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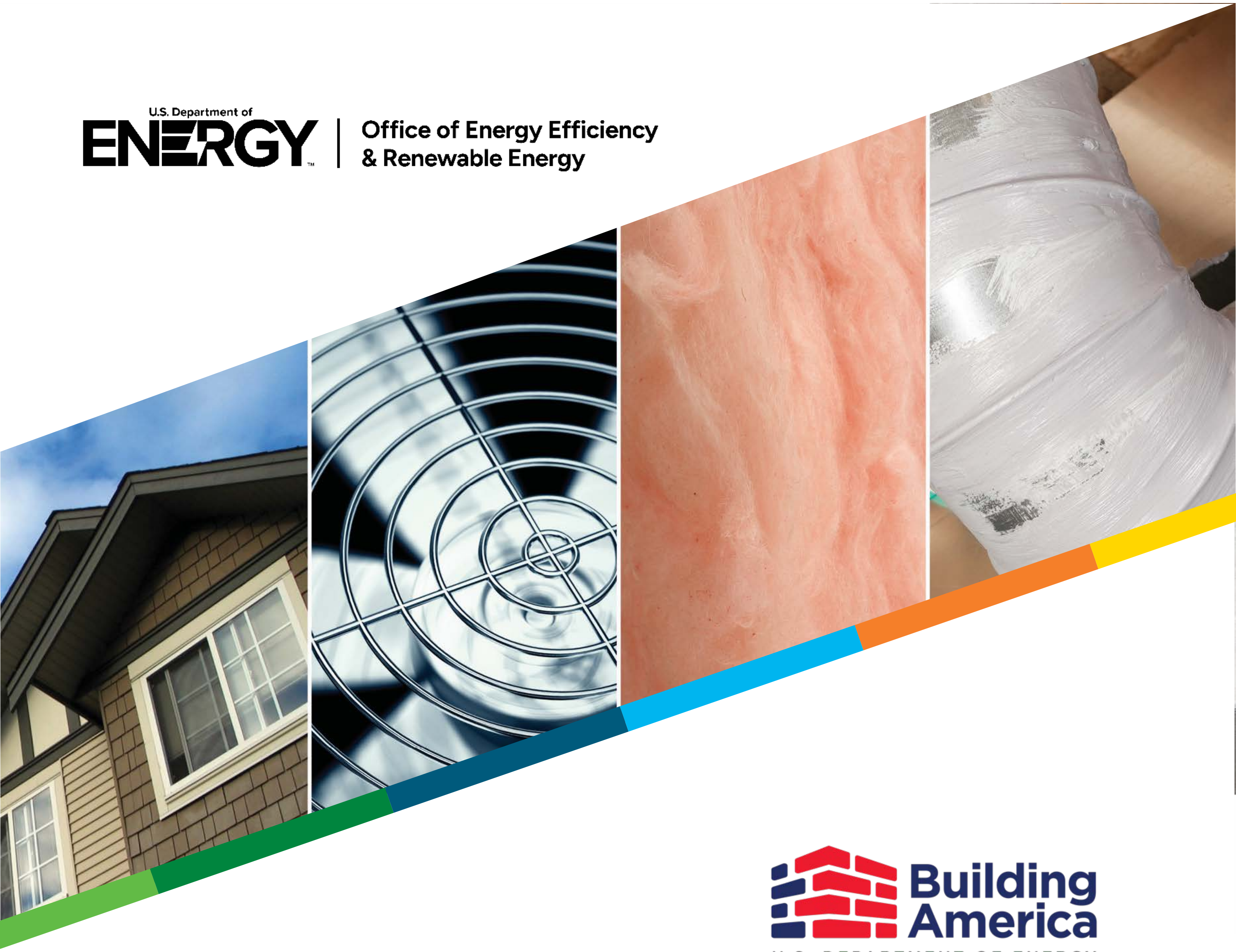

Building America
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Design Heating and Cooling Load Calculation Versus Building Load Simulation for Cold Climate Heat Pumps: Understanding the “Gap”

November 2024

Disclaimer

Design Heating and Cooling Load Calculation Versus Building Load Simulation for Cold Climate Heat Pumps: Understanding the "Gap"

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Executive Summary

This report explores the differences between Manual J-equivalent block load calculations and building HVAC energy simulation results using EnergyPlus™ calculations when designing cold climate heat pump systems for residential use. This study will help HVAC researchers and advanced designers understand the impacts of oversizing heat pumps on home energy use.

