ComStock Measure Scenario Documentation: Variable-Speed Pumps

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ComStock

Acknowledgments

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List of Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
DHO	dynamic head optimization
EIA	U.S. Energy Information Administration
HVAC	heating, ventilating, and air conditioning
IEC	International Electrotechnical Commission
kBtu	thousand British thermal units
NEMA	National Electrical Manufacturers Association
TBtu	trillion British thermal units
URDB	Utility Rate Database
VSD	variable-speed drive

Executive Summary

Building on the 3-year End-Use Load Profiles project to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models, this work produces national datasets that enable cities, states, utilities, and other stakeholders to answer a broad range of questions regarding their commercial building stock.

ComStock is a highly granular, bottom-up model that uses various data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual sub-hourly energy consumption of the commercial building stock across the United States. The "baseline" model intends to represent the U.S. commercial building stock as it existed in 2018. The methodology of the baseline model is discussed in the ComStock Reference Documentation.

The goal of this work is to develop energy efficiency and demand flexibility measures that cover market-ready technologies and study their mass-adoption impact on the baseline building stock. "Measures" refers to various "what-if" scenarios that can be applied to buildings. The results for the baseline and measure scenario simulations are published in public datasets that provide insights into building stock characteristics, operational behaviors, utility bill impacts, and annual and sub-hourly energy usage by fuel type and end use.

This report describes the modeling methodology for a single ComStock measure scenario—Variable-Speed Pumps—and briefly introduces key results. The full public dataset can be accessed on the ComStock data lake or via the Data Viewer at comstock.nrel.gov. The public dataset enables users to create custom aggregations of results for their use cases (e.g., filter to a specific county or building type).

Key modeling assumptions and technology details are summarized in Table ES-1.

Table ES-1. Summary of Key Modeling Specifications

Technology Description	• This study evaluates the replacement of pump motors (both constant and variable speed) with variable-speed high-efficiency pump motors in existing water-based systems for space heating and cooling, excluding service/domestic water heating. • High-efficiency pumps refer to top-tier products currently available in the U.S. market as of July 2025. • The motors used in these efficient pumps meet or exceed the International Electrotechnical Commission (IEC) IE5 efficiency standard, which is comparable to the National Electrical Manufacturers Association (NEMA) ultra-premium class (not yet standardized). These motors are typically synchronous reluctance motors, which operate at synchronous speed by generating torque through the magnetic reluctance difference in the rotor's anisotropic paths, without requiring permanent magnets or rotor windings. • Enhanced part-load efficiency is achieved through advanced control strategies, such as dynamic differential pressure control—a method for variable-speed pumps that continuously adjusts pump speed to maintain an optimal differential pressure setpoint based on real-time demand, often measured at critical points in the hydronic system.
Performance Assumptions	• The nominal efficiencies of pump motors range from 91% to 96%, depending on the motor's horsepower, compared to ComStock pumps, which typically range from 70% to 96%. • Part-load efficiencies of pump motors vary between 84% and 93%, depending on the part-load ratio, which ranges from 0.1 to 1. • These upgraded pump motors represent the performance characteristics of synchronous reluctance motors currently available on the market. • The pumps represent a dynamic differential pressure control strategy, indicating that they operate as variable-speed pumps.
Applicability	• Applicable to pumps used for space heating and cooling: chiller system, boiler system, and district heating and cooling system. • Constant-speed pumps in existing buildings are replaced with variable-speed pumps featuring advanced part-load performance enabled by modern control strategies. • Older variable-speed pumps are upgraded to newer models with advanced part-load efficiency through modern control technologies, such as dynamic static pressure reset. • Not applicable to pumps used for service/domestic water heating.
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National annual results for site energy and energy bills are summarized in Table ES-2 and Table ES-3.

Table ES-2. Summary of Key Results for Annual Site Energy Savings

"Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (trillion British thermal units [TBtu])
Natural gas	-0.22%	-0.51%	-3.1
Electricity	0.43%	1.6%	14.4
Fuel oil	-0.39%	-0.71%	-0.21
Propane	-0.1%	-0.88%	-0.043
Total	**0.23%**	**0.71%**	**11.1**

Table ES-3. Summary of Key Results for Annual Utility Bill Savings

Electricity bill savings in this table are calculated using the mean available electricity rate available for each building. Other electricity rate structures are available in this report and in the public dataset. "Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

End Use/Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (million USD, 2022)
Natural gas	-0.21%	-0.5%	-0.034
Electricity	0.37%	1.4%	0.41
Fuel oil	-0.39%	-0.71%	-0.0069
Propane	-0.091%	-0.85%	-0.0011
Total	**0.28%**	**0.96%**	**0.37**

Table of Contents

List of Figures

List of Tables

No table of figures entries found.

