MORANDUM

To: The Massachusetts Program Administrators and Energy-Efficiency Advisory Council

From: Zack Tyler, Scott Walker, Matt Woundy, and Sam Manning, NMR Group

Date: July 17, 2019

Re: Passive House Literature Review

This memo presents the results of a literature review designed to provide additional details on key questions identified by the Massachusetts Program Administrator's (PA's) and the Energy Efficiency Advisory Council (EEAC) Consultants for the new Passive House offering within the Residential Homes and Renovations Initiative. The primary focus of this memo is to provide a high-level summary of Passive House using currently available literature. The memo covers the following topics:

- The history of Passive House
- Prevalence of Passive House in the market
- Descriptions of the two current Passive House certification bodies in the U.S.
- General details on requirements and certification process for both certification bodies
- Review case studies and existing reports on the actual vs. modeled performance of passive buildings
- Review incremental costs associated with building Passive House buildings

It should be noted that the two passive house certification bodies that are operating in the U.S., the Passive House Institute (PHI) and the Passive House Institute U.S. (PHIUS), have different certification requirements which may lead to different decisions in the design and building process.

Key Findings

- ***Studies providing quantitative energy use comparisons between passive buildings and code-compliant or above-code homes is lacking, leaving some ambiguity in the performance gap between passive design and current high-performance buildings.***
- ***There are relatively few certified passive buildings in the US. There is not yet a mature market of Passive House professionals or an extensive track record of buildings.***

- ***PHIUS is the dominant certification organization in the US. Their certification scheme is adapted to US climate variations, in contrast to the PHI standard, which applies uniformly regardless of location.***
- ***Passive House modeling software options use different inputs, default values, and assumptions – creating multiple definitions of what a Passive House can be in practice.***
- ***Data are limited, but case studies suggest that model assumptions for lighting and plug load energy use based on European trends are not appropriate for use with American homes.***
- ***Reduced energy use in other areas means occupant behavior can have a major impact on overall observed energy use, causing discrepancies between modeled and actual energy use in a passive building.***
- ***Passive buildings usually have higher up-front costs than code-compliant buildings but are found to generate savings for occupants in energy and maintenance costs.***
- ***There is ambiguity around quantifying incremental costs given different comparison points and methods of estimation, but literature suggests Passive House costs can be brought more in line with current prices with added experience and fine-tuning of methods.***

Section 1 Introduction to Passive Buildings

This section provides a brief history of the Passive House movement and the prevalence of passive buildings in the U.S. Market.

1.1 History

The Passive House design concept began in the 1970's in response to the energy crisis. The Passive House approach focuses on construction of a building envelope that has highly-insulated walls and very low levels of air infiltration.[1] In addition, Passive House design focuses on optimized window performance, optimized solar and internal gains, and balanced heat and moisture recovery ventilation. The Passive House design principles are intended to lower peak heating and cooling loads and to allow minimized mechanical systems for heating and cooling.[2] Occupant comfort is a primary driver behind the design principles, as the building is designed to maintain optimal interior temperature and moisture conditions.[3]

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[1] 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 large temperature swings from the heavy focus on southerly glazing.

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

[3] http://www.phius.org/what-is-passive-building/the-history-of-passive-houses

A small number of experimental homes were constructed between the 1970's and the 1980's in North America, including the Low-Cal house and the Saskatchewan Energy Conservation House. This was followed by physicist William Shurcliff detailing the concepts of "superinsulation" in the mid-1980s, a term made up of concepts that are also core tenets of Passive House. With the end of the energy crisis, the movement for energy conservation subsided in the U.S. construction industry and the Passive House movement fizzled.[4]

Meanwhile, German physicist Wolfgang Feist refined Passive House design principles to increase the efficiency of buildings by developing a Passive House (known in Germany as Passivhaus) concept that had an annual heating demand of 15 kWh/m^2. The first pilot project, the Kranichstein Passive House, achieved a documented heating energy consumption of under 10 kWh/m^2. The Passive House Institute (PHI) was founded by Wolfgang Feist in 1996, which acts as an independent research institute. Since inception, PHI has developed an energy modeling tool, the Passive House Planning Package[5] (PHPP), developed a research group for cost-effective Passive Houses, and developed certification requirements that are used internationally.[6,7]

The Passive House Institute US (PHIUS) was founded in 2007, after the first Passive House buildings were constructed in the US to a certification standard.[8] The organization began as an affiliate certifier and trainer for PHI. PHIUS and PHI began operating independently in 2011. Both certification bodies used the same performance requirements for certification until March 2015.

