ASHRAE 90.1 Appendix G/ PHIUS+/Passivhaus Comparison Evaluation for Multifamily Buildings

Final Report

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Advance innovative energy solutions in ways that improve New York's economy and environment.

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Serve as a catalyst – advancing energy innovation, technology, and investment; transforming New York's economy; and empowering people to choose clean and efficient energy as part of their everyday lives.

ASHRAE 90.1 Appendix G/PHIUS+/Passivhaus Comparison Evaluation for Multifamily Buildings

Final Report

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Notice

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Executive Summary

In 2014, Governor Andrew M. Cuomo launched Reforming the Energy Vision (REV), his strategy to build a clean, resilient, and affordable energy system for all New Yorkers. One pillar of REV is the Clean Energy Fund (CEF), which was designed to help the State achieve its goal of reducing greenhouse gas emissions 40% by 2030. The CEF is intended to support market transformation, enabling the creation of a new, integrated, and self-sustaining clean energy market. This comparison study was completed in support of this theme, and specifically to inform NYSERDA's development of the Multifamily New Construction Program (MF NCP) in accordance with the Clean Energy Fund Investment Plan: Resource Acquisition Transition Chapter, dated Feb 28, 2016.

In developing MF NCP, NYSERDA's goals included promoting the design and construction of advanced clean energy buildings, focusing on identifying and supporting market-based solutions. NYSERDA historically supported projects following the ENERGY STAR® Multifamily High-Rise (MFHR) program and wanted to identify alternatives approaches and standards to promote high-performance buildings. Substantial interest in applying Passive House principles to inform this type of design and construction existed in the market, not only for single-family homes, but also in the multifamily market sector. This study was initiated to compare the two market-based Passive House standards with the ASHRAE 90.1 Appendix G Performance Rating Method, the modeling protocol relied on by the U.S. EPA's MFHR program as well as a critical and underlying reference within the 2013 Energy Conservation Construction Code of New York State (ECCC of NYS). The goal of this comparison was to identify equitable performance thresholds, regardless of performance method followed by the project's design team and the certification standard intended to be met by a given project.

Four independent teams with advanced knowledge of Appendix G, Passive House Institute US (PHIUS), and Passivhaus Institute (PHI) protocols and the associated energy modeling tools were asked to create energy models to reflect several configurations of multifamily building designs, applying the protocol with which they are proficient. The building designs ranged from those minimally compliant with 2013 ECCC of NYS to low-energy design alternatives intended to substantially exceed that minimum. All energy models were shared between the teams for peer review and went through many rounds of adjustments. It is important to note that when this study was initiated, the ECCC of NYS referenced ASHRAE 90.1-2010, was the original version used for this study. Subsequently, NYSERDA updated this study to include the new version of U.S. EPA's ENERGY STAR Multifamily High-Rise Simulation Guidelines – Appendix G 90.1-2016 (MFHR SG 2016) for projects in the states with the energy code aligned with ASHRAE 90.1-2013 or later. In addition to incorporating the updated version of ASHRAE 90.1, this analysis also investigated the impact of using source energy to calculate performance thresholds in lieu of energy cost, which has historically been used by NYSERDA's new construction programs. At a future date, NYSERDA expects this initial study will be updated to address relative performance thresholds for low-rise residential homes and buildings.

The results produced by comparing these three protocols for each of the building configurations highlight significant differences. Analysis based on Appendix G predicted the highest energy usage for all cases, while PHI-based calculations predicted the lowest consumption for the same building designs. PHI standards rely on more optimistic assumptions for occupant behavior, as well as for the energy used by systems and equipment not inherent in building design, such as consumer electronics and in-unit lighting. These assumptions are key contributors to this trend, in comparison to those prescribed by EPA's MFHR Simulation Guidelines. The assumptions reflected by these guidelines are based on sources such as Building America and ASHRAE Applications Handbook. Validating the assumptions to determine which ones are more representative of the typical loads and occupant behaviors was beyond the scope of this study. Differences in the modeling rules was another important contributing factor. For example, PHIUS+ and PHI protocols allow credit for the use of manual controls, such as opening windows to provide free cooling, whereas only automatic controls that are inherent in design can contribute toward savings following the Appendix G protocol.

Capabilities of the simulation tools used by each protocol were compared based on the software requirements of ASHRAE Standard 90.1 Section G2.2.1. WUFI and Passive House Planning Package (PHPP) tools, used by PHIUS+ and PHI protocols respectively, do not meet several of those requirements. For example, neither WUFI nor PHPP can explicitly model 8,760 hours per year, 10 or more thermal zones, part-load performance curves for mechanical equipment, and fan power.

The impact of the units of measure used to express building performance was also explored. The key Appendix G metric is Performance Rating, defined as reduction in the energy cost of the proposed design compared to the baseline. PHIUS+ and PHI protocols both require multiple metrics be met to achieve certification, with a maximum source (or primary) energy metric identified as a key metric to be met. Therefore, this study focused on the predicted source or primary energy as a key performance threshold to compare. The source energy metric is calculated using significantly different site-to-source conversions and normalization methods for each standard. PHIUS normalizes usage based on occupancy (kWh/Person-Yr), while PHI normalizes by unit floor area (kBtu/SF-Yr).

Additionally, a comparison of ASHRAE 90.1-2010 and ASHRAE 90.1-2013 was performed. ASHRAE 90.1-2013 is more stringent than ASHRAE 90.1-2010, thus the margin of improvement over 90.1-2013 achieved by each package is expected to be lower than its margin of improvement over 90.1-2010. The results of this additional analysis show that the percent improvement over ASHRAE 90.1-2013 is 3-4% lower than the percent improvement over ASHRAE 90.1-2010, which aligns with the anticipated changes. In this study, the impact of using source energy in lieu of energy cost to determine percent improvement was investigated. The results of this investigation differed between the proposed packages, depending on the relative contribution of electricity and gas toward the package's total energy use. However, using source energy is a critical element of how performance improvement should be measured for buildings relying on electricity in lieu of natural gas or other fossil fuels to deliver space heating, as using energy cost does not provide an accurate reflection of the impact of choosing different fuels.

The study results and methodology may help this team establish equitably stringent performance thresholds for the three protocols. Areas of focus that may warrant further investigation are identified, and potential solutions to improve consistency with each protocol are discussed.

1 Purpose and Methodology

The study compared the PHIUS+, PHI, and ASHRAE Standard 90.1-2010 Appendix G protocols, seeking to identify performance targets predicted when following each standard, to allow projects to follow any of the three alternative protocols to qualify for the support and incentives offered through NYSERDA's new Multifamily New Construction Program (MF NCP). The intent is for buildings to be designed and constructed in a manner that will achieve similar energy performance, independent of the original performance standard relied on to guide the project's design.

It is important to note that a key goal of this study was to establish the approximate mapping between the native performance metrics of Appendix G, PHIUS+, and PHI protocols as they would be applied in real-world (i.e., non-research) context. The examined protocols assume different operating conditions, such as lighting runtime hours and thermostat setpoints, and different energy use of systems and equipment not shown on drawings, such as kitchen appliances and consumer electronics in apartments. As such, it was expected that the energy usage estimated by each protocol for the same design would differ.

A case study of a typical high-rise multifamily building designed and constructed in New York State was developed based on the DOE/PNNL Prototype Models. Several packages of improvements were considered for the case study, based on building design components that are common for projects participating in MF NCP. Each design package was modeled by the four independent teams described in Table 1. All models were shared between the teams to enable peer review and went through multiple rounds of adjustments in response to the comments.

Table 1. Protocols and Team Overview

	Guiding Documents	Simulation Tool	Teams
Appendix G	ASHRAE Standard 90.1 2010 Appendix G; EPA Energy Star MFHR Simulation Guidelines	eQUEST v3.65	**Appendix G Team:** Maria Karpman and Mike Karpman (Karpman Consulting)
Appendix G – ASHRAE 2013	ASHRAE Standard 90.1 2016 Appendix G; EPA Energy Star MFHR Simulation Guidelines – Appendix G 90.1-2016	eQUEST v3.65	**Appendix G Team:** Maria Karpman and Nick Allen-Sandoz (Karpman Consulting)
PHIUS+	PHIUS+ Certification Guide Book V1.01	WUFI V.3.0.3.0	**PHIUS Team:** James Ortega and Katrin Klingenberg (Passive House Institute US)
Passivhaus	PHPP v9.5 – PH Classic	PHPP v9.5	**PHI Team 1**: Lois B. Arena (SWA) **PHI Team 2**: Jessica Grove-Smith (Passivhaus Institute)

The following variations of the case study were analyzed:

Base Case: ASHRAE 90.1-2010 Appendix G Baseline Design, or, for the ASHRAE 90.1-2013 model only, per ASHRAE 90.1-2016 Appendix G Baseline Design.
Package A: Base Case modified to include building components found in better performing MF NCP projects. The modifications to the building design for this package included improved envelope, condensing boilers for space and service water heating, higher performing cooling system, improved fan control, improved in-unit and corridor lighting, ENERGY STAR® appliances, and low-flow fixtures.
Package B: Same as Package A, but with exhaust air heat recovery added to the corridor rooftop unit.
Package C: Same as Package B, but with the Variable Refrigerant Flow (VRF) heat pumps in apartments instead of the hydronic baseboards and room air conditioners.
Package D: Similar to Package B, but with additional measures reflecting certification requirements and common features found in PHIUS projects, as proposed by PHIUS Team.
Package E: Similar to Package B, but with additional measures reflecting certification requirements and common features found in PHI projects, as proposed by PHI Team 1.
Package F: Similar to Package C, but with additional measures reflecting certification requirements and common features found in PHI projects as proposed by PHI Team 2.

The optimal package to achieve high-performance will vary for each building. The configurations reflected in Packages D, E, and F are not the only possible solutions and may not be the best choice for every building. Real-life project designs must be optimized based on actual climate data and specific project requirements such as cost effectiveness.

Each package was modeled following PHIUS+, PHI, and Appendix G guiding documents and simulation tools as shown in Table 1. The packages modeled by each team are shown in Table 2.