Performance Systems Development is an energy efficiency technology and services provider based in Ithaca, New York, that partnered with Building America to investigate the sizing recommendation “gap” between Manual J calculations and EnergyPlus simulations for cold climate heat pumps. The remainder of the report summarizes their findings and is organized as follows: First, the Methodology section describes the house, heat pump, climates, and envelope improvement packages used in the modeling work. Then, the Comparison section analyzes the differences between the Manual J calculations and EnergyPlus simulations, including the effect of envelope improvements and solar and internal gains at different times of day and with different peak load timing. Finally, the Conclusion section reiterates the overall findings of this work, including that sizing heat pump systems should be combined with high-efficiency envelope improvements to minimize heating loads. This combination avoids unnecessary cooling and heating energy costs associated with high building infiltration, and avoids degrading the system efficiency when low heating loads quickly met by high-capacity equipment cause rapid on-off cycling.

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1 Background

Traditionally, ensuring appropriate capacity for heating, ventilating, and air-conditioning (HVAC) equipment is relatively straightforward—even for extreme temperatures. However, with the rise in popularity of cold climate air-source heat pumps, using the same approach as traditional HVAC equipment can lead to an oversized unit that is less efficient and more expensive than it needs to be.

1.1 Manual J Calculations

The Air Conditioning Contractors of America (ACCA) Manual J national standard dictates that the building heating load for determining HVAC equipment size (using ACCA Manual S) should be based on the 99th percentile cold weather temperature for a given location. This means that equipment sized for that extreme will be oversized for the majority of cold weather conditions. That may be acceptable for traditional HVAC equipment, but oversizing a heat pump results in increased on-off cycling because the unit is unable to maintain continuous operation at a low enough capacity to match heating loads during milder temperatures. The Manual J methodology relies on the bulk heat transfer calculation $U * Area * \Delta Temperature$ to determine annual heating needs, disregarding heat gains from internal sources or solar radiance.

1.2 EnergyPlus Simulation Results

EnergyPlus™ is an energy simulation program that can be used an alternative to the Manual J methodology. EnergyPlus’ hourly heating load calculations for the same building and temperature conditions are consistently lower than the Manual J calculations. This is due, in part, to inclusion of heat gains to the building and ability to capture the variation in load throughout the heating and cooling seasons. Use of a simulation tool like EnergyPlus, rather than a bulk heat load calculator, supports the evidence for improving overall heating efficiency and home energy performance by sizing a variable-speed heat pump for more typical heating conditions and using backup heat during infrequent extreme cold events (Smith 2022).[1]

2 Methodology

2.1 Residential Building Characteristics

To assess cold climate heat pump performance when meeting residential heating and cooling loads, Performance Systems Development modeled a single-family detached home with a ducted heat pump in a selection of colder climates, using EnergyPlus as the modeling engine in the OpenStudio-HPXML v.1.7.0 workflow. The building

[1] Note that a dedicated analysis of backup heat costs, grid emissions, and peak load impacts under these conditions is outside the scope of this case study and could be appropriate for future work.

description is summarized in Table 1, with building occupancy schedules as per the Building America House Simulation Protocols.[2]

Table 1. Modeled Residential Building Details

Building Characteristic	Value in Simulation
House Style	Colonial
Vintage	1980
Foundation Style	Unconditioned basement
Attic Style	Vented
Number of Conditioned Floors	1
Total Square Feet	2,400
Conditioned Square Feet	1,200
Heating Setpoint Temperature (°F)[2]	68
Cooling Setpoint Temperature (°F)[3]	77

2.2 Cold Climate Heat Pump Specifications

Performance Systems Development selected a ducted, variable-speed multi-split heat pump prototype for the model based on a compilation of actual equipment rated in the Northeast Energy Efficiency Partnership's (NEEP) performance database. The prototype exhibits good cold temperature performance as measured by the rated coefficient of performance (COP) at 5°F, good moderate temperature performance (rated COP at 47°F), average COP maintenance, and average modulation performance as determined by Performance Systems Development's equipment scoring protocol. The heat pump scoring protocol rates each equipment option in the NEEP list against the remainder of the database and assigns a four-digit score. The scores are scaled from 1–9 reflecting low-temperature COP and moderate-temperature COP performance (1 reflects worst performing equipment in a given category) and from 1–5 reflecting capacity maintenance and capacity modulation. Using this protocol, prototype heat pumps were created for analysis purposes, based on a group of real equipment earning the same performance score. These prototypes were modeled using EnergyPlus and compared to actual equipment results to confirm they were an accurate representation of real heat pump performance.

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[2] Workflow Inputs — OpenStudio-HPXML documentation

[3] Hourly load simulation was based on heating setpoint of 68°F and cooling setpoint of 77°F, in compliance with modeling requirements for New York State incentive programs. Manual J-equivalent loads were calculated using that standard's required setpoints of 70°F heating temperature and 75°F cooling temperature. Thie Manual J setpoints will dictate selection of a heat pump with slightly larger heating and cooling capacities, and would impact comparisons of heating and cooling energy use between the two methods (energy use comparisons are not applicable to this work).

