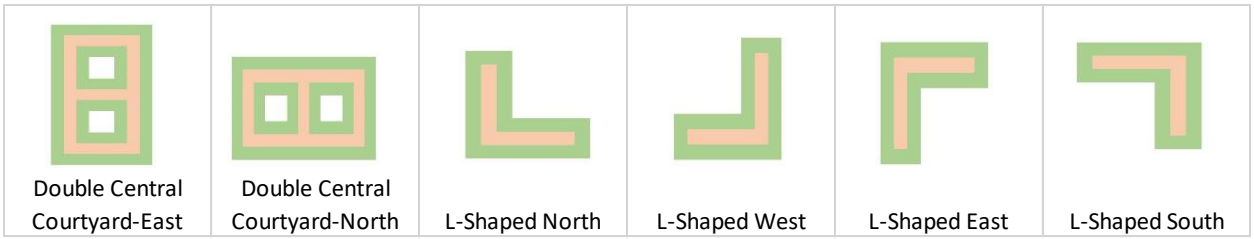


Figure 8: Seed Geometries



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 multi-family 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)

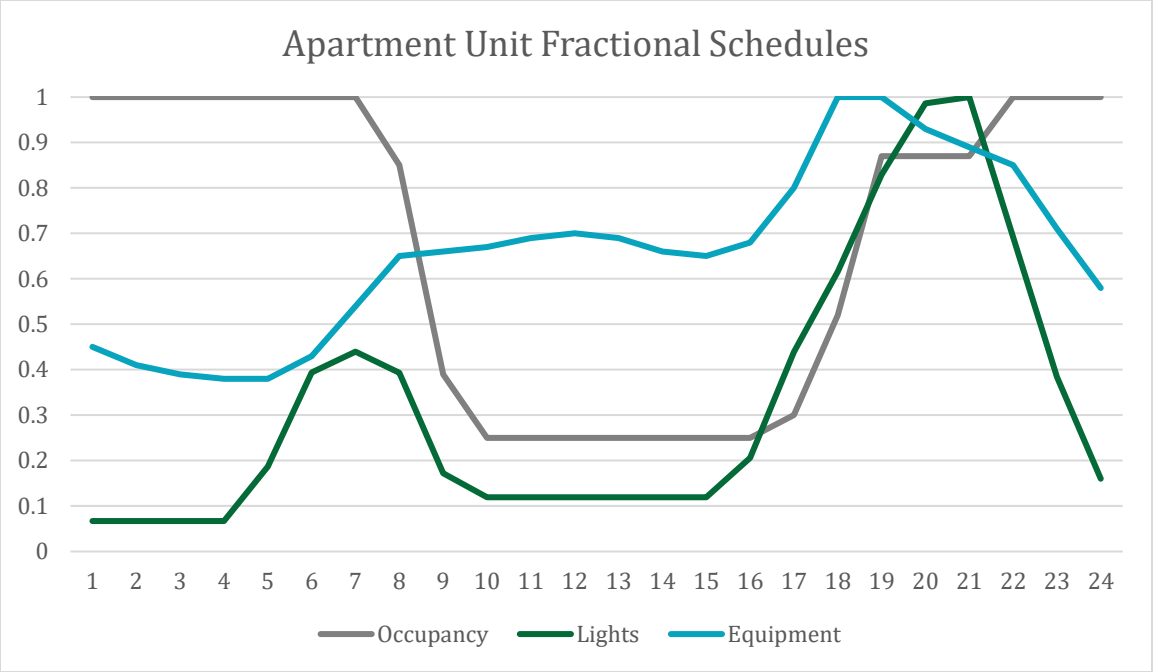
The loads in the residential units follow a fractional schedule as outlined below. This schedule is constant for every day of the year. Note that ventilation is not listed because it has a constant 1.0 fractional schedule; however, the ventilation requirement varies with the current occupancy in the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