Table 2. Models Completed by Each Team

	Base Case	Package A	Package B	Package C	Package D	Package E	Package F
Appendix G Team	x	x	x	x	x	x	x
PHIUS Team	x	x	x	x	x		
PHI Team 1	x	x	x	x		x	
PHI Team 2	x	x	x	x			x

For the ASHRAE 90.1-2010 models, the performance rating was calculated following ASHRAE 90.1-2010 Appendix G section G1.2, which states:

Performance Rating (% above code) = 100 x (BBP – PBP) / BBP

where:

PBP = Proposed Building Performance. The annual energy cost of the proposed building design including both regulated and unregulated energy use.

BBP = Baseline Building Performance. The annual energy cost of the baseline building design including both regulated and unregulated energy use.

The methodology of calculating the percent improvement over code for ASHRAE 90.1-2013 models, which was based on the MFHR Simulation Guidelines – Appendix G 90.1-2016 differs from the methodology used for ASHRAE 90.1-2010.

PCI = PBP / BBP

PCI_t = (BBUEC + (BPF x BBREC)) / BBP

Performance Rating (% above code) =100 x (PCI_t−PCI) / PCI_t

where:

PCI = Performance Cost Index. The new metric used to rate building performance used by ASHRAE 90.1-2016 Appendix G.

PCI_t = The maximum Performance Cost Index (PCI) for a proposed design to comply with a particular edition of Standard 90.1.

BBUEC = Baseline Building Unregulated Energy Cost. The portion of the annual energy cost of a baseline building design that is due to unregulated energy use, calculated by subtracting regulated energy cost from total energy cost.

BBREC = Baseline Building Regulated Energy Cost. The portion of the annual energy cost of a baseline building design that is due to regulated energy use, calculated by multiplying the total energy cost by the ratio of regulated energy use to total energy use for each fuel type.

BPF = Building Performance Factor; Following MFHR SG 2016, BPF=0.83 was used in the calculation based on 90.1-2013 reference edition of the standard and Climate Zone 4A.

In addition to analyzing the results of ASHRAE 90.1-2013 models using energy cost to determine the percent improvement over code, this study also investigated the percent improvement beyond code using source energy. The site-to-source conversion used for this study were based on the current State conversion factors of 1:2.55 for electricity and 1:1.05 for natural gas (NYSERDA Overlay). For source energy comparison, BBUEC, BBREC, and BBP were expressed in units of source energy instead of energy cost when calculating percent improvement over code. For the cost-based comparison, the fuel costs used in the original study were preserved.

2 Base Case Descriptions

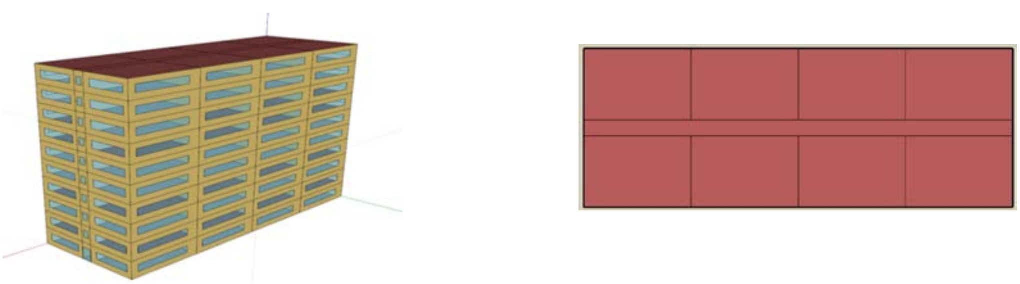
2.1 Baseline Configuration for ASHRAE 90.1-2010 and Passive House models

2.1.1 General Configurations

The building configuration was based on the PNNL high-rise multifamily building prototype. The PNNL prototype models are used by the DOE to evaluate the impact of changes in energy code (ASHRAE Standard 90.1) on the U.S. commercial building stock. PNNL prototypes in Climate Zone 4A are modeled using the Baltimore weather file. Since the study is focused on New York, the Queens, NY weather file was used instead of Baltimore. The key parameters of the case study are summarized as follows:

- Ten-story apartment building—84,360 sf2
- Located in Queens, NY
- Eight, two-bedroom apartments on each floor—the ground floor has seven apartments and a lobby
- No exterior or interior shading
- Windows account for 30% of gross exterior wall on each exposure
- Long axis is along north-south
- Slab-on-grade foundation

Figure 1. Prototype Elevation and Plan Views



2.1.2 Envelope

- Steel-framed walls, U-0.064
- Flat roof insulated entirely above deck, U-0.048
- Operable steel-frame windows, NFRC rating U-0.55/SHGC-0.4
- Slab-on-grade foundation, R-10 insulation for 24”
- Infiltration 0.4 cfm/ft^2 of the building envelope at 75Pa—the default air leakage prescribed by 90.1-2013 Appendix G for all buildings where air-leakage testing was not performed

2.1.3 HVAC

Mechanical system type and efficiency is based on Appendix G: Baseline Design for Residential Occupancies.

2.1.3.1 Apartments

- Each apartment served by packaged terminal AC unit(s) (PTAC) with hot water coils and DX cooling
- Hot Water to PTACs provided by 80% efficient natural draft fossil fuel boiler oversized by 25% relative to the heating load
- Cooling capacity of each PTAC is oversized by 15% relative to the cooling load; EER 11.4 cooling efficiency
- PTAC fans run continuously at 0.3 W/CFM
- 20 CFM continuous/50 CFM intermittent exhaust per bathroom, 100 CFM intermittent per kitchen (NYS Mechanical Code)

2.1.3.2 Corridors

- Each corridor served by PTAC (same as apartments)
- Heating and cooling efficiencies and sizing same as in apartments, except EER 9.3 cooling efficiency
- Outdoor air 0.06 CFM/SF (500 CFM total) based on NYS Mechanical Code
- PTAC fans run continuously at 0.3 W/CFM

2.1.4 Service Water Heating

Service water heating system type and control based on PNNL prototype; efficiency based on minimum mandatory and prescriptive requirements of ASHRAE 90.1, hot water demand based on the EPA's MFHR Simulation Guidelines.

- Central 80% efficient water heater
- A 600-gallon storage tank
- Setpoint at 140°F
- Faucets and showerheads minimally compliant with 1992 EPACT (2.5. gpm per fixture)

2.1.5 Lighting and Plug Loads

- Apartment lighting: 0.7 W/SF
- Corridor lighting: 0.66 W/SF
- Lobby lighting: 1.3 W/SF
- No exterior lighting
- Plug loads as prescribed by each protocol
- One traction elevator
- Occupancy as prescribed by each protocol, assuming each apartment has two bedrooms

2.2 Baseline Configuration for ASHRAE 90.1-2013 Model

The 2016 ECCC of NYS, which references ASHRAE 90.1-2013 with addenda, was adopted in October 2016. To support the analysis, a new baseline model was developed for the packages used in the original study following the rules MFHR SG 2016. The changes to the baseline are summarized below.

2.2.1 Envelope

- Non-residential above grade exterior walls for lobby & corridor changed from U- 0.063 to U-0.124.
- Roof changed from U-0.048 to U-0.063
- Windows changed from U-0.55 / SCHG 0.4 to U-0.57 / SHGC 0.39

2.2.2 Lighting

- Apt LPD changed from 0.7 W/SF to 1.1 W/SF
- Lobby LPD changed from 0.9 W/SF to 1.3 W/SF
- Corridor LPD changed from 0.66 W/SF to 0.83 W/SF

2.2.3 Water-Side HVAC

- Boiler efficiency changed from 80% to 75%

2.2.4 Air-Side HVAC

- Apt PTAC Cool-EIR changed from 0.2590 to 0.3169
- Corridor PTAC Cool-EIR changed from 0.3170 to 0.2682

3 Energy Efficient Packages

Packages A, B, and C were specified based on the Base Case 1, with the commonly improved building components found in projects that participated in the previous rounds of NYSERDA's multifamily programs. In addition, PHI teams 1 and 2, as well as the PHIUS team each defined and modeled a high-performance package of their choice. Appendix G models were developed for all packages. Configurations for all packages are shown in Table 3.

Table 3. Modeled Configurations

Envelope							
	Base Case	**Package A**	**Package B**	**Package C**	**Package D**	**Package E**	**Package F**
Exterior Walls	U-0.064	U-0.054 (R-10ci instead of R-7.5ci)			Same as A - C	Same as A - C	U-0.042
Exterior Shading	None	None			Interior blinds on all windows, 5' overhangs on the 1st floor windows/doors, 1.5' window overhangs on top floor on all facades.	Same as A - C	Default temporary shading in summer (reveals, surroundings etc.) for all fenestration
Roof	U-0.048	(R-25ci instead of R-20ci)			Same as A - C	Same as A - C	Same as A - C
Windows	NFRC U-0.55 (metal framing)	NFRC U-0.32			NFRC U-0.2785	NFRC U-0.14	NFRC U-0.15
	SHGC – 0.4	SHGC - 0.33			SHGC - 0.24	SHGC - 0.27	SHGC - 0.3
Slab-on-grade	R-10 for 24"	R-15 for 24"			Same as A - C	Same as A - C	Same as A-C
Infiltration at wind pressure	0.186 ACH	0.186 ACH			0.017 ACH	0.03 ACH	0.05 ACH

HVAC - Apartments							
	Base Case	**Package A**	**Package B**	**Package C**	**Package D**	**Package E**	**Package F**
Heating System Type	PTAC	Hydronic baseboard		VRV IV heat pumps Daikin FXDQ indoor REYQ144T outdoor units	Same as B	Same as B	Same as C
Heating plant	Natural draft boiler	Condensing boiler		NA			
Rated heating plant efficiency	80%; 180F supply, 50F design temperature drop	95%		COP 3.7 (COP 4.0 excluding indoor fan power)			
Cooling system type	PTAC	Room AC		Daikin VRF per above			

Table 3 continued

HVAC - Apartments							
	Base Case	**Package A**	**Package B**	**Package C**	**Package D**	**Package E**	**Package F**
Cooling efficiency	11.4 EER	13 EER		EER 12.4 (COP 3.9 excluding indoor fan power)	COP 3.8 (13 EER)	Same as B	Same as C
Supply Fan	Running continuously 0.257 W/CFM	No supply fan for heating, room AC fan cycles with load 0.257 W/CFM		Cycling with heating/cooling load 0.214 W/CFM	Same as B	Same as B	Same as C
Exhaust Fan	55 CFM continuous bathroom exhaust, 100 CFM intermittent kitchen exhaust 2.8 cfm/W				Ventilation rate reduced to 0.3 ACH	Same as B	See Energy Recovery
Energy Recovery	None				Balanced HRV, 75% recovery effectiveness, 0.8 W/CFM fan, 63 CFM per apartment (Note 1)	Balanced HRV 75% recovery effectiveness, 1.2 W/CFM fan 63 CFM per apartment (Note 1)	Balanced ERV 80%/60% sensible/ latent effectiveness; 0.76 W/CFM; 3,577 CFM apartments + corridors, w/summer bypass