This selection process helped ensure that the home's maximum loads could be served by a single heat pump, to simplify analysis. The prototype heat pump is sized to the home's heating load in each model scenario, as calculated by the National Renewable Energy Laboratory (NREL) Manual J8-equivalent calculation in the OpenStudio-HPXML version 1.7.0 workflow, avoiding the need to model and compare different equipment options.

Table 2. Prototype Cold Climate Heat Pump Description

Ducted Variable-Speed Heat Pump Performance Specification	Prototype Value
Rated Cooling Capacity, Btu/h	60,000
Rated Heating Capacity, Btu/h	66,000
Heating Season Performance Factor, Btu/Wh	10
Seasonal Energy Efficiency Ratio/Energy Efficiency Ratio, Btu/Wh	17/12.5

2.3 Residential Envelope Features

The building model allows assessment of various envelope improvements, applied as incremental packages. Prior to any envelope improvements, the baseline building includes minimal above-grade wall and attic floor insulation, a baseline air leakage rate of 2,000 CFM50 (cubic feet per minute at 50 pascals of pressure), and standard double-pane windows. The envelope improvement packages tested were:

- Package 1: Seal and insulate rim joists to R-14, seal and insulate attic roof deck to R-49.
- Package 2: Insulate above-grade (2x4) walls to R-11.9, below-grade walls to R-17, and insulate foundation ceiling (plus Package 1).
- Package 3: Install ENERGY STAR®-equivalent windows (plus Package 2).

Performance Systems Development applied Typical Meteorological Year (TMY3) average weather data produced by NREL to the analysis for four cold climate locations: Albany, Massena, and Westchester in New York State, and Philadelphia, Pennsylvania. The simulation outputs include design heating and cooling loads by component system given the 99th percentile outdoor air temperatures for each location (the Manual J-equivalent design conditions), and hourly heating and cooling component loads as predicted by the EnergyPlus simulation.

3 Comparing EnergyPlus Simulation to Manual J Bin Method Calculations

The Manual J residential load calculations consider only one extreme heating and one extreme cooling set of temperature conditions for sizing HVAC equipment—but the loads that must be met by this equipment vary across a wide range of temperatures and are subject to a variety of occupancy and behavioral factors. Figure 1 illustrates the range of hourly loads to be met by the modeled cold climate variable-speed air-source heat pump in cycling, modulating, and backup modes, in a baseline building in Albany, New York. The cycling mode is simulated when the equipment is below the modulating range. The backup mode reflects all load hours when the heat pump heating output is being supplemented by electric backup heat to meet the EnergyPlus hourly load. Because the equipment is autosized to meet the Manual J8 load at heating design temperatures, the backup supplemental heat only affects the hours below the design tempeature in these simulations.

The loads in Figure 1 are displayed across 2ºF temperature bins to equivalently compare with the ACCA Manual J approach. The Manual J-equivalent dark blue line is extrapolated from the design heating load temperature to the temperature at which heating load is zero for that location. In the baseline building, the modeled heat pump is in heating mode 56% of the time, in cooling mode 16% of the time, and requires backup heat in addition to the heat pump (pink data points) only 5 hours out of the year. The simulated hourly heating loads are significantly lower than those predicted by the interpolated Manual J-equivalent calculation across most temperature bins. Note that a higher capacity heat pump may be required per Manual S sizing guidance to meet the design heating load than the EnergyPlus simulations suggest.