In March 2015, PHIUS released the PHIUS+ 2015 Passive Building Standard, which was the result of a cumulative research effort that explored climate-specific passive building standards in the U.S.[9,10] The standard developed requirements that considered climate, construction costs, and energy costs through the use of the Building Energy Optimization tool (BeOpt).[11] PHIUS updated their 2015 standards to PHIUS 2018 as of April 1, 2019.

There are guiding Passive House principles that overlap between the two organizations. PHI and PHIUS now, however, implement distinct requirements for buildings that they certify, which may lead to differences in design decisions between buildings pursuing one certification over the other. See Section 2 for details on the requirements for both certifications.

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[4] https://www.eesi.org/articles/view/the-history-of-passive-house-a-global-movement-with-north-american-roots

[5] The PHPP modeling tool is an open-source model that is distributed through Microsoft Excel software.

[6] https://passivehouse.com/01_passivehouseinstitute/01_passivehouseinstitute.htm

[7] https://passipedia.org/examples/residential_buildings/multi-family_buildings/central_europe/the_world_s_first_passive_house_darmstadt-kranichstein_germany?s[]=kranichstein

[8] The Smith House was the first home built in the U.S. to meet PHI standards in 2003 in Urbana, Illinois. The home was built by PHIUS co-founder Katrin Klingenberg.

[9] The research was conducted with Building Science Corporation on behalf of the National Renewable Energy Laboratory and the U.S. Department of Energy.

[10] Wright and Klingenberg (PHIUS). July 2015. "Climate-Specific Passive Building Standards." Prepared for The National Renewable Energy Laboratory.

[11] Building Energy Optimization "BeOpt" is a tool developed by the National Renewable Energy Laboratory to assess the costs and energy performance of buildings. https://www.energy.gov/eere/buildings/building-energy-optimization-beopt-software

1.2 PREVALENCE OF PASSIVE BUILDINGS

The number of certified Passive House projects from both PHI and PHIUS in the U.S. is small but growing as knowledge and awareness of Passive House design principles have increased. Table 1 and Table 2 show the number of PHI and PHIUS projects certified and the total certified square footage in the U.S. The estimated combined number of certified Passive House structures is 257, which includes projects that have been constructed and passed either of the certification requirement processes.[12]

Table 1: PHI Certified Projects in U.S.

Year	Number of certified projects	Total Certified Square Footage
2006	1	4,316
2007	1	2,045
2008	--	-
2009	--	-
2010	2	6,405
2011	6	7,718
2012	11	29,655
2013	9	29,708
2014	10	32,033
2015	7	74,217
2016	3	11,647
2017	1	198,336
2018	1	2,581
Total	53	398,660

*Source PHI certified project database: https://passivehouse-database.org/index.php#k_

Table 2: PHIUS Certified Projects in U.S.

Year*	Number of certified projects	Total Certified Square Footage
2006	1	4,316
2007	1	1,242
2008	--	--
2009	4	7,542
2010	7	10,694
2011	15	34,760
2012	18	35,754
2013	21	46,394
2014	19	55,446
2015	19	113,723
2016	25	245,151
2017	22	88,958
2018	26	242,200
Total**	204	1,085,828

*Yearly approximations provided by PHIUS (these figures do not sum to the total values).
**Total: Source PHIUS certified project database: http://www.phius.org/phius-certification-for-buildings-products/certified-projects-database

[12] Approximately 4 projects are dual certified

There are some PHIUS projects that are currently in the design or construction phase and have met preliminary certification requirements and are considered “pre-certified.” Pre-certification is a design review process administered by PHIUS. The number of PHIUS pre-certified projects totals 117 and accounts for an additional 2,244,722 ft^2 of floor area where the developer has expressed the intention to pursue Passive House certification or is actively pursuing certification with PHIUS. Note that the PHI project database did not explicitly identify projects that were pursuing PHI certification, so a corresponding estimate of pre-certification PHI buildings is not available.

The number of Passive Houses that are certified in Massachusetts is very small: there is currently one certified PHI project and six projects that were certified through PHIUS.[13],[14] Currently there is only one certified multi-family building in Massachusetts, one commercial building, and the rest are single-family homes.