HVAC - Corridors							
	Base Case	**Package A**	**Package B**	**Package C**	**Package D**	**Package E**	**Package F**
Heating System Type	PTAC	Rooftop unit			Same as A- C	Same as A- C	VRV Heat pumps, same as Apt Package C
Heating plant	Natural draft boiler	Gas furnace			Condensing boiler	Same as A- C	NA
Rated heating efficiency	80%	82%			90% boiler	Same as A- C	COP 3.7 (COP 4.0 excluding indoor fan power)
Cooling system type	PTAC	DX cooling			Same as A- C	Same as A- C	Daikin VRF per above
Cooling efficiency	EER 9.3	EER 13			Same as A- C	Same as A- C	EER 12.4 (COP 3.9 excluding indoor fan power)
Exhaust Air Energy Recovery	None	None		Yes, 85% effectiveness	Same as B- C	Cycling with heating/cooling load 0.214 W/CFM	Included under HVAC – Apts, Energy Recovery
Supply Fan	Running continuously 0.3 W/CFM	Running continuously 0.7 W/CFM		Running continuously 1.2 W/CFM (1.4" increase in total pressure drop)	Same as B- C	Same as B- C	Cycling VRV, plus ERV (see Apartment Energy Recovery)

Table 3 continued

Service Water Heating							
	Base Case	**Package A**	**Package B**	**Package C**	**Package D**	**Package E**	**Package F**
Boiler efficiency	80%	95%			Same as A- C	Same as A- C	Same as A-C, but 8 Btu/hr-F heat loss
Hot water demand	All fixtures 2.5 gpm	Low flow fixtures 1.5 gpm showerheads / kitchen faucets, 0.5 gpm lavatory faucets			Same as A- C	Same as A- C	6.6 gal/day/person
Internal Loads and Lighting							
	Base Case	**Package A**	**Package B**	**Package C**	**Package D**	**Package E**	**Package F**
Apartment lighting	0.7 W/SF	0.5 W/SF			Same as A- C	PHI default, 14 W/person for 2900 hours per year (174 people).	PHI default, 7,249 kWh/yr. equivalent to 0.28 W/SF
Corridor lighting	0.66 W/SF	0.5 W/SF			Occupancy sensors (25% reduction in usage)	Same as Package A-C	Reduced by 80%, to 0.28 W/SF+ daylighting + occupancy sensors
Appliances	Regular refrigerator	Energy Star refrigerator			Same as A- C	Same as A- C	Same as A-C
Elevator	5000 kWh/yr				4000 kWh/yr (ThyssenKrupp elevator calculator and rounded to 1,000 kWh)	Same as A- C	4500 kW/yr

Notes:

* Sixty-three CFM per apartment continuous HRV ventilation was calculated based on MF NCP tool calculation, as equivalent to 55 CFM continuous plus two hours/day 100 CFM intermittent.

** The baseline fan power in apartments was allocated between PTAC supply and kitchen and bathroom exhaust fans, with the total equal to 0.3 W/CFM as required by Appendix G.

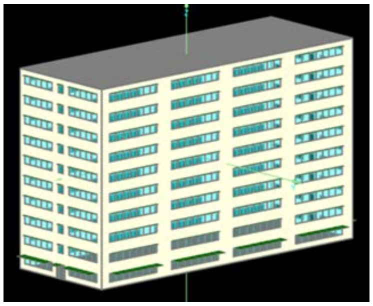
*** Infiltration reduction does not qualify for performance credit under the MF NCP rules in effect at the time of the study but was modeled at 100% of the specified rate for all packages.

3.1 Measures in Packages D, E, and F excluded from Appendix G models

3.1.1 Package D (defined by PHIUS team)

Measure: Each window 'strip' was input as multiple smaller 4x4 windows.

Figure 2. Window Modeling Simplification



Exclusion Rationale: Modeling windows as a single strip for each thermal block is a simplification allowed by 90.1 and is expected to be energy neutral because the NFRC rating (U-value and SHGC) remains unchanged and is based on the case study description.

Measure: Site shading was modeled as 20% shading reduction for all facades for winter and summer to simulate a city-like environment.

Exclusion Rationale: Site shading is not treated as an improvement over baseline with Appendix G protocol, because the baseline design would also be modeled with the same site shading. In other words, projects that have site shading, such as from the surrounding buildings in an urban setting, are modeled with site shading, however, the equivalent shading is included in the baseline.

Measure: Interior blinds entered for all windows with a 25% shading reduction factor incorporated (75% solar availability).

Exclusion Rationale: Appendix G does not allow credit for any manual controls since they depend on occupants' behavior and are not an inherent attribute of the design. Such controls are modeled energy neutral (the same) in the baseline and proposed models.

Measure: Summer night ventilation at 0.1342 ACH based on 30% of the operable windows being counted up to 4" open.

Exclusion Rationale: Same as previous measure. Appendix G does not allow credit for any manual controls.

Measure: Interior walls specific heat capacity of 23 Btu/SF-F (from 11 Btu/SF-F in Packages A through C).

Exclusion Rationale: Interior walls are not regulated by ASHRAE 90.1 and, therefore, must be modeled energy neutral.

Measure: Four water heaters with 150-gallon storage tanks each instead of a single water heater.

Exclusion Rationale: With PHIUS protocol, this measure decreased the circulation pipe lengths compared to a single 600-gallon storage system, creating a more efficient circulation piping layout. Appendix G protocol does not take distribution losses into account, thus there is no performance credit from the measure.

3.1.2 Package E (defined by PHI Team 1)

Measure: In-unit lighting was reduced from 0.5 W/SF in Packages A through C to 14 W/person in Package E, which is the standard assumption used in Passivhaus certification.

An average wattage is 14W per person when lighting is on (for eight hours per day). This accounts for the assumption that not all lights are turned on throughout the apartment (i.e., a reduction factor with respect to the installed power density to account for fact that, for example, lights are off in the kitchen or bathroom when these rooms are not in use). The standard protocol for residential projects is to use the default PHPP lighting. The consultant/certifier checks whether efficient lighting fixtures have been installed, but does not enter the actual specified W/ft² into the model. Package E apartment lighting was set to PHPP default of 7,249 kWh/yr.

Exclusion Rationale: With Appendix G method, in-unit lighting in the proposed design is modeled the same as in the baseline if fixtures are not specified, and as a default approach. Thus improvement to in-unit lighting was not modeled.

Measure: Interior blinds were modeled.

Exclusion Rationale: Features that depend on manual controls cannot contribute toward savings using the Appendix G protocol.

Measure: Ventilation in apartments is reduced.

Exclusion Rationale: Ventilation in Base Cases and Packages A through C is already the minimum required by code. Furthermore, Appendix G allows ventilation reduction credit only if Demand

Control Ventilation (DCV) is specified. Otherwise, it should be modeled the same in the baseline and proposed models except if the proposed ventilation exceeds minimum code requirements, in which case the baseline is modeled as matching code.

3.1.3 Package F (defined by PHI Team 2)

Measure: Reduction in in-unit lighting modeled with package F reflects Passivhaus default (i.e., protocol assumption).

Exclusion Rationale: See discussion for in-unit lighting reduction in Package E.

Measure: Some additional temporary shading was included into Passivhaus model during summer for non-opaque envelope, based on a PHPP default value meant to reflect typical shading from reveals, surroundings, etc.

Exclusion Rationale: With Appendix G protocol, site shading (e.g., shading from surrounding buildings) must be modeled the same between the baseline and proposed design, based on the actual site conditions. Shading that is inherent in design, such as reveals, can be modeled for the proposed design, and contribute toward the savings. In Appendix G model, the exterior shading integral to the building (e.g., reveals, etc.) was approximated by adding 0.3 feet deep overhangs, left, and right fins on all windows, but other shading types were not included.

Measure: Savings associated with occupants manually opening windows.

Exclusion Rationale: Manual controls cannot contribute towards savings following Appendix G protocol.

Measure: The total average ventilation for corridors and apartments was modeled as 3,577 CFM.

Exclusion Rationale: Ventilation prescribed in the baseline and packages A through C was based on minimum required by code. Thus, ventilation reduction was not modeled in Appendix G version of this package.

3.2 Package changes for ASHRAE 90.1-2013 Appendix G Model

Package A-F as described above were not changed for the ASHRAE 90.1-2013 analysis, even though some differences are expected. For example, ASHRAE 90.1-2013 requires daylighting in corridors and lobby, which must be explicitly modeled; however, daylighting was not included in any of the packages in the original study. The impact of such differences is likely small and will not affect the findings.

4 Results

Table 4 shows energy consumption for Packages A through F with ASHRAE 90.1-2010 Appendix G, PHI, and PHIUS protocols. The metric that may be used to establish MF NCP performance thresholds in each protocol is highlighted in brown.