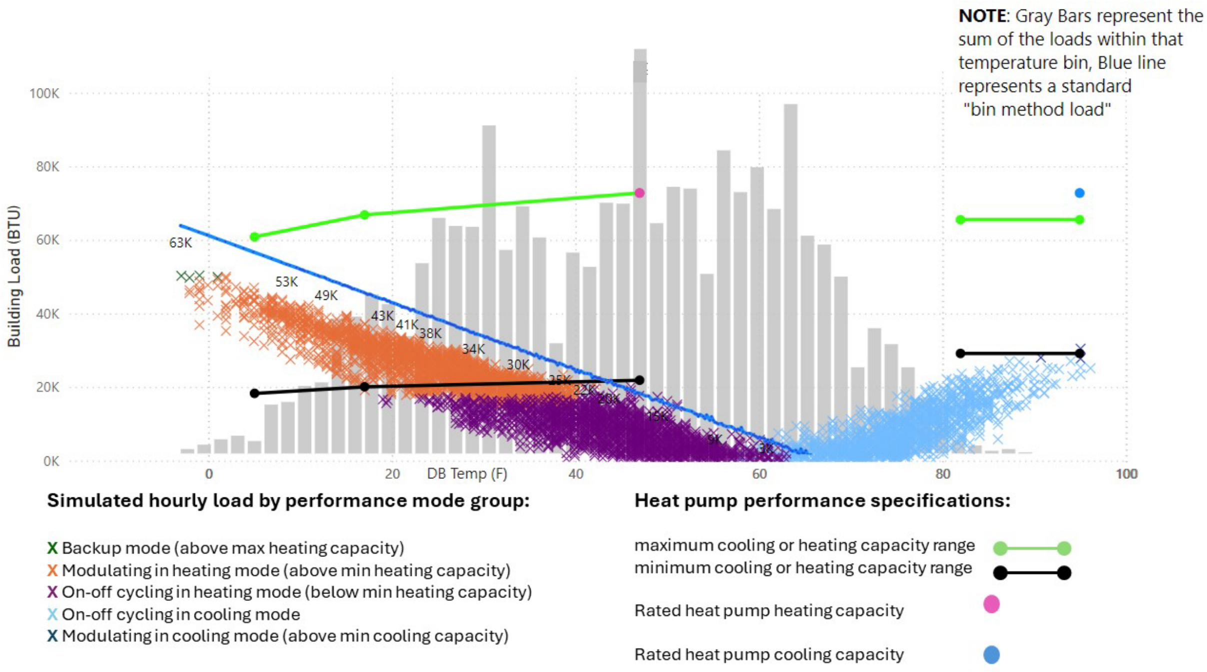

Figure 1. EnergyPlus simulated hourly residential load and Manual J-equivalent load with prototype heat pump by 2-degree temperature bin. Note: HP refers to heat pump. NEEP reported minimum and maximum heating and cooling capacities for the prototype are superimposed over the calculated load data.

The difference between Manual J-equivalent calculation and EnergyPlus simulation results diminishes when the envelope is improved prior to heat pump sizing, as indicated by the change in the hourly expected heating load data points and Manual J-equivalent extrapolated load line in Figure 2. In this modeled scenario, Package 3 was applied as a comprehensive building envelope improvement strategy and accounted for in the load calculation, reducing the impact of the envelope U-factors on the expected load. The auto-sized heat pump for this reduced-load scenario is expected to spend 14% fewer hours in cycling mode, compared to the heat pump auto-sized for the baseline building load in Figure 1.

Ensuring that building heating and cooling loads are minimized (via thermal envelope improvements) prior to heat pump sizing is critical to help homeowners manage the costs of building conditioning and minimize energy use. Accounting for building envelope improvements in the Manual J inputs or in any building performance modeling software to assess the impacts prior to installation will allow contractors to select better-sized heat pumps. In addition, undersizing heat pumps and relying on small supplemental backup heat only for extreme conditions is recommended, rather than relying on an oversized, modulating heat pump. A smaller system will help to limit system cycling and avoid higher equipment costs (Smith 2022). Modulation range is important but should not be counted on to compensate for the effects of oversizing on system efficiency.