There are some Passive House projects that are currently in development in Massachusetts that are not included in either certification database. These include multi-family and mixed-use buildings. Winthrop Center, a skyscraper currently under construction in downtown Boston, would be the largest Passive House building in the world. The project will reach 691 vertical feet and encompass 750,000 ft^2 of residential, office, commercial, and public space.[15] Another Passive House project in development is Concord Highlands, a 6-story, 98-unit affordable multifamily building in Cambridge.[16]

The Massachusetts Clean Energy Center is currently offering a Passive House Design Challenge that offers grants of up to $4,000 per unit.[17] Projects must meet certain criteria which include:

- Affordable multifamily buildings that are newly constructed
- Buildings must include 25 or more units
- Grant recipients must track the incremental costs of proceeding with Passive House design
- Both PHI and PHIUS certification are acceptable

Section 2 Passive House Certification

As described above, there are two certification organizations for Passive House structures in the U.S., PHI and PHIUS. The following subsections describe each organization’s certification requirements.

2.1 Passive House Institute (PHI)

The certification process for PHI is a pass/fail standard, 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

13 https://passivehouse-database.org/index.php#k_
14 http://www.phius.org/phius-certification-for-buildings-products/certified-projects-database
15 https://phmass.org/passive-house-reaches-for-the-sky-and-the-record-books-in-boston/
16 http://passivehousebuildings.com/magazine/fall-2018/affordable-multifamily-housing-in-cambridge/
17 https://www.masscec.com/passive-house-design-challenge

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.[18] 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). A general overview of the required documentation includes:

- Passive House Planning Package (PHPP) submission
- Architectural plans and details
- Treated floor area[19]
- Windows, doors, ventilation, HVAC, electrical devices, and lighting
- Renewable energy
- Airtightness of building
- Photographs

The PHI's Passive House criteria are displayed in Figure 1. There are additional occupant comfort criteria that a project must demonstrate as well, which include considerations for temperature and humidity resiliency of the building. There are three options within the Passive House category: Classic, Plus, and Premium. The Plus and Premium options consider renewable primary energy (PER) conditions added to the project, while Classic only focuses on the core demand-side criteria. The Plus and Premium options were developed by the PHI to incentivize the use of certain technologies and fuel types in design that allow for the offset of energy consumption through renewable energy production (either on-site or off-site).

Figure 1: PHI Passive House Certification Standards

			Criteria[1]			Alternative Criteria[2]
Heating						
Heating demand	[kWh/(m²a)]	≤	15			-
Heating load[3]	[W/m²]	≤	-			10
Cooling						
Cooling + dehumidification demand	[kWh/(m²a)]	≤	15 + dehumidification contribution[4]			variable limit value[5]
Cooling load[6]	[W/m²]	≤	-			10
Airtightness						
Pressurization test result n_{50}	[1/h]	≤	0.6			
Renewable Primary Energy (PER)[7]			Classic	Plus	Premium	
PER demand[8]	[kWh/(m²a)]	≤	60	45	30	±15 kWh/(m²a) deviation from criteria...
Renewable energy generation[9] (with reference to projected building footprint)	[kWh/(m²a)]	≥	-	60	120	...with compensation of the above deviation by different amount of generation

2.1.1 Passive House Planning Package

The Passive House Planning Package (PHPP) tool is required to be used to achieve PHI certification. The PHPP is an energy-efficiency planning tool that calculates an energy balance and the projected annual energy consumption of the building. The tool is currently on its 9th version and is able to be combined with a 3-D design tool, designPH, which is also developed by PHI.

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[18] https://passivehouse.com/downloads/03_building_criteria_en.pdf

[19] Treated floor area is the measure of usable internal floor area, contained within the thermal envelope

The tool is built in Microsoft Excel which allows the user to view how the results are calculated as they input the required data. The PHPP also produces modeled results for heating and cooling demand, renewable energy needs, economic feasibility, efficiency comparison, and potential occupant comfort issues.

2.2 Passive House Institute U.S.

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. Additional requirements include:

- Heating and cooling space conditioning targets must be achieved for both annual load and annual demand
- Space conditioning targets are calculated based on specific climate and the buildings envelope-to-floor area[20]
- Annual source energy use for residential buildings must meet a 3,840 kWh/person/year
- Annual source energy use for non-residential buildings must meet a 34.8 kBtu/ft^2 energy use intensity (EUI)
- Must achieve an air-tight envelope of 0.06 CFM/ft^2 of exterior envelope area[21]

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.[22] 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. A general overview of the required documentation includes:

- WUFI model submission[23]
- Architectural plans and details
- Interior conditioned floor area[24]
- Windows, doors, ventilation, HVAC, electrical devices, and lighting
- Renewable energy
- Airtightness of building-post construction test
- Pre-process paper work, registering, payment
- QA/QC Rating-must be conducted by PHIUS trained Rater or Verifier