Table 4. Simulation Results by Package and Protocol

	Baseline			Package A			Package B			Package C			Package D (PHIUS)		Package E (PHI, Team 1)		Package F (PHI, Team 2)	
	Base Case App G / eQUEST	PHIUS, WUFI	PHI, PHPP, Team 2	App G / (eQUEST)	PHIUS (WUFI)	PHI (PHPP, Team 2)	App G / (eQUEST)	PHIUS (WUFI)	PHI (PHPP, Team 2)	App G / (eQUEST)	PHIUS (WUFI)	PHI (PHPP, Team 2)	PHIUS (WUFI)	App G / (eQUEST)	PHI (PHPP, Team1)	App G (eQUEST)	PHI (PHPP Team 2)	App G (eQUEST)
Performance Rating (% $ better than code)	0%	0%	15%	30%	8%	22%	29%	10%	22%	23%	6%	21%	28%	39%	39%	35%	48%	40%
HEATING DEMAND (kBtu/ft2.yr)	15.32	11.21	14.7	11.43	11.81	10.6	11.29	10.54	4.0	11.41	10.54	10.0	4.07	8.06	3.21	8.90	2.9	7.88
HEATING LOAD (Btu/hr.ft2)	17.4	9.34	9.6	9.9	10.75	7.4	9.5	10.17	7.2	5.8	10.17	7.2	3.86	5.1	3.21	3.8	3.5	3.7
COOLING DEMAND (kBtu/ft2.yr)	3.5	11.98	8.3	2.0	11.05	7.4	2.1	10.99	7.5	1.8	10.99	7.5	4.87	1.8	4.98	2.4	4.3	1.9
COOLING LOAD (Btu/hr.ft2)	15.3	4.58	6.4	11.4	4.2	5.4	11.3	4.12	5.3	11.4	4.12	5.3	2.26	8.1	2.83	10.0	3.0	7.9
PRIMARY ENERGY	10,257	7,409	7,724.3	7,289	6661	5,873	7,266	6486	5,818	7,324	6373	5,224	4962	6,015	4,267	6,314	3,533	5,699
PRIMARY ENERGY kBtu/SF-	98.3	72.8	60.4	69.9	65.5	45.9	69.7	63.7	45.5	70.2	62.6	40.9	48.8	57.7	33.37	60.5	27.6	54.6
SITE ENERGY (kBtu/ft2.yr)	52.0	37.0	37.4	38.3	33.01	27.3	37.1	31.59	26.8	27.1	24.76	19.5	22.12	26.6	18.02	25.6	13.5	21.5
Energy consumption by end use																		
Cooling kWh	87,874	93,922	59,911	50,829	70,154	64,176	52,352	69,747	43,521	45,499	69,747	43,422	37,815	45,226	26414	60,721	25,113	48,217
Heating kWh	-	0	-	1,266	0	-	1,205	0	71,059	111,826	74,940	74,017	0	485		241	22,251	27,320
Pumps kWh	2,604	7,579	2,505	4,548	7,579	2,505	4,726	7,579	2,505	2,071	7,579	2,505	5,079	2,380	2523	1,425	2,505	3,894
Lighting kWh	105,806	89,912	66,542	72,828	78,272	49,622	72,828	78,272	49,622	72,828	78,272	49,622	71,489	63,674	43665	72,828	14,573	58,181
Plug Loads kWh	190,456	158,530	107,716	182,311	150,456	99,639	182,311	150,456	99,605	182,311	150,456	99,605	149,456	181,402	76300	182,311	101,061	182,264
Fans kWh	130,350	15,615	48,503	39,617	34,358	18,719	50,159	32,886	20,909	79,646	32,886	20,909	28,074	58,469	51475	80,967	23,955	58,752
Total kWh	517,090	365,558	285177	351,399	340,819	234662	363,581	338,940	287221	494,181	413,881	290080	291,912	351,636	200377	398,493	189457	378,628
Space Heating Therms	17,362	11,576	13,875	14,589	10,415	8,726	13,172	9,304	990	285	1,130	1,037	3,719	4,758	2,711	2,281	0	-
DHW Therms	8,871	6,091	4,720	5,692	5,103	3,974	5,691	5,111	3,974	5,695	5,111	3,974	4,724	5,689	3,982	5,682	3,744	5,255
Total Therms	26,233	17,667	18,595	20,281	15,518	12,701	18,863	14,415	4,964	5,980	6,241	5,012	8,443	10,447	6,693	7,963	3,744	5,255
Total Energy Cost	$ 103,796	72,501	61,371	$ 73,055	66,641	$ 47,900	$ 73,470	65,256	$48,047	$ 80,226	68,323	$ 48,524	52,229	$ 63,191	36,750	$ 67,807	32,162	$62,059

Table notes on next page

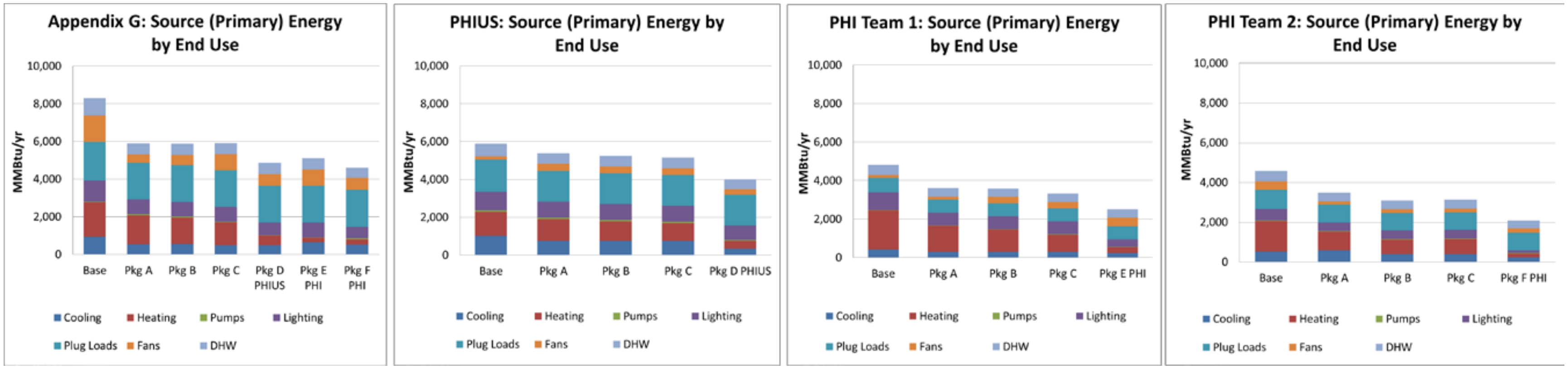
Notes for Table 4:

- All results are site energy unless noted as primary (source) energy.
- The following site to source (primary) energy conversions were used:
  - Appendix G: 3.14 for electricity, 1.05 for gas (based on EPA Portfolio Manager).
  - PHIUS: 3.16 for electricity; 1.1 for gas.
  - PHI: 2.6 for electricity; 1.1 for gas. PHI allows adapting conversion factors for electricity in PHPP, based on national or regional data. Those factors applied to NYS and/or U.S. projects could be changed in the future. The Primary Energy targets would be adjusted to allow the higher source energy use associated with those higher or adjusted conversion factor.
- Energy Cost is based on $0.15/kWh (electricity) and $1/therm (gas) for all protocols.
- Some of the measures in PHIUS and PHI packages were excluded from the corresponding Appendix G simulations for reasons described in the previous section. Therefore, the impact of these measures was reflected in the results from PHIUS and PHI teams, but not in Appendix G results for these packages.

4.1 End Use Analysis

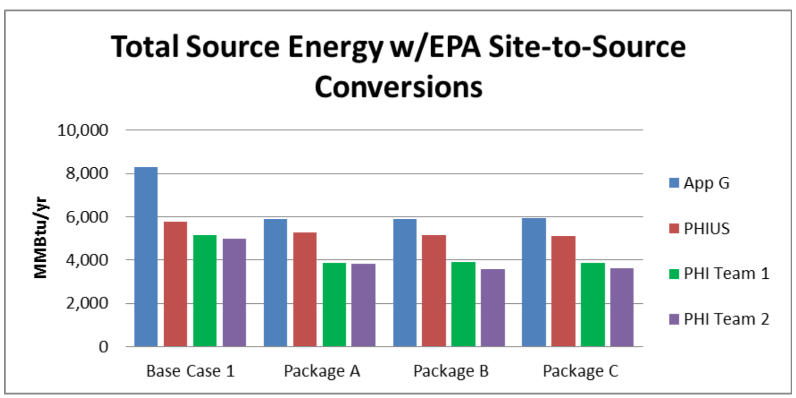
Source energy usage using native site-to-source conversion for all packages with each method is shown in Figure 3. Appendix G protocol results in higher (more conservative) usage across the board, followed by PHIUS, and then PHI. The difference in results between the protocols is significant; for example, the total source energy for the Base Case 1 (configuration minimally compliant with ASHRAE 90.1-2010) following the Appendix G protocol is almost twice that of PHI.

Figure 3. Annual Source Energy by Protocol and End Use (Native Site-to-Source Conversions)



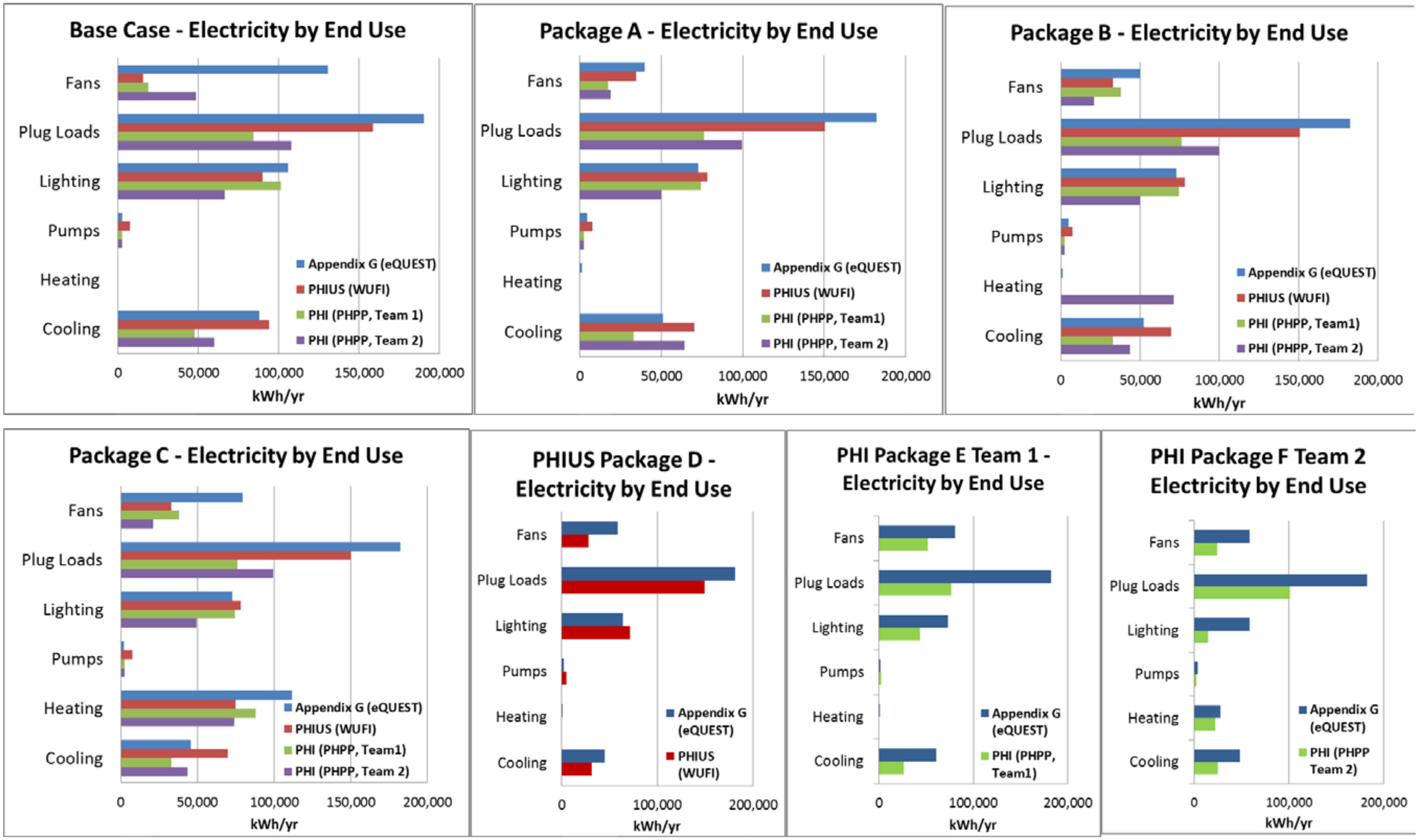
Different electricity site-to-source conversions account for difference in the total source energy use between the protocols; however, even after the same (EPA Portfolio Manager-based) site-to-source conversions are applied across the board, the patterns are largely unchanged as shown in Figure 4.