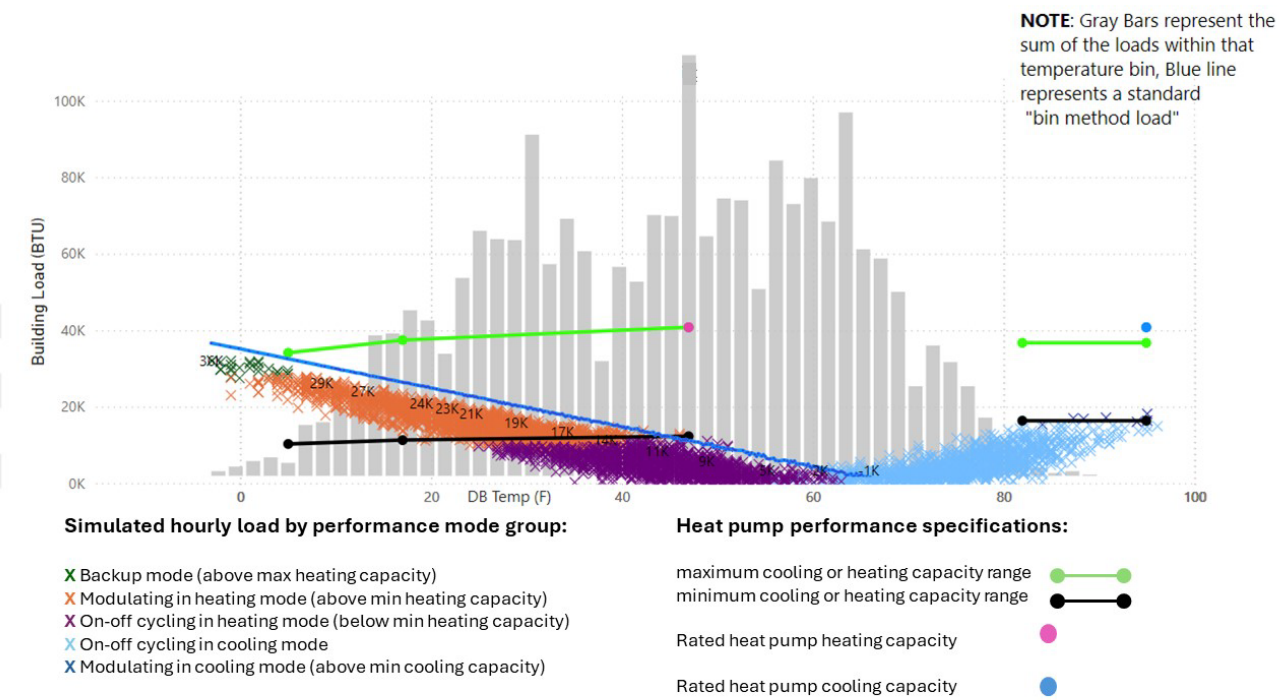

Figure 2. EnergyPlus simulated hourly residential load and Manual J-equivalent load by 2-degree temperature bin *with improved envelope*

3.1 Comparing Calculated Residential Loads by Hourly Simulation and Bin Methods

Figure 3 further illustrates the divergence of hourly loads simulated in EnergyPlus and bin method calculations, especially during mild heating season temperatures (20°–40°F). The majority of heating hours in these locations occur in this temperature range, as indicated by the gray bars in the figures. The two load calculation methods converge at very low temperatures, which align with the 95% coldest temperature condition applied for the Manual J method. However, those conditions will occur fairly infrequently. Heating with a heat pump in a cold climate location might be better served with an undersized system relying on backup for rare extreme cold, than by sizing according to the Manual J calculation.

As seen in Table 3, the relative difference between EnergyPlus simulation results and bin method calculations used for total heating load estimates persists even when varying insulation and air sealing measures, regardless of weather conditions (e.g., Massena, New York, weather differs greatly from Philadelphia, Pennsylvania, or Albany, New York, weather). However, adding window improvements to the models reduces this difference by roughly 5%. Manual J-equivalent load calculations account for heat gains through windows differently than EnergyPlus simulations. Table 3 suggests that the two calculation methods treat reduction of heat transmittance through opaque surfaces (by reducing leakage and improving insulation R-value) similarly, because there is little change in the relative heating load results as those improvements are added from base building to Package 2. However, when windows are included, which further reduces heat transmittance as well as solar heat gain, the two methods’ differences shrink. Therefore, solar gains may be a contributor to some of the disparity between EnergyPlus simulation results and Manual J-equivalent calculations that could be further explored, given that the same high-performance window parameters are applied to both calculation methods. While solar gains are clearly not the only source of differences in Manual J-equivalent versus EnergyPlus calculated loads, investigating and addressing the solar gain terms of the Manual J calculation could contribute to a design load better matched to actual expected heating loads, resulting in a better-sized heat pump expected to use less energy during the heating season.

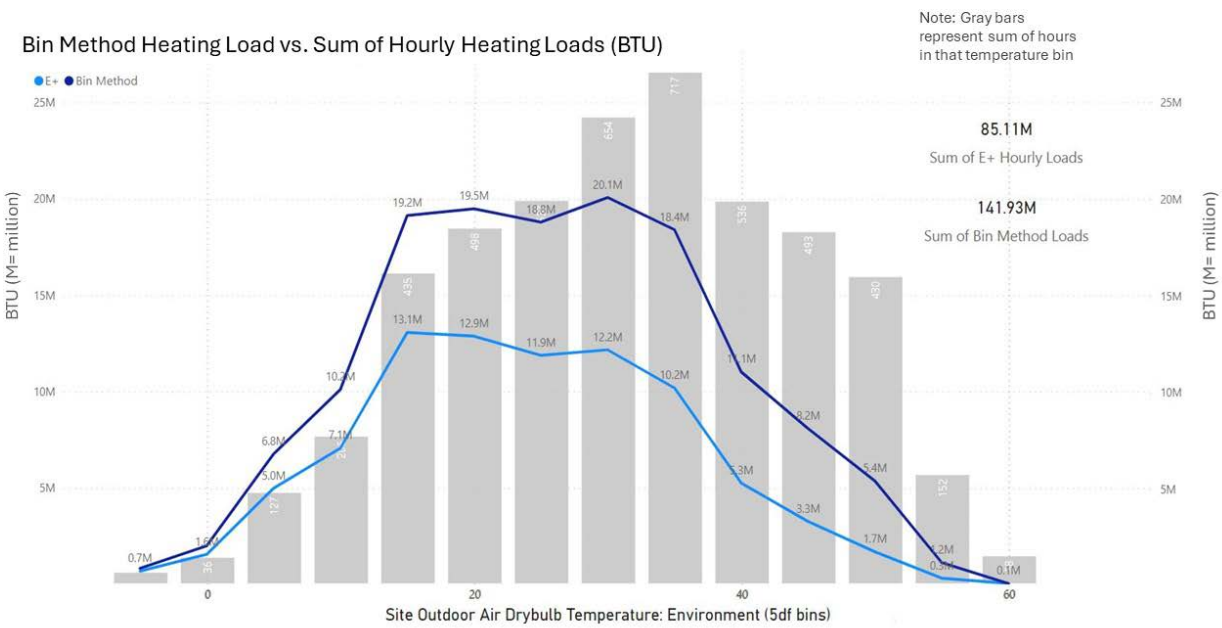

Figure 3. Baseline building heating load calculated with Manual J vs. EnergyPlus by 5-degree temperature bin, Albany NY