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[20] PHIUS uses the iCFA metric to calculate floor area, which is the measurement of interior conditioned floor area.
[21] This metric for measuring air leakage differs from typical calculations that use total volume of the building. This calculation methodology essentially loosens the prior requirement of 0.6 ACH50 for buildings smaller than 10,000 ft^2 and increases the air-leakage requirements for buildings over 10,000 ft^2. The default residential air infiltration load used by the MFHR program in MA is equivalent to 0.40 CFM_{75}/ft^2, while for PHIUS+ 2018 it is either .110 CFM_{75}/ft^2 (>5 floors and constructed of non-combustible materials) or 0.08 CFM_{75}/ft^2 (all other buildings).
[22] PHIUS. February 2019. "PHIUS+ 2018 Passive Building Standard Certification Guidebook Version 2.0."
[23] WUFI modeling software is developed and distributed by Fraunhofer IBP.
[24] Treated floor area is the measure of usable internal floor area, contained within the thermal envelope

2.2.1 WUFI

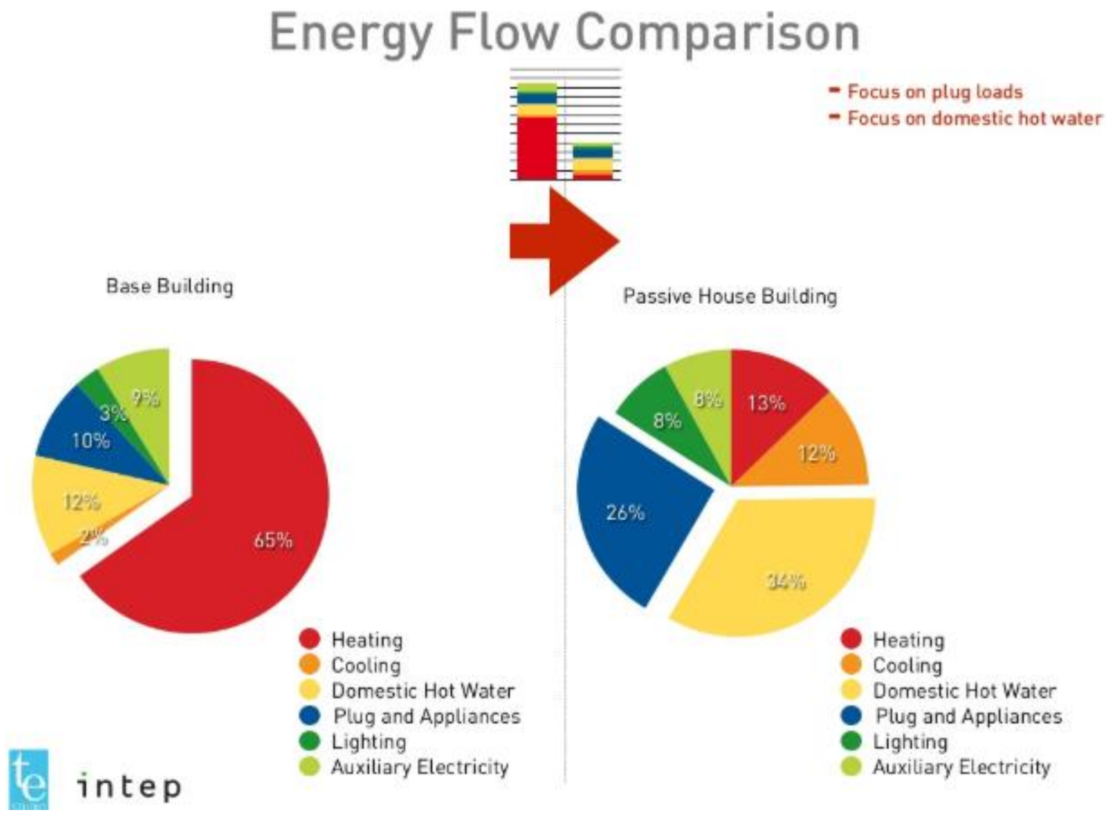
PHIUS requires certification using the WUFI Passive energy modeling software. The software calculates a monthly energy balance and is used for the design and verification of building performance. WUFI Passive offers both free and paid versions of the software. The free version can be used for certification, but the paid version of the software includes several additional features such as user-defined database entries, importing XML files, and exporting results. The paid version also includes the hygrothermal analysis of components, but only for Passive Houses.[25] WUFI also offers WUFI Plus software, a certification tool that supports hygrothermic analyses of components and additional analyses such as hourly simulations and simulating the indoor environment to assess occupant comfort for any building design.