Figure 4. Annual Source Energy by Protocol (using EPA Portfolio Manager Site-to-Source Conversions)



Electricity consumption broken out by end use for all packages and protocols is shown in Figure 5.

Figure 5. Electricity consumption by End Use for all Packages and Protocols



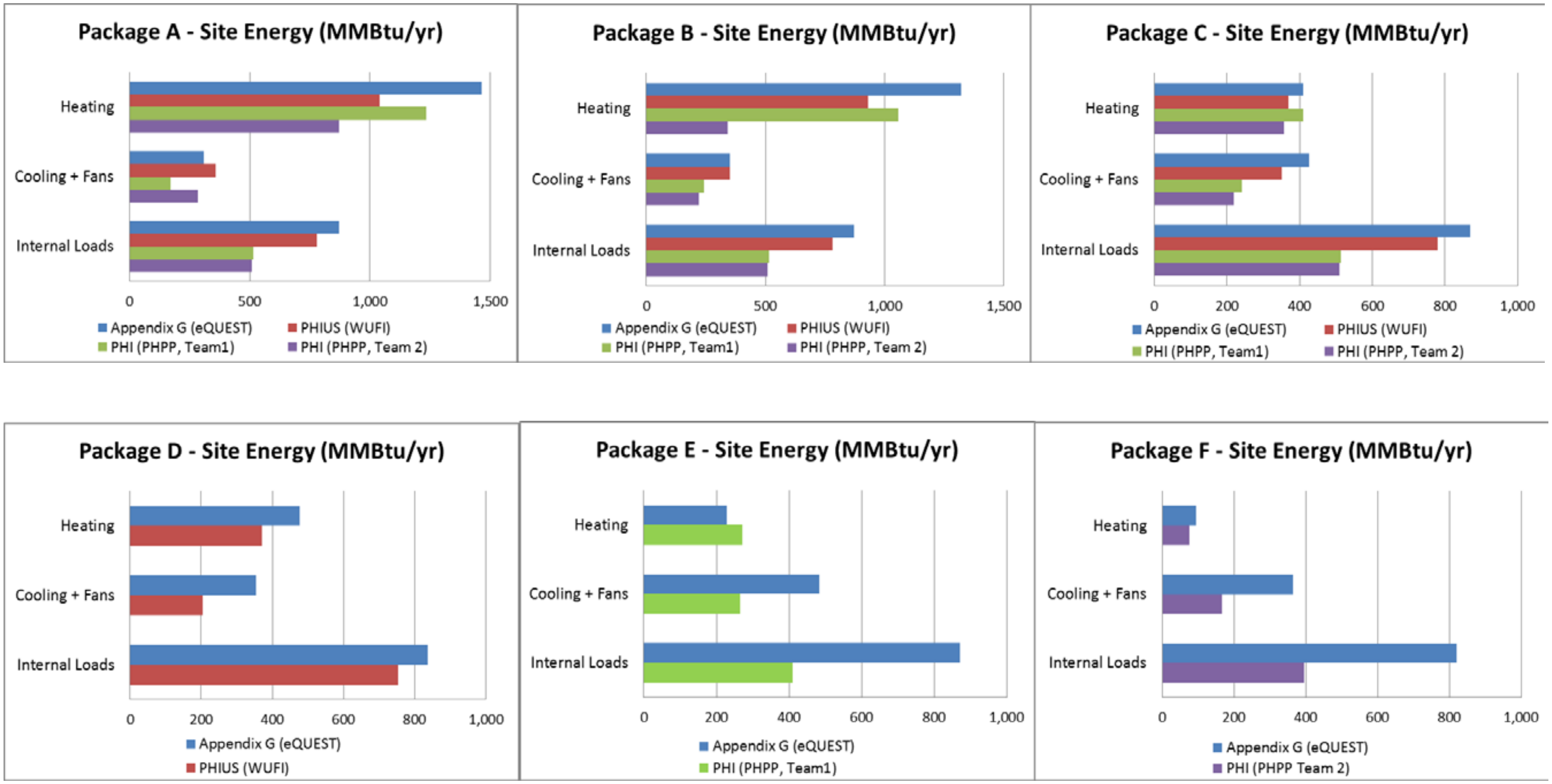
The Plug Loads category accounts for the largest share of electricity consumption with all protocols, but its magnitude varies significantly. For example, the usage associated with plug loads in PHI models is about 50% less than the plug loads with Appendix G protocol and PHIUS is 17% lower than Appendix G. This end-use category includes elevator, kitchen appliances, consumer electronics, and miscellaneous other equipment that is not shown on drawings but is typically present in multifamily buildings and contributes to electricity usage. Except for the elevator, these loads were not included in the case study description and were based on the defaults prescribed by each protocol. Variations in this category are expected due to differences in the protocols' assumptions, but the magnitude of the difference appears excessive, and warrants further investigation. Aside from affecting the total electricity consumption, plug loads interact with heating and cooling and significantly impact the total energy use of high-performance buildings.

Lighting is the second largest electricity end use for most packages. There is a notable difference in how in-unit lighting is treated by Appendix G protocol compared to PHIUS and PHI. With Appendix G, it was modeled as prescribed by MF NCP simulation guidelines at 0.7 W/SF, based on the maximum lighting power density prescribed for multifamily buildings in NYS ECCC. Performance credit is allowed only for the hard-wired fixtures shown on drawings and typically only in spaces where lighting is fully specified (e.g., bathrooms, kitchens, closets) and meets IESNA-recommended illuminance levels. No performance credit can be documented for spaces where tenants' plug-in lighting fixtures (e.g., living rooms and bedrooms). On the other hand, both PHI and PHIUS protocols use default lighting usage (kWh/hr) based on the default assumptions irrespective of whether any fixtures are specified.

Cooling and fans are the other two significant electricity end uses in all three protocols. Fan energy is higher in Appendix G models compared to the PHIUS and PHI models for all packages, which is expected since the simulation tools used by PHI and PHIUS protocols do not model heating/cooling fans explicitly, but the fans are included in the cooling end use. ASHRAE 90.1 requires fan energy to be extracted from efficiency ratings and modeled explicitly, which captures continuously running heating/cooling fans such as in the PTACs, and fan energy consumption associated with heating, for the Base Case. This is further discussed in the section about tool capabilities.

Figure 6 shows combined cooling and fan energy, combined internal gains (plug loads and lighting), and heating, all expressed as site energy to provide comparison between the end uses for each package with the three protocols.

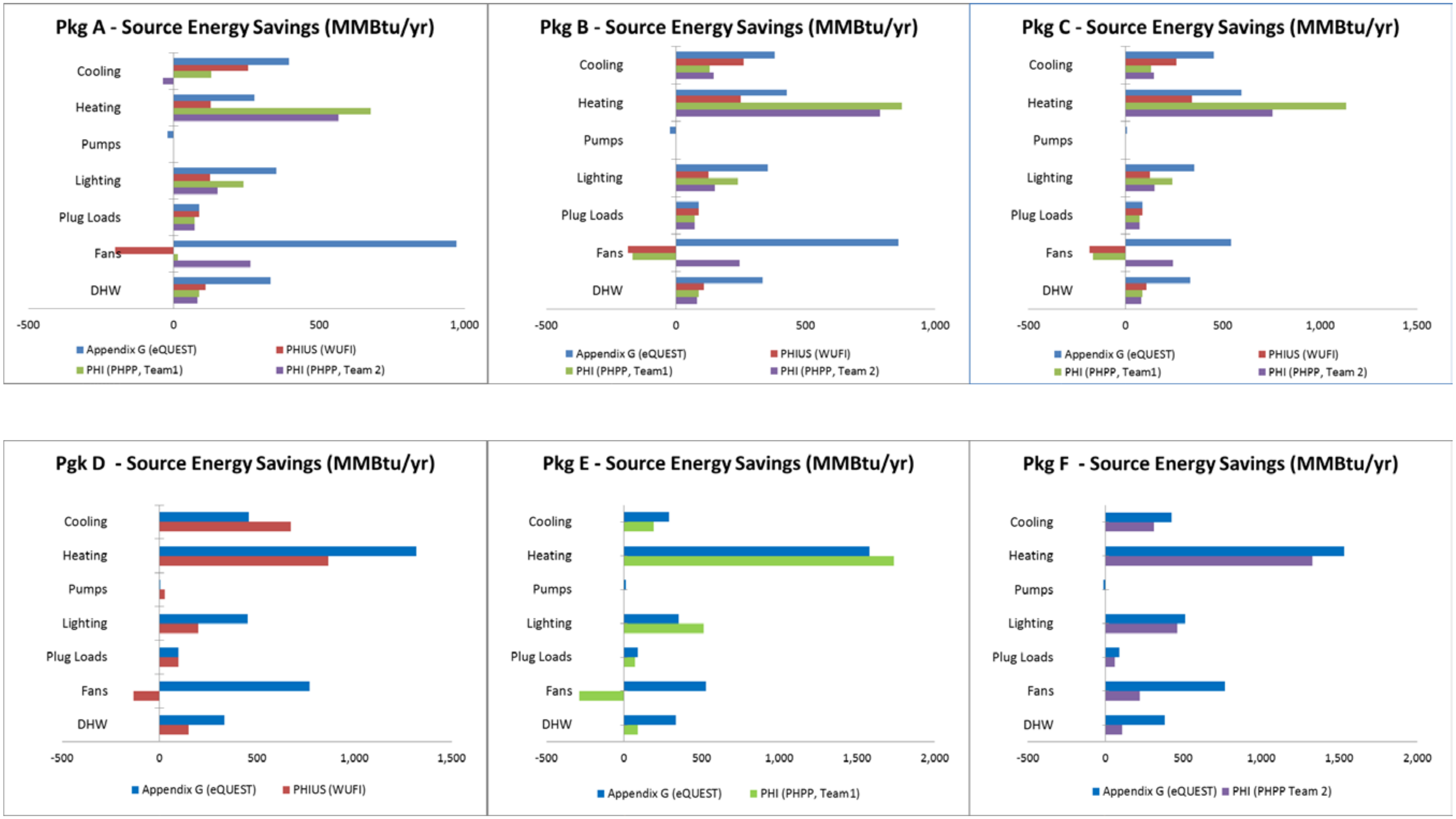
Figure 6. Package Site Energy by Protocol and Aggregated End Uses