Table 3. EnergyPlus Total Heating Loads in Two Cold Weather Locations, as Percent of Bin Method Heating Loads

Building Model	Massena, NY	Philadelphia, PA	Albany, NY
Base Building (No Improvements)	63%	55%	60%
Package 1 Envelope Improvement	63%	54%	59%
Package 2 Envelope Improvement	65%	56%	62%
Package 3 Envelope Improvement	71%	61%	67%

3.2 Time of Day and Component Influence on Residential Load Calculations

Hourly simulation results for the baseline building in Albany suggest a heating peak load occurring in mid-January and a cooling peak in mid-July. A closer look at those days (Figures 4 and 5) reveals that the home's modeled system components contributing most to peak heating load include walls, infiltration, and window conduction, while top contributors to peak cooling load include window solar gain, walls, and ceilings. These vary somewhat with time of day, as expected. In cold weather, the heating loads from window conduction (sea green color), walls (beige), and infiltration (dark pink) generally decline during the afternoon and become more significant during the hours of 12 p.m. to 12 a.m., in inverse relation to outdoor temperature. Heating load contributions from ducts (orange) and floors (dark purple), are smaller but more constant. Over the course of a few days during peak cooling season, load from ceilings (sky blue), walls (sea green), and solar gains through windows (salmon pink) all increase with increasing temperature and over the daylight hours, with evening declines in ceiling and wall load lagging decline in temperature.

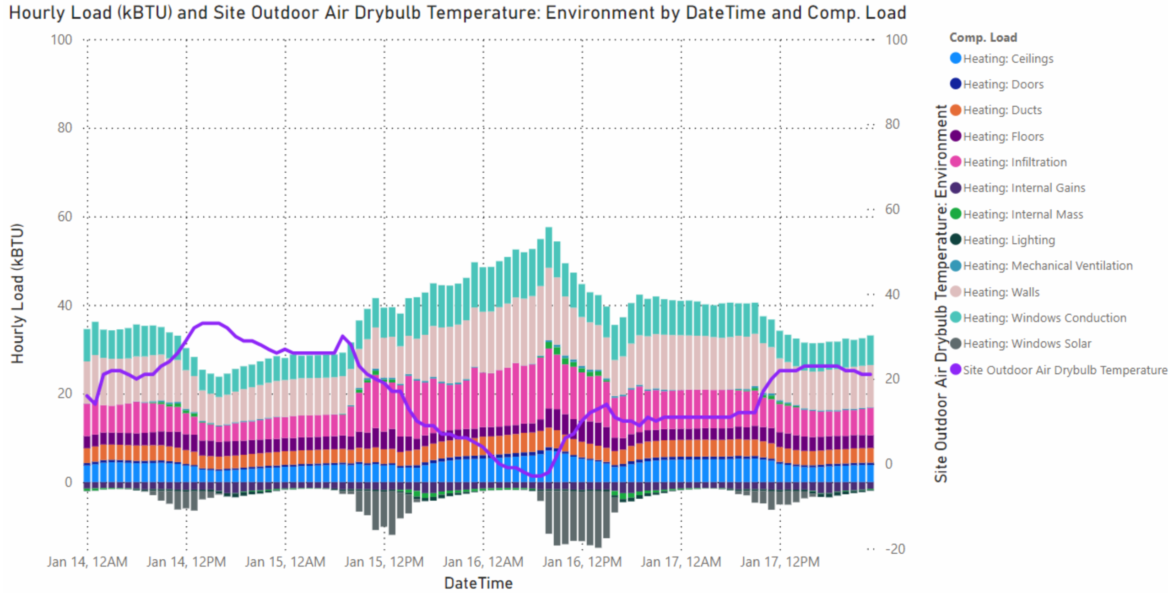

Figure 4. Hourly mid-January heating load (kBtu) by component with outdoor temperature, Albany NY