Section 3 Modeled versus Actual Performance of Passive Buildings

The literature on Passive House performance reveals a few key themes when comparing modeled to actual consumption, but much of the comparisons revolve around one takeaway—occupant behavior is key to the actual energy performance of a passive building. Greatly reduced heating and cooling loads, due to high levels of insulation and air sealing, increase the relative impact of occupant behavior on the total building energy performance. In Passive House software, as with other energy models, careful construction of the model can only go so far in accurately predicting performance-- actual energy use relies on the way the occupants use lights, appliances, HVAC controls, windows, and shading mechanisms. Figure 2 displays an example of how energy use attributed to plug loads can shift between standard construction and passive homes to play a larger role in the energy profile.

[25] Hygrothermic analysis refers to the movement of heat and moisture through buildings. This analysis is typically done on building components to verify that the building design will not result in moisture issues or failed components. The building design must come within a certain threshold of meeting PHIUS certification to access the hygrothermic analysis feature.

Figure 2: Energy Use Comparison Between Standard and Passive Construction[26]



There are other issues at play as well, including the model used, and the assumptions and defaults built into their respective algorithms. Based on several studies published on Passive House performance, certain modeling software assumptions may underestimate the plug load and lighting use in American households. The following case studies explore findings in the Passive House literature that highlight how buildings perform relative to modeled energy consumption, and the factors that play into the observed differences. Case studies are limited, and often limited to single buildings in different contexts being studied with diverse methodologies; making it difficult to derive concrete conclusions.

3.1 NYSERDA Study

NYSERDA commissioned a study in 2014 to monitor the performance of four passive buildings and compare their energy use to modeled predictions. In every case, the building used more energy than predicted by Passive House Planning Package (PHPP) software, with a range of 24% to 82% more total energy used.[27] Consumption attributable to plug loads, lighting, and appliances ("other" consumption in the PHPP model) were consistently higher for all sites. The default value for consumption is based on typical European occupant behavior, rather than data

[26] Eian, T. (2017). *Passive House for Commercial Projects.* Presentation delivered at the Duluth Energy Design Conference. Retrieved from https://www.slideshare.net/timeian/commercial-passive-house-case-studies

[27] Levy Partnership, Inc. & CDH Energy Corp. (2014). *Measured Performance of Four Passive Houses on Three Sites in New York State.* Final Report Prepared for New York State Energy Research and Development Authority.

from American homes. To the evaluation team, this finding highlighted the influence of occupant behavior on Passive House consumption—the number of electronics plugged in and occupant use of lighting are factors that can diverge widely from one home to another and between model defaults and reality. Findings from one case study provide an example of the way occupants can change the entire complexion of a passive home's energy performance—in one home, energy consumption was 57% higher than the model predicted, and "other" energy exceeded the modeled prediction by 2.4 times, in large part because both occupants worked from home.

Another aspect of occupant behavior focused on indoor air temperature and cooling. Generally, across each site, more energy was used for cooling than expected. One takeaway was that occupants did not utilize free cooling as much as modeled via opening windows. Windows stayed closed generally, due to issues such as noise and allergens, and so indoor air temperatures remained higher at night, necessitating more cooling. Depending on the site, indoor air temperatures and occupant comfort were affected by behavior such as heat pump operation (on-off versus continuous operation) and set point alterations that diverged from what was modeled. Monitoring of indoor air temperatures and humidity in these homes, along with behavior of the occupants with regard to window operation, highlights the need to plan mechanical ventilation and cooling accordingly to deal with less fresh air and natural cooling than may be anticipated by modeling.

3.2 Massachusetts' First Certified Passivhaus

Results of energy monitoring at the first passive home in Massachusetts published on the Green Building Advisor website showed that higher than anticipated plug loads can create increased internal gains and, in turn, greater cooling demand (with the positive side effect of reduced heating demand, though not enough to offset the increased cooling loads in this case).[28] PHPP software defaults to 621 continuous watts of internal load, while the passive home in question was operating at over 1,000 continuous watts; with the difference driven mainly by high plug loads. If the occupant plugs in several more electronic devices than the software plans for, and leaves the lights on longer than anticipated, building energy performance can diverge drastically from modeled performance. In addition to highlighting the importance of occupant behavior, this passive home case study also questioned whether the default plug load assumptions for PHPP are appropriate for an American household, as opposed to the German households that were considered when developing the software. The evaluation team saw a connection here to questions raised by the NYSERDA study, where they pointed out that PHPP predicted much lower "other" energy use (plug loads, lighting, appliances) than was observed in the monitored households.