Since envelope and mechanical system efficiencies were prescribed, the protocols with lower internal gains are expected to have higher heating and lower cooling energy. This trend held true between PHIUS and PHI. That said, PHI has much lower internal loads, higher heating, and lower cooling than PHIUS for packages A through C. However, Appendix G shows higher consumption for all end uses in the majority of packages except for PHIUS cooling in packages A and B, and PHI heating in packages C and D. This may be due to the difference in tool algorithms or inputs that affect results but were not directly prescribed in the case study description.

Source energy savings by end use for each package and protocol are based on the site-to-source conversions native to each protocol, as illustrated in Figure 7. The savings are relative to the baseline modeled with the corresponding protocol.

Figure 7.Source Energy Savings by Package and End Use

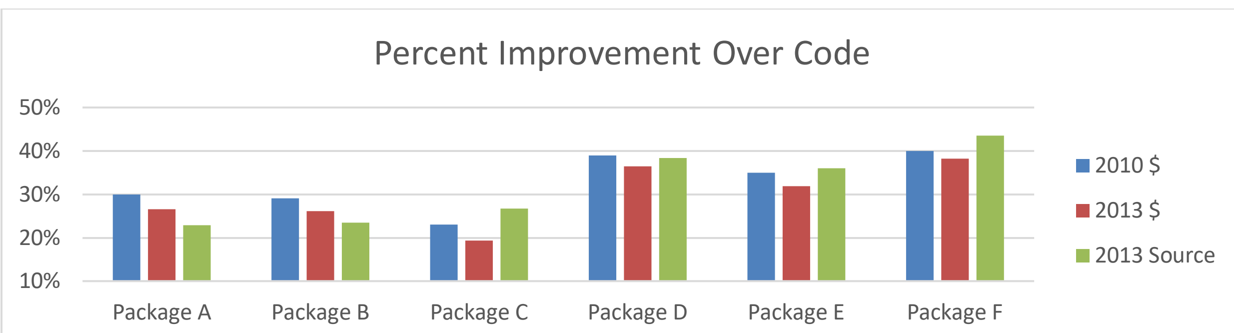


The graph highlights differences in how the same package of measures impacts individual end uses in each tool/protocol. For example, with Appendix G, the largest savings for packages A through C are due to the cycling PTAC fans compared to continuously running fans in the base case. These savings are not reflected in either PHI or PHIUS packages, with the PHI Team 1 and PHIUS showing fan penalty relative to the baseline, likely due to increased fan power of rooftop unit serving corridors (package A, PHIUS) and added energy recovery (packages B through D, PHIUS and PHI). The PHI Team 2 showed fan power savings for all packages relative to the baseline by modeling continuously running fans using a work-around not utilized by PHI Team 1. For PHI, heating end use drives source energy savings in all packages. The Appendix G protocol shows sizable service water heating savings in all packages due to low-flow fixtures and improved water heater efficiency, with much lower savings indicated by the PHI and PHIUS protocols.

4.2 Comparison of ASHRAE 90.1-2010 and 2013

Figure 8 shows performance ratings from the original study (2010 $), the rating based on the new MFHR SG 2016 (2013 $), and the NYSERDA Overlay rating (2013 Source). ASHRAE 90.1-2013 is more stringent than ASHRAE 90.1-2010, thus the margin of improvement over 90.1-2013 achieved by each package is expected to be lower than its margin of improvement over 90.1-2010. This expectation matches the observed pattern, as illustrated in Figure 8, with a 3–4% decrease in the percent improvement over 90.1-2013 (2013 $ column) compared to the improvement over 90.1-2010 (2010 $ column).

Figure 8. Performance Rating Comparison by Package



4.3 Site Energy, Source (or Primary) Energy, and Energy Cost Units

The main output of the Appendix G protocol is the performance rating, defined as percentage reduction in energy cost of the proposed design relative to the baseline. Since utility rates often include demand and time of use charges, the comparing energy costs can reflect the impact of energy conservation strategies on peak demand, including demand reduction or shifting peak demand away from grid peak hours.

PHI and PHIUS outputs are expressed in the units of site and source (or primary) energy. Site energy is the total combined energy content of the fuels that are used at the building site and measured by a building's utility meters. Source energy reflects the total amount of raw fuel required to operate the building, including all transmission, delivery, and production losses. The current national average site-to-source conversion factors based on EPA Portfolio Manager are shown in Table 5. The coefficients change with time and are updated periodically.

Table 5. EPA Portfolio Manager Site-to-Source Conversion Factors

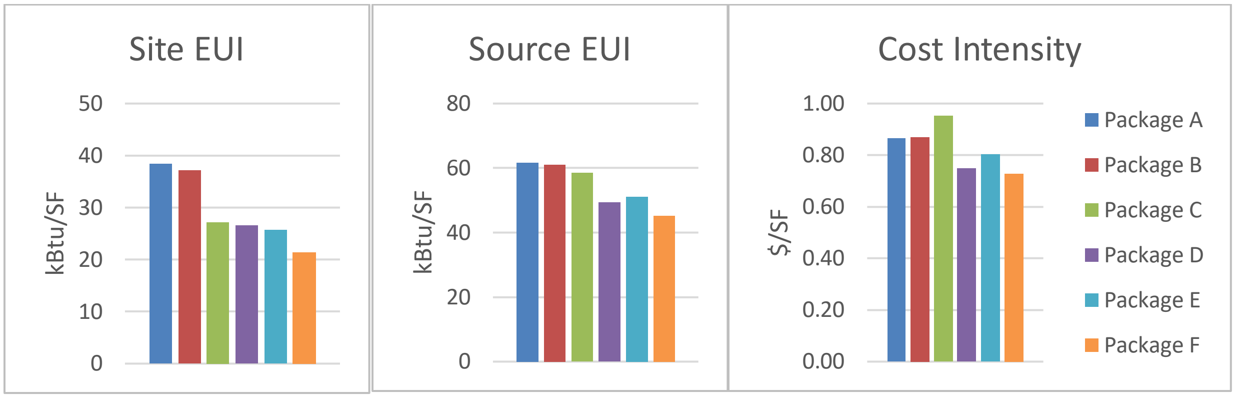
Energy Type	U.S. Ratio	Canadian Ratio
Electricity (Grid Purchase)	3.14	2.05
Electricity (on-Site Solar or Wind Installation)	1.00	1.00
Natural Gas	1.05	1.02
Fuel Oil (1,2,4,5,6,Diesel, Kerosene)	1.01	1.01
Propane & Liquid Propane	1.01	1.03
Steam	1.20	1.20
Hot Water	1.20	1.20
Chilled Water	1.00	0.71
Wood	1.00	1.00
Coal/Coke	1.00	1.00
Other	1.00	1.00

There is some correlation between source energy and energy cost, but an exact conversion does not exist because both fluctuate based on variety of independent factors. For example, electricity site-to-source coefficients depend on generation methods (e.g., hydro, coal, nuclear) and transmission losses in power lines; these differ from utility to utility. Cost is also affected by generation and distribution efficiency, but is also subject to market forces—for example, oil is now cheaper relative to electricity compared to a few years ago, but site-to-source coefficients remained about the same during this time. Energy costs used in this study were 0.15 [$/kWh] / 3.412 [kBtu/kWh]*1000 [kBtu/MMBtu]=$44/MMBtu electricity, and 1[$/therm]/100[kBtu/therm]*1000[kBtu/MMBtu] =$10/MMBtu for gas. This effectively means that BTU of electricity has 4.4 times greater weight than BTU of gas in performance rating calculations. With EPA Portfolio Manager site-to-source conversions as previously shown, BTU of electricity has 3.14/1.05= 3 times greater weight than BTU of gas. PNNL analysis of relative stringency of different versions of ASHRAE 90.1 uses electricity cost of $0.1032 per kWh ($30.272 per MMBtu of electricity) and gas cost of $0.99 per therm ($9.9 per MMBtu), which is closer to EPA site-to-source weighting factors.

PHIUS site-to-source conversion coefficients are similar to those used by EPA Portfolio Manager. PHI has a new metric called Renewable Primary Energy Demand (PER) that evaluates the efficiency of renewable resources available in each climate zone for each type of end use. For example, cooling has a lower PER factor because solar generation is abundant in summer and helps offset the energy use. For heating the PER is higher because of the reduced availability of the sun's energy in winter. Gas has a worse PER than electric because of the standby losses associated with producing and storing gas from renewable sources. Modeling for the case study was completed using the latest version of the PHPP, which shows the traditional PE and the new PER metric. The results included in this report are based on the traditional conversion factors (i.e., 2.6 factor for electricity) to simplify comparison to other protocols. However, PE will eventually be phased out of PHPP for PHI certification, and the comparative evaluation may have to be updated to take into account PER metric.