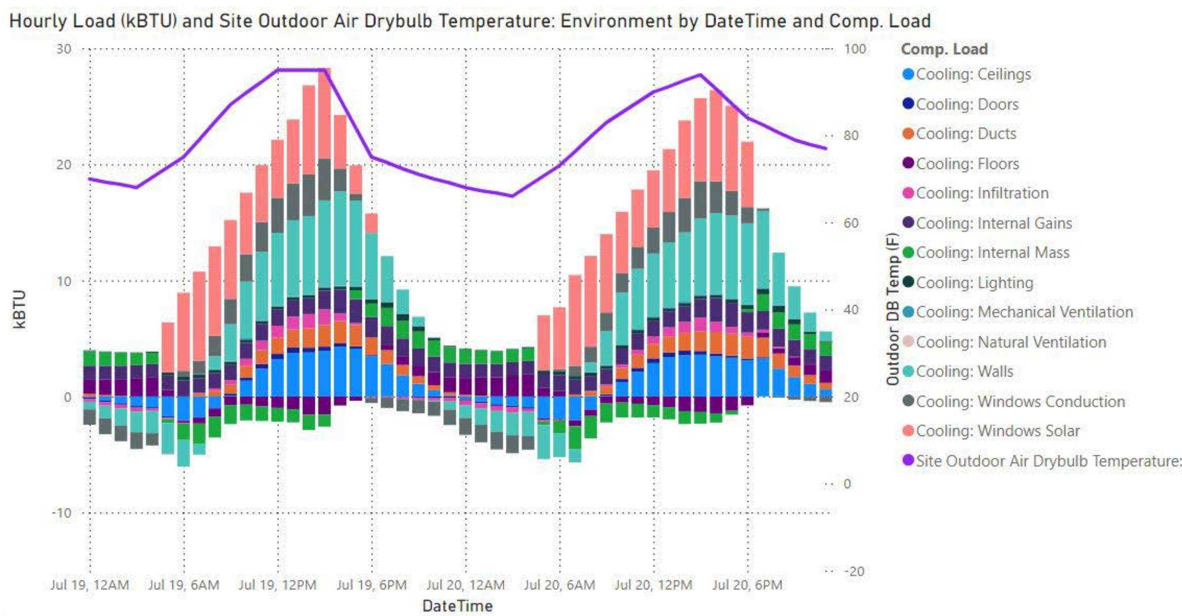

Figure 5. Hourly mid-July cooling load (kBtu) by component with outdoor temperature, Albany NY

Occupant activity, building equipment operation, outdoor temperature, wind, and weather all change with time of day, and contribute to variation in calculated building heating and cooling loads. Figure 6 provides a 24-hour view of hourly simulated heating loads, temperature (purple line), and interpolated Manual J-equivalent loads (dark blue line) for the base building by time of day to explore this contribution.

Walls, window conduction, and infiltration are top component contributors to modeled heating loads over the heating season. In Figure 6, solar and internal gains offset other heating losses (orange line) during a January peak heating day (10 a.m. to 4 p.m. local time) to reduce the net heating load (red line) predicted by EnergyPlus, widening the gap with the Manual J-equivalent load (dark blue line). Outside of daytime hours, internal gains contributions are low and solar gain is not applicable, thus this gap narrows. On the other hand, heating load attributed to floors is one positive load that appears largest during daytime hours and is minimized overnight.

The EnergyPlus predicted peak heating load (red line) at 4 a.m., which represents net heating losses and gains, represents about 80% of the peak Manual J-equivalent load at 7 a.m. The EnergyPlus predicted peak gross heating load (orange line) at 8 a.m. represents 91% of that peak Manual J-equivalent load. An HVAC contractor designing a system for this house could consider sizing a heat pump nearly 10% smaller than the Manual J load would dictate and expect it to maintain comfort on the coldest day.

Figure 6 illustrates the role that building heat gains play in determining heating load for heat pump sizing; however, they also support the case for selecting a smaller-sized heat pump that will maintain thermal comfort even when internal gains are negligible, while reducing on-off cycling operation.