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[28] Holladay, M. (2012, March 9). *Occupant Behavior Makes a Difference.* Retrieved from https://www.greenbuildingadvisor.com/article/occupant-behavior-makes-a-difference

3.3 PEMBINA INSTITUTE REPORT – MODEL PERFORMANCE

The Pembina Institute, a think-tank focused on policies to promote clean energy transformation in Canada, included a compilation of modeled versus measured energy performance metrics for numerous Passive House projects as part of a 2016 report on the state of the Passive House and high-performance building market.[29] The first metric considered was thermal load intensity (measured in kWh/sq. meter of CFA). The report chooses to point out that in most cases, the measured load intensity is within "a few kWh/m^2" of the modeled value, however given that the total modeled values rarely exceed 15 kWh/m^2, looking at measured load as a *percent* of modeled load may be more appropriate. Breaking down thermal load intensity this way, the measured intensity is, on average, over 20% higher than the modeled value. The other metric considered in the energy use compilation was site energy use intensity (EUI), which shows the measured EUI was only 4% greater than modeled EUI, on average. It should be noted that the sample size of sites where site EUI data were available was much smaller than the number of sites with measured thermal load intensity data.

In situations when sizeable gaps existed between modeled and measured energy performance, some studies cited in the report pointed toward occupant behavior. The Pembina report cites one study done on a passive apartment building in Vienna, where occupants were directed to use windows and window shades to modulate indoor temperatures. Multiple factors in occupant behavior were cited as causes for higher indoor temperatures—occupants might leave windows closed at night over concerns about noise, safety, or insects; and occupants were not willing to utilize window shades for the amount of time necessary in summer months, due to the shades blocking sunlight for large portions of the day.[30] The evaluation team noted that this behavior is similar to that observed in the NYSERDA study, where they found that windows were rarely used for nighttime cooling, causing indoor temperatures to remain elevated and cooling loads to be higher than anticipated.

3.4 CHIFLEY PASSIVE HOUSE CASE STUDY

The Chifley Passive House is an example of a Passive Home that performed better than the modeled predictions (using PHPP). The caveat here is that one of the authors of the case study lived in the home, and thus can be reasonably expected to have a greater awareness of what occupant behaviors and decisions affect the overall energy performance of the home. Indeed, the occupants of the home used windows to provide free cooling to the home at night, lowering indoor temperatures. Even here though, energy use attributable to appliances, lighting, and domestic hot water was 28% higher than the modeled prediction through PHPP.[31] Our team noted that this is lower than other findings from American passive homes included in other case studies, but still

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[29] Frappé-Sénéclauze, T., Heerema, D., Tam Wu, K. (2016). *Accelerating Market Transformation for High-Performance Building Enclosures: State of market, policy developments, and lessons learned from the Passive House movement.* The Pembina Institute, Calgary, Alberta (Canada).

[30] Morishita, M. & Bednar, T. (2013). *The Impact of Occupants' Exterior Shading Use and Window Opening on Summer Comfort in a Lowest-Energy Apartment Building.* Presented at Thermal Performance of the Exterior Envelopes of Whole Buildings XII International Conference. ASHRAE.

[31] Truong, H., & Garvie, A. M. (2017). *Chifley Passive House: A Case Study in Energy Efficiency and Comfort*. Energy Procedia, 121, 214-221.

suggests that extra care needs to be given to modeling plug load assumptions in passive homes in various country locations. The higher than predicted plug load energy consumption was more than offset by heating energy use that was much lower than predicted, in part due to internal gains from lighting, appliances, and domestic hot water.

3.5 Case Study of Multifamily High Rise in Sweden

A 2013 study of a multifamily high rise in Sweden monitored the energy performance of an eight-story passive building that included analysis of occupant behavior over the first year of building operation. An interesting caveat to this study was that the building was only partially occupied during the first year of operation.[32] This is important when comparing modeled and actual building energy performance, because of the role internal gains play in assessing heating and cooling loads. Unlike situations detailed above where occupant behavior leads to higher cooling loads than expected (via higher than expected internal gains, occupant use of passive ventilation or shading, etc.), this building demonstrated much higher than anticipated heating loads. This is attributed in the study to a combination of lower than anticipated internal gains due to reduced occupancy as well as occupant use of windows for natural ventilation in the winter months. Extrapolating the observed energy use of the partial occupant pool out to full building occupancy showed that electricity use would have been 30% higher than anticipated in modeling.