Part of the analysis done in the study for the ASHRAE 90.1-2013 models was to investigate the impact of using source energy to calculate the performance rating instead of energy cost. The impact of this change is demonstrated in Figure 8. Switching from energy cost (2013 $) to source energy (2013 Source) impacted the packages differently, depending on the relative contribution of electricity and gas toward the package energy use, and the electricity and gas weighing factors implicit in the selected units. Based on the utility rate used in the cost analysis ($0.15/kWh electricity and $1/therm gas), the cost of 1 BTU of electricity consumed at the building site is 4.4 times higher than the cost of 1 BTU of gas (1:4.4 electricity weighing factor). This penalized packages C and F, which despite having very efficient electric heating systems (VRF), had higher heating energy cost compared to the less efficient natural gas systems in other packages. For example, package C had lower Site Energy Use Intensity (EUI) compared to packages A and B, but higher Cost Intensity (Figure 9), and resulted in less savings than packages A and B when compared using energy cost savings. Using Source EUI units with the NY site-to-source conversions reversed the trend. Package C has lower source EUI than packages A and B, and thus shows higher improvement over code using Source EUI units. In summary, using source energy instead of energy cost as the basis of Appendix G performance rating results in a higher percentage improvement for packages where a greater proportion of savings is associated with gas and a lower percentage improvement for packages where greater savings are associated with electricity.

Figure 9. Site EUI, Source EUI and Cost Intensity Comparison by Package



4.4 Establishing Equivalent Targets

The key performance metrics for each package with the three protocols are shown in Table 7, which may be used to establish equitable targets for the evaluated protocols.

Table 6. Performance Metrics Comparison

Standard	Version	Metric	Package A	Package B	Package C	Package D	Package E	Package F
Appx G	ASHRAE 90.1-2010	**Performance Rating,** % savings ($)	30%	29%	23%	39%	35%	40%
	ASHRAE 90.1-2013	**Performance Rating,** % savings ($)	27%	26%	19%	36%	32%	38%
	ASHRAE 90.1-2013	**Performance Rating,** % savings (source)	23%	24%	27%	38%	36%	43%
PHIUS	PHIUS+ 2015	**Primary Energy,** kWh/Person-Yr	6,661	6,486	6,373	4,964	N/A	N/A
PHI	PH Classic, Team 1	**Primary Energy,** kBtu/ft^2-Yr	47.7	47.6	43.7	N/A	33.4	N/A
	PH Classic, Team 2	**Primary Energy,** kBtu/ft^2-Yr	45.9	45.5	40.9	N/A	N/A	27.6

The highlighted performance descriptors may be used as the basis of the mapping. For example, target may be expressed as performance rating (% energy cost improvement over the baseline) for projects following Appendix G protocol, as primary energy (kWh/Person-Yr) for projects following PHIUS protocol, and primary energy (kBtu/SF-Yr) for PHI projects.

The table also highlights the approximate nature of the mapping. For example, package A has 30% performance rating with Appendix G protocol and is perceived as slightly more efficient than package B, which has 29% performance rating. However, the opposite trend is seen for these packages with PHIUS protocol, where package A has slightly higher Primary Energy compared to Package B. In addition, the variations in results for Packages A, B, and C reported by PHI Teams 1 and 2 illustrate that different analysts working on the same project and using the same protocol and simulation tool will get different results. Exploring such variations was outside of the scope of the study; however, this is expected and may be more significant for Appendix G protocol, which is more complex and allows use of different simulation tools. Results are also likely affected by the climate (e.g., if analysis was performed for State climate zones 5a and 6a instead of 4A) or if analysis is from a different building configuration, such as significantly different window to wall ratio, area of common spaces, central laundry, etc.

5 Tool Comparison

Appendix G protocol may be implemented using any tool compliant with ASHRAE Standard 90.1 Section G2.2. PHI protocol requires the use of PHPP and PHIUS requires WUFI-Passive, with the option of using the more robust WUFI-Plus software. Table 8 compares the tools based on the software requirements of ASHRAE Standard 90.1 Section G2.2.

Table 7. Simulation Tool Comparison

Tool capability	eQUEST v3.65	WUFI Plus and WUFI Passive (PHIUS)	PHPP (PHI)
8,760 hours per year	Yes	WUFI-Plus does hourly simulations, but its use is not required for certification. WUFI-Passive does monthly balance-based calculation.	No
hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat setpoints, and HVAC system operation, defined separately for each day of the week and holidays	Yes	Possible in WUFI-Plus. It may be approximated in WUFI-Passive by assigning typical schedules. For a school or business that operates only part of the year, WUFI-Plus would be needed to account for operations schedules for specific parts of the year.	Average annual values are typically calculated separately and entered in the PHPP. Supplementary tools are available to help calculate the appropriate averages for different systems such as ventilation and lighting.
thermal mass effects	Yes	Yes. However, it is a single simplified input in WUFI-Passive. WUFI-Plus does a much more detailed calculation.	Yes
ten or more thermal zones	Yes	Multiple zones can be input in the model, but since WUFI-Passive is a whole building energy model, these zones would only influence the dynamic side of the software (WUFI-Plus).	PHPP is a one-zone model.
part-load performance curves for mechanical equipment	Yes	No	Pre-calculation is currently required to account for part load performance, except for partial support for some types of heating systems.
capacity and efficiency correction curves for mechanical heating and cooling equipment	Yes	No. Average efficiencies are typically calculated outside of the software and entered into the tool.	No. This is typically calculated externally, and adjusted values are entered into the tool, except for partial support for some types of heating systems.
air-side economizers with integrated control	Yes	WUFI can only account for this during the cooling season, through the ERV ventilation.	Yes

Table 7 continued

Tool capability	eQUEST v3.65	WUFI Plus and WUFI Passive (PHIUS)	PHPP (PHI)
Capable of performing design load calculations to determine HVAC equipment capacities and air and water flow rates in accordance with generally accepted engineering standards and handbooks (for example, ASHRAE Handbook—Fundamentals)	Yes	WUFI Passive will calculate a heating/cooling load per square foot. As of now, the latent load is not included in the cooling load result. These are whole building results per square foot rather than zone by zone. It does not calculate required air/water flow rates for heating and cooling equipment.	The PHPP calculates heating and cooling loads (sensible and latent), as maximum daily average per square foot, which can be used as a reference for equipment sizing. Guidance is also provided on the required air change rates for the HVAC system. A secondary calculation is available for an estimate for water flow rates, not intended for system sizing.
Tested according to ASHRAE Standard 140, except Sections 7 and 8, and results furnished by the software provider.	Yes	WUFI Plus has been tested	No

PHPP Notes:

- Capabilities are limited to a single gas heating system per project. For example, an 82% efficient gas fired rooftop unit serving common spaces and a 95% efficient condensing boiler in apartments cannot be modeled explicitly, but a rated capacity-weighted average efficiency must be entered. More than one heating system can be captured using a work-around by entering the main system (e.g., boiler serving apartments) and supplementary heating system (e.g., rooftop unit) with the associated efficiencies, as well as entering the percentage of heating demand covered by each system (e.g., weighted by area).
- The tool cannot capture impact of part load on heating/cooling efficiency. Boiler capacity is entered to ensure that loads are met. Entering heat pump capacity affects how much heating is being supplied by electric resistance.
- Up to 10 different ventilation systems can be modeled with different efficiencies and control strategies, including a mix of exhaust-only and balanced systems. However, exhaust only in apartments and energy recovery in the corridors cannot be explicitly modeled.
- Cannot explicitly model continuously running fans, but can model constant vs. variable volume fans that cycle with load for cooling only. Fan energy is calculated by using the charts; multiple flow rates and associated W/cfm at those flow rates can be captured.
- Assumes heating/cooling efficiency is unchanged throughout the year and is as entered; cooling efficiency is entered as SEER. Efficiency from charts is not taken verbatim—a seasonal calculation is performed based on manufacturer data at different temperatures.
- Most of the evaluated packages have ventilation air conditioned by different mechanical systems in apartments (e.g., boilers in Packages A-B, VRF in package C) vs. corridors (rooftop unit in packages A through C). PHPP is a one-zone model and cannot capture this explicitly. As a workaround, the energy balance is based on one average ventilation rate. Ventilation systems can be entered separately to have PHPP calculate the corresponding average ACH. For example, in package C, apartments are served with VRF (have electric heating), but corridors are served by gas fired roof top unit. The proportion of gas and electric heating is entered manually—the simplest and typical approach is based on area, e.g., apartments vs. corridors. It is possible to make a detailed assessment by accounting for differing loads, but the protocol developers believe the impact on the results are small and accept the simplified area-based approach.
- PHPP allows for manual shading controls, but includes a reduction factor, which reflects the fact that users will not always use shading when it is beneficial. Only exterior shading is modeled as interior shading devices do not contribute to significantly reducing solar loads.

- PHPP allows for manual control of night ventilation. Supplementary calculations are provided for a realistic assessment of air change rates.
- PHPP has one combined factor for specific heat capacity, which includes thermal mass of exterior and interior elements.
- PHPP includes distribution losses, which are considered to have significant effect on cooling demand and cooling peak load, as well as the total source energy (increased energy demand for DHW).
- When building is served by systems of different efficiencies, weighted average efficiency is entered into PHPP. For example, in the models done for this study, the overall weighted average cooling efficiency was used for corridors and apartments (EER 11.2 for Base Case 1, EER 13 for Base Case A through C and F).