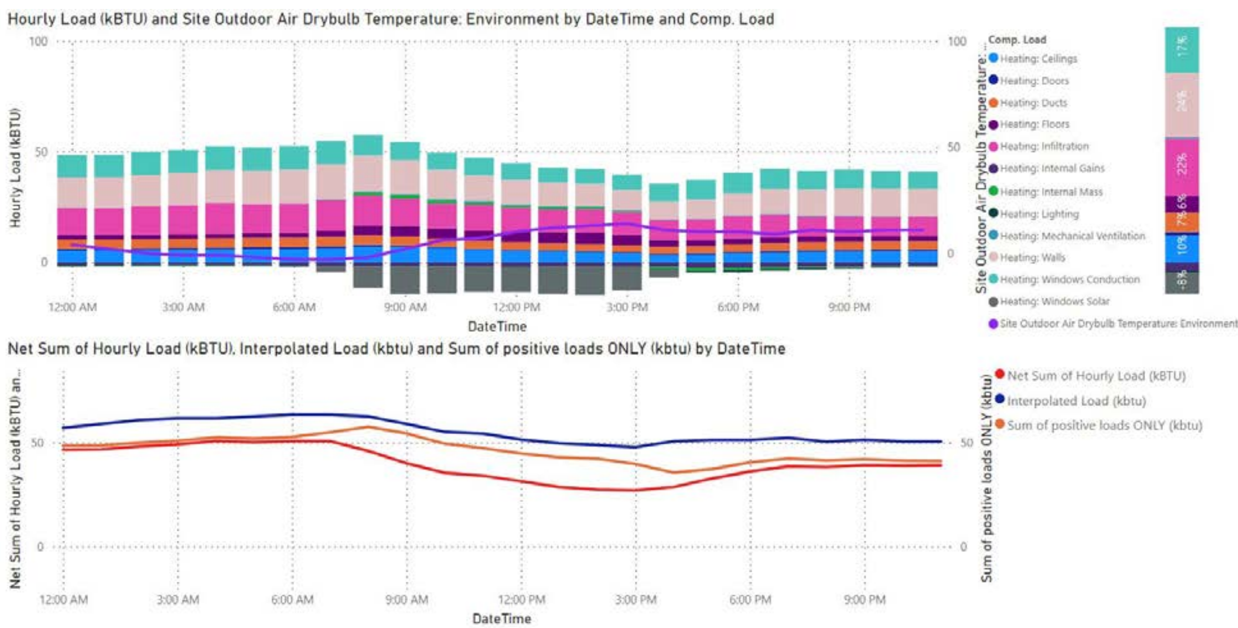

Figure 6. Time of day impact on simulated component heating loads and Manual J-equivalent calculations, Albany NY

The influence of time of day on the two load calculation methods and the components contributing to their differences is further illustrated in Table 4, where peak heating and cooling months of simulated or Manual J-equivalent extrapolated hourly loads, summed over all hours in their time-of-day bins, are compared to their ratios. EnergyPlus hourly load calculations, summed over the heating month of January, are closest to the interpolated specific load given the design load calculations in nighttime hours and early morning hours, when the benefits of solar gains and internal mass heat absorption are minimized. In the cooling month of July, these two calculation methods most closely converge during evening hours. This further supports the conclusion that solar and internal gains experienced during the daytime and morning hours are driving the divergence of the two methods. A heat pump design that considers these gains will result in a smaller heat pump selection that maintains comfort and minimizes on-off cycling during the heating season, compared to a heat pump sized to meet the design heating load.

Table 4. Time of Day Influence on the Relationship Between EnergyPlus and Manual J-Equivalent Load Calculations

Time of Day (Albany, NY)	January Heating Energy from EnergyPlus, kBtu	January Heating Energy from Manual J, kBtu	January EnergyPlus to Manual J-Equivalent Heating Energy Ratio	July Cooling Energy from EnergyPlus, kBtu	July Cooling Energy from Manual J, kBtu	July EnergyPlus to Manual J-Equivalent Cooling Energy Ratio
Morning (5 a.m.– 9 a.m.)	5,273	6,942	76%	395	894	44%
Daytime (10 a.m.– 4 p.m.)	5,282	8,494	62%	2,314	3,769	61%
Evening (5 p.m.– 8 p.m.)	3,552	5,094	70%	999	1,393	72%
Nighttime (9 p.m.– 4 a.m.)	8,337	10,863	77%	73	127	57%

4 Conclusions

Manual J design load calculations used to inform sizing of HVAC equipment with Manual S may drive selection of larger-sized heat pumps than needed to meet most heating load needs in cold climates. The majority of a home’s heating load in a cold climate occurs in moderately cold temperatures in the range of 20°–40°F, rather than when experiencing 99th percentile design temperatures. Sizing a cold climate heat pump to the capacity required to meet heating loads at this design temperature can result in a system that operates below its ideal heating capacity, achieves the target space temperature quickly, and cycles on (at high startup power) and off to compensate, lowering the effective efficiency of the system.

HVAC designers, researchers, and industry stakeholders, such as government or utility program managers, utilizing Manual J for system design or compliance may want to select a smaller-sized heat pump than the capacity needed to meet the Manual J design heating load, allowing the system to operate near its heating capacity during most of the heating season, and allowing backup heat to assist with comfort at the (few) most extreme cold temperatures. Contractors installing heat pumps should encourage their customers to reduce building heating load through envelope improvements, and account for that reduced load when sizing heat pumps to allow the system to modulate more often and spend less time in inefficient cycling mode, resulting in energy and cost savings for the homeowner.

The influence of solar gains, internal gains, and thermal mass explain some but not all of the difference between the Manual J calculation method and the EnergyPlus hourly simulation method when time of day is considered. Further investigation into heating loss assumptions in both approaches could reveal opportunities to further improve heat pump sizing methods for optimized home comfort and energy performance, and further develop this methodology to be a standard-practice HVAC industry tool.

References

Smith, I. (2022). *Variable Speed Heat Pump Product Assessment and Analysis.* Northwest Energy Efficiency Alliance. https://neea.org/resources/variable-speed-heat-pump-product-assessment-and-analysis

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