A key takeaway for the evaluation team from this case study was that when considering if actual energy consumption will match modeled performance in larger buildings, the occupancy variable is important (especially when using a defined timeline, like the first year of occupancy). An occupancy rate differing from that used in modeling will affect building energy performance in multiple ways and has implications for incentive programs designed to reward measured performance that might plan to use consumption data from early phases of building operation. It is also important to promote certain occupant behaviors—for example window use. In the study, occupants reported kitchen smells that caused them to open the windows, even when the temperature was not comfortable.

3.6 PHIUS Monitored Performance Analysis for Affordable Multifamily

PHIUS employees performed an analysis on three affordable multifamily properties where building energy data were collected for comparison to the predictions of two passive modeling techniques.[33] Both PHIUS+ modeling—the older method used by PHIUS to certify buildings using PHPP software—and PHIUS+2015 modeling, an updated method using WUFI Passive software, were used to model building performance. Note that this was not independent research of WUFI Passive model performance compared to observed performance, rather research by PHIUS assessing their own methodologies. Independent research providing clear comparisons between

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[32] Kildsgaard, I., Jarnehammar, A., Widheden, A., & Wall, M. (2013). *Energy and Environmental Performance of Multi-Story Apartment Buildings Built in Timber Construction Using Passive House Principles*. Buildings, *3*(1), 258-277.
[33] White, L. & Ortega, J. (2016). *Measured v. Modeled Performance Data Analysis for Affordable Occupied Passive Multifamily Projects.* Presented at the 2016 North American Passive House Conference. Retried from http://www.phius.org/NAPHC2016/White-Ortega_Monitored-Data.pdf

modeled and actual passive building performance using WUFI Passive was difficult to identify during this literature review.

In each of the three case studies presented, actual energy use was higher than predicted by both model methods, though PHIUS+2015 predictions using WUFI Passive were closer to the measured consumption. Findings from the first case showed that PHIUS+ modeling via PHPP greatly underestimated plug loads and lighting consumption. Using WUFI Passive, modeled energy use was 7% lower than actual energy use, while modeled consumption with PHPP was 24% lower than actual consumption. Both modeling approaches underestimated domestic hot water use. WUFI Passive overestimated the energy used in reality by plug loads and lighting, in contrast to PHPP. According to this study, PHPP also overestimated the heating load required by the building to a large degree.

The first case study also showed a breakdown of the worst-performing apartment unit (in terms of energy consumption, referred to as Unit B) compared to an average unit (Unit C), using only WUFI passive results for comparison. The increased consumption of Unit B was driven by high plug load and water heating demands relative to those predicted by WUFI; while in Unit C water heating used more energy than predicted by WUFI, but plug loads and lighting used far less. In the other two case studies, increased observed energy use over modeled predictions was tied to common space energy use.

Section 4 Incremental Costs of Passive Design

Building to passive standards requires certain additional costs compared to a base code building of similar size: additional insulation, high-efficiency windows, detailed air sealing, ventilation equipment, etc. There are also the added costs of contractor training, specialist design consultants and contractors, and the costs of the certification process. Figure 3 below shows an example from PHIUS of their certification fees, broken down by building square footage. Similar numbers were not readily available for PHI certification fees, hence their absence here.

Figure 3: PHIUS Certification Fees[34]

iCFA	0-2,500 ft^2	2501-4500 ft^2	4501+ ft^2	Hourly Rate
Base Fee	$1,500	$2,000	Custom*	$150
PHIUS Professional (CPHC, Builder) & PHAUS Member	$1,275	$1,700	Custom*	$125

*For projects 4501 square feet and larger, a custom quote is required. To request a quote, please email certification@passivehouse.us and provide the estimated iCFA (see Section 4.4.1.4 of the PHIUS+ Certification Guidebook v1.1).

Here are estimated fees for larger buildings:

iCFA	10,000 ft^2	20,000 ft^2	50,000 ft^2	100,000 ft^2	200,000 ft^2	500,000 ft^2
Base Fee	$4,000	$6,750	$11,875	$16,250	$21,875	$33,125
PHIUS Professional (CPHC, Builder) & PHAUS Member	$3,400	$6,150	$11,275	$15,650	$21,275	$32,525

On the other hand, costs are projected to decrease as contractor techniques and training are fine-tuned, and passive buildings provide savings in energy use and maintenance from day one with their higher build quality and increased thermal performance. The literature covering Passive House and incremental cost is built to a large degree on cost estimates and comparisons to different baselines, creating a layer of ambiguity on top of the uncertainty inherent in this fairly new building practice. The consensus suggests there is much work to be done in creating more certainty regarding incremental cost, an issue further complicated by the likelihood that these costs will change as designers and contractors gain experience and fine-tune their approach.