WUFI Notes

- The software (WUFI Plus) is a dynamic model and uses hourly simulations. The software has a simplified WUFI-Passive mode that uses annual simulation. WUFI-Plus may be used for dynamic whole building energy simulation or optimizing individual components—e.g., to evaluate single wall assembly for risks due to condensation and comfort. Hourly simulation is not typically used for the whole building analysis due to long simulation time and is not required for PHIUS certification. All results for the case study are based on WUFI Passive (non-hourly analysis).
- WUFI-Passive can model multiple heating systems per project, based on the area of the zones being heated by gas vs. electricity, for example. In package C, the corridor heating is supplied via an 85% efficiency natural gas system while the apartments are supplied with heating via a VRF heat pump with a COP of three. Users have to assign specific percentage of heating use to each system, usually based on floor area, assuming relatively similar load per square foot for most of the building.
- Heating/cooling efficiency of heat pumps are calculated externally, based on monthly demands and ambient temperatures, using COP ratings at different temperatures.
- Cooling capacity is input in order for the model to estimate dehumidification potential of heat pump system and to ensure cooling load is met. Boiler capacity is input to make sure loads are met. Efficiency adjustment based on part load is not automatically captured.
- WUFI-Passive can model intermittent exhaust systems at the same time as a continuous balanced ERV. The intermittent exhaust systems assume unconditioned make-up air is supplied at the same rate as the exhaust.
- Fans load W/CFM can be entered for any user-specified period of time; however, fan runtime cannot be automatically established based on the periods when heating or cooling is needed.
- Since fan power of packaged HVAC systems is not a direct input into WUFI, the fan energy is accounted for as part of the cooling efficiency (e.g., EER).
- WUFI has relatively simplistic inputs for the mechanical systems, while the envelope (walls, windows, and roof) require more detail inputs with regard to shading, etc. It was designed to model low-load buildings with relatively simple mechanical systems.

6 Summary of Observations

1. PHI uses much more optimistic assumptions for in-unit lighting and plug loads compared to EPA MFHR Guidelines and PHIUS+, which results in a significantly lower source EUI for equivalent designs.
2. PHI and PHIUS+ assumes hot water consumption of 6.6 gal/person/day, which is significantly lower than 14-54 gal/person/day provided in ASHRAE Applications handbook, as shown in Figure 8. However, service water heating usage for equivalent designs is not significantly different between PHI, PHIUS+ and Appendix G method, possibly because PHI and PHIUS+ account for DHW distribution losses while Appendix G does not.
3. Default PHI site-to-source conversations differ significantly from values used by the EPA Portfolio Manager, resulting in lower source EUI compared to protocols that use more conservative conversions.
4. Neither WUFI nor PHPP meet all the ASHRAE Standard 90.1 software requirements. For example, neither can support explicit modeling of multiple zones with different HVAC systems serving each zone and have limited capacity to reflect fan energy. The tools were designed to model high-performing buildings with relatively simple mechanical systems. Therefore, use of these tools to model buildings with complex HVAC may produce unreliable results.
5. PHIUS+ and PHI protocols incorporate savings from manual controls, such as occupants opening windows when outdoor temperatures are favorable. This results in more optimistic usage projections compared to Appendix G protocol, which allows credit only for automatic controls that are inherent to design.

Figure 10.Typical Hot Water Demand from ASHRAE Applications Handbook

Table 8 Hot-Water Demand and Use Guidelines for Apartment Buildings (Gallons per Person at 120°F Delivered to Fixtures)

	Peak Minutes						Maximum	Average
Guideline	5	15	30	60	120	180	Daily	Daily
Low	0.4	1.0	1.7	2.8	4.5	6.1	20	14
Medium	0.7	1.7	2.9	4.8	8.0	11.0	49	30
High	1.2	3.0	5.1	8.5	14.5	19.0	90	54

7 Additional Observations and Recommendations

7.1 Appendix G

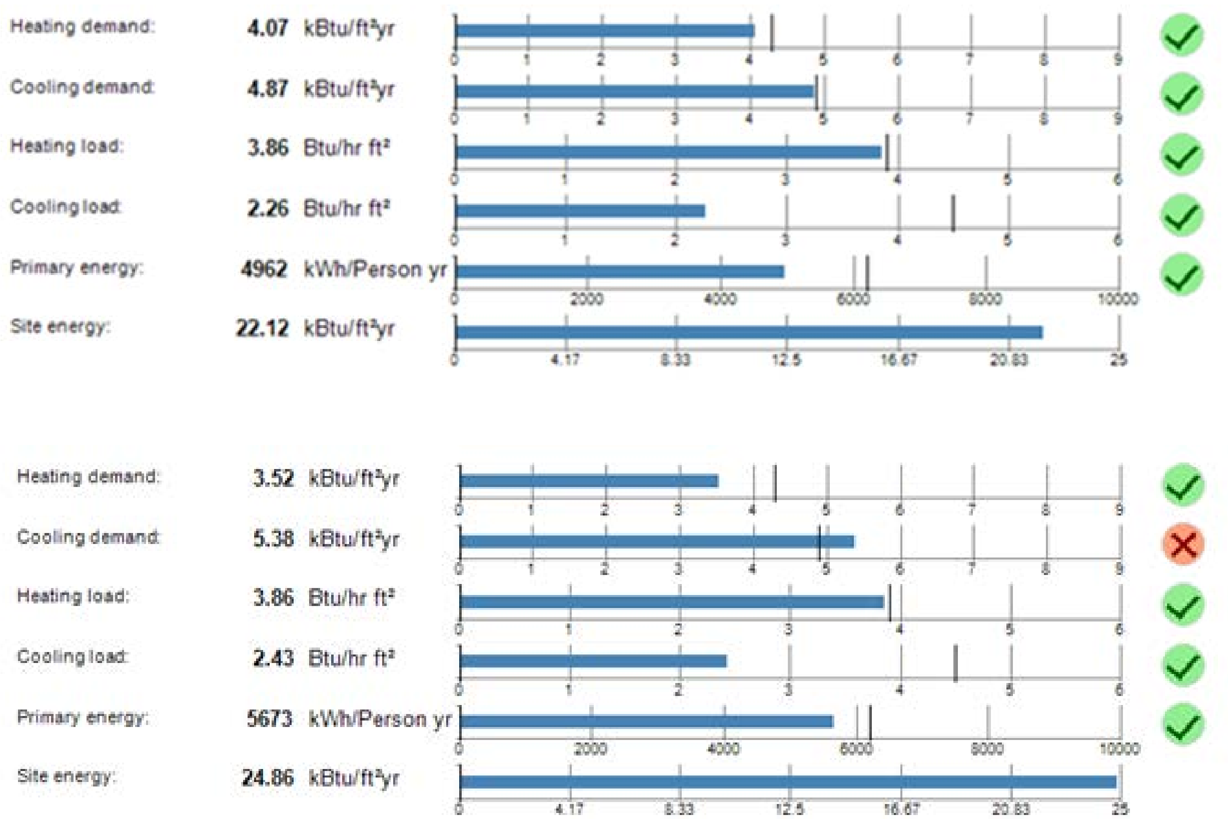
1. Performance rating for all packages includes credit for cycling fans compared to continuously running fans in the baseline. This credit is allowed following 90.1 Appendix G and contributes ~13% toward performance rating. Based on hundreds of projects that participated in NYSERDA multifamily program for new and existing buildings and EPA MFHR program, in-unit HVAC systems almost never run continuously because they do not supply OA. Thus, the currently prescribed baseline fan control significantly reduces the stringency of the Appendix G baseline relative to which the performance rating is calculated for multifamily projects.
2. The current MF NCP guidelines do not allow credit for infiltration reduction as per earlier versions of 90.1 Appendix G. 90.1 2013 Table G3.1 #5 Exception allows modeling credit from infiltration reduction "when whole-building air leakage testing, in accordance with ASTM E779, is specified during design and completed after construction." The credit was modeled in Appendix G Package D and contributed 2.5% to 3.5% toward performance rating. MF NCP guidelines could be modified to allow this credit to encourage and recognize tighter envelope design. Infiltration was modeled at 100% of the rates specified in Table 3, with hourly schedule fraction of one, year-round, to reflect balanced ventilation.
3. Energy cost ($/kWh and $/therm) has significant impact on performance rating. Rating authorities should review relative cost of fuels prescribed by the programs, reference COMNET values, or base the required performance rating on source energy. Performance targets should be established based on the selected approach.
4. Changes between different versions of ASHRAE 90.1 can significantly impact the results of this analysis. The adopted targets and equivalency to other protocols should be re-evaluated with each new released version of ASHRAE 90.1.

7.2 Passivhaus and PHIUS

1. PHI / PHIUS+ certification thresholds are expressed as absolute values (i.e., primary energy kWh/Person-Yr, primary energy kBtu/SF-Yr) and will be affected by changes to simulation tools (PHPP, WUFI) and certification protocols, such as updates to simulation assumptions (occupancy, lighting runtime hours, plug and process loads, etc.) and site-to-source conversions. Thus, PHIUS and PHI performance targets must be specified in conjunction with the version of the modeling tool and protocol, as Appendix G references its own version of 90.1.
2. PHIUS/PHI targets should be re-evaluated with each new release of certification tools and guidelines.
3. Confirm with PHIUS/PHI that operating assumptions (e.g., thermostat setpoints, plug loads, etc.) cannot be used to game the system.
4. WUFI and PHPP focus on envelope and loads and have limited capabilities for modeling projects with diverse and/or complex HVAC systems serving multiple zones that are found in some larger multifamily and commercial buildings. This should be addressed for each standard by the software developer.

5. PHIUS and PHI primary energy thresholds capture the energy usage of all systems that are present in the building design, including optional amenities such as exterior lighting, dishwashers and in-unit laundry, which are not found in every multifamily building. As a result, buildings that have these amenities must incorporate additional efficiency measures to offset the added use and meet the fixed certification targets. To avoid inequitably penalizing projects that offer certain amenities to residents, consider allowing those amenities to be excluded when determining if PHIUS and PHI projects will meet the MF NCP primary energy thresholds, provided that the excluded systems meet prescriptive requirements such as the ENERGY STAR label. The impact of these additional systems on the PHIUS metric is illustrated in Figure 9.
6. PHI defaults for in-unit lighting and appliances energy use are significantly more optimistic than presented in references such as Building America and COMNET, which contributes to a much lower EUI projected by the protocol for equivalent design. It is recommended that PHI review those default assumptions made regarding multifamily buildings in the U.S.
7. PHPP and WUFI Passive were not tested following ASHRAE Standard 140, and do not meet many of the software requirements prescribed by ASHRAE 90.1. Vendors may consider updating the tools to meet these requirements, to make the protocol applicable to a wider range of commercial buildings.

Figure 11. PHIUS report for package without (top) and with (bottom) dishwashers and in-unit Laundry



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