4.1 Sonoma House Passive House Retrofit

The project covered in this study was a Passive House retrofit, which has cost implications that differ from new construction. That said, the findings are useful to show how Passive House measure upgrades price out relative to a more conventional "green building" upgrade, which was the usual standard for this builder. Overall, the cost to retrofit the Sonoma House to Passive House standards was estimated to be $96,000, or an increase of 11% over the cost of a more conventional green retrofit.[35] That equates to an additional $453 monthly payment on a 30-year mortgage at 3.9% APR. Energy bill savings were estimated by BEopt modeling to be $61 per month. A majority of incremental cost was attributed to building envelope upgrades, including added materials, labor, and training for the builder and subcontractors. Window upgrades and the switch to heat pump HVAC were also cited as areas where incremental costs were high. The builder highlighted some lessons learned that he believed would lower incremental costs in the

[34] PHIUS. Retrieved from http://www.phius.org/phius-certification-for-buildings-products/project-certification/submitting-a-project. Accessed on 4/30/19.

[35] German, A., Weitzel, B., Backman, C., Hoeschele, M., & Dakin, B. (2012). *Sonoma House. Monitoring of the First US Passive House Retrofit* (No. DOE/GO-102012-3632). Alliance for Residential Building Innovation (ARBI), Davis, CA (United States)

future, including using a staggered double-stud method for wall assemblies to simplify insulating the building shell.

4.2 Pembina Institute Report – Incremental Costs

Much like their exploration of modeled versus observed energy performance in passive homes, the Pembina Institute collected findings from a variety of projects covered by Passive House literature to explore incremental costs. The overall findings were first, not surprisingly, that incremental costs are higher in initial projects, and decrease as designers and builders gain experience. Overall, incremental costs were below 10% in the majority of cases explored and averaged around 6%.[36] The issue here, which the report touches on, is baselines. In many studies that touch on incremental cost, the methodologies differ, with some compared to a code compliant building in that area, and others using terms like “standard construction costs” and “common” or “typical” practices.

Their data compilation shows examples of some more common building types where passive designs are built within typical construction budgets. Good design choices and cost savings in downsizing certain building aspects like mechanical systems can offset increased costs in other areas (windows, insulation). The report also mentions that costing studies or other estimates on projects in the literature suggest that incremental costs for mid-rise residential buildings in North America can likely be absorbed in typical construction budgets.

Much of these reports revolve around heavy use of estimation and comparisons to differing baselines, so naturally there is a great deal of variation in incremental cost estimates. A more thorough study of two passive homes in Vancouver cited by the Pembina report looked at life cycle costs and compared the builder and homeowner sides from a cost perspective. To achieve a return on investment equal to that of a typical building, the builder would require a price premium not lower than 2.5%, while the buyer would require a price premium of not more than 2% to achieve a positive net present value from energy savings alone.[37] For one of the two passive homes included in the Vancouver study, a 3% price premium would mean a 14-year payback period, while the other home offered a more palatable 5-year payback period for the same premium.

4.3 Brookfield Homes Passive House

The Brookfield Passive House in Colorado was designed as a model home by Brookfield Residential Colorado to enhance its market position as a high efficiency home developer, model advanced building technologies, and to use as a marketing tool aimed at homebuyers. The home sold for $529,000 after originally being priced at $569,000. The incremental cost for upgrading the home to passive design standards was estimated by the builder to be about $85,000, or 18%

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[36] Frappé-Sénéclauze, *Accelerating Market Transformation,* 54

[37] Scott, I., Doucette, J., Grantner, H., & Tuck, R. (2015). *The Business Case for Passive House.* Synergy Sustainability Institute, Vancouver, British Columbia (Canada).

of the base price of the home.[38] The builder assigned the incremental cost increase to individual measures via an estimated breakdown of: $21,000 for improved windows, $28,000 for the HVAC system, $11,000 for upgraded insulation, $15,000 for framing material, exterior insulation, and labor, and $10,000 for miscellaneous other costs. The final sale price did not cover the builder's investment into the Passive House. With it being a model home, contractors had to learn new construction details, which added costs to the project as a foreman had to show them new construction methods prior to the start of construction.

[38] Herk, A., Poerschke, A., & Beach, R. (2016). *Brookfield Homes Passive House Performance Evaluation* (No. DOE/GO-102016-4791). IBACOS, Inc., Pittsburgh, PA (United States)