1 Introduction

Water-based (hydronic) heating and cooling systems are widely used in commercial and residential buildings, relying on pumps to circulate fluid throughout piping loops in the building. Pumps play a critical role in the operation of these systems. According to data from the Commercial Buildings Energy Consumption Survey (CBECS) [1], pumps are most commonly used in commercial buildings for space heating and cooling hydronic systems. Figure 1 illustrates the importance of pumps worldwide and in the United States, highlighting the rapidly increasing energy demand associated with motor-driven systems. The energy consumption attributed to pumps varies depending on factors such as building type, size, and system design, but pumps generally represent a noticeable portion of a building's electrical load. Many existing pumps operate at fixed speeds with throttling control, which often leads to inefficiencies. However, there is a growing adoption of variable-speed drives (VSDs) and advanced control strategies to improve pump efficiency and reduce energy use [2]. Upgrading pumps and optimizing their control thus present important opportunities for energy and cost savings in the commercial buildings sector.

Beyond buildings, pumps driven by electric motors constitute a substantial share of global electricity consumption [2]. Motors already account for roughly one-third of global electricity use, with projections indicating this demand could double by 2040. In the United States, industrial motor systems are primarily composed of three key applications: pump systems (40%), fan systems (20%), and compressed air systems (22%) [2]. These segments together dominate motor-driven electricity consumption, emphasizing their critical role in future energy efficiency initiatives.

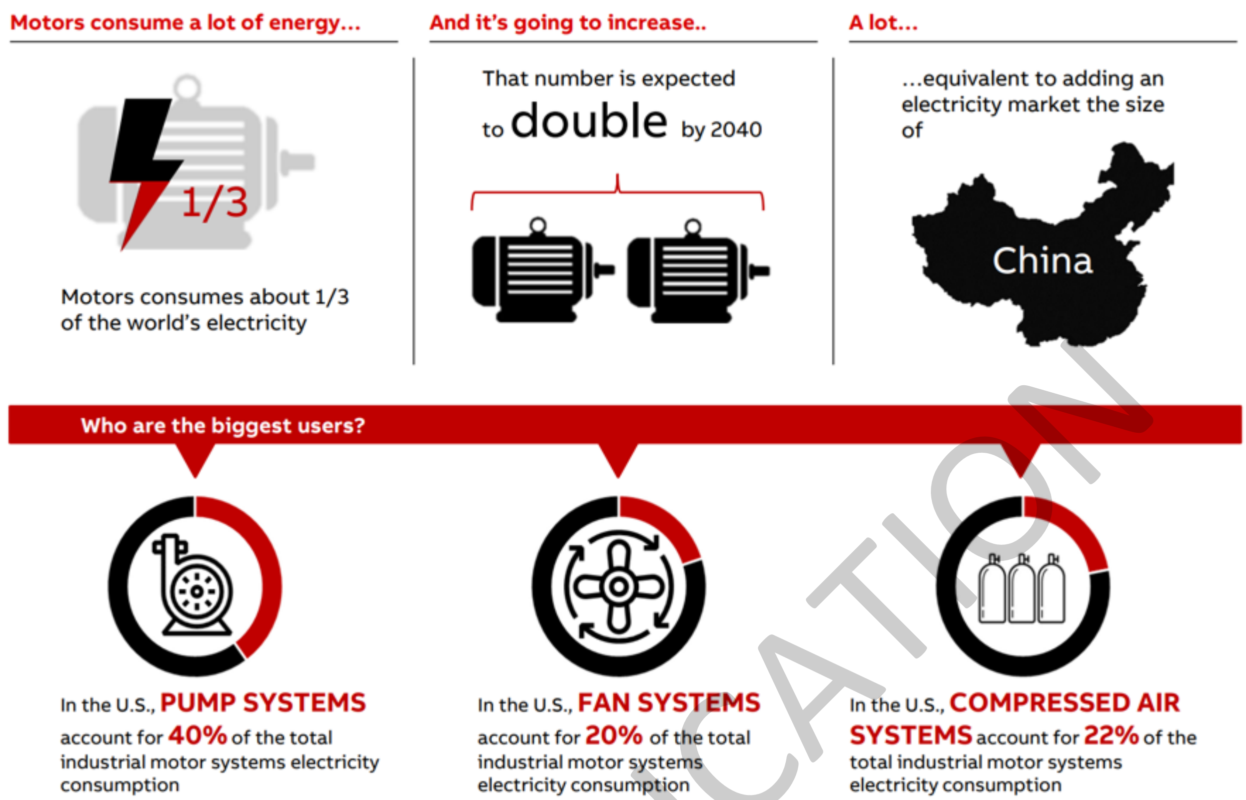


Figure 1. Importance of pumps [2]

Recent advances in pumping technology have been driven by improvements in motor design, control strategies, and system integration. The pumps evaluated in this study utilize motors that meet or exceed the International Electrotechnical Commission's (IEC) IE5 efficiency standard [3], representing the emerging ultra-premium class as defined by the National Electrical Manufacturers Association (NEMA) [4]. These high-efficiency motors are typically synchronous reluctance motors (and more advanced motors using ferrite-assisted rotor design), which generate torque through magnetic reluctance differences in the rotor without requiring permanent magnets or rotor windings. This design achieves a balance of high efficiency and reliability, making synchronous reluctance motors particularly well-suited for variable-speed pump applications [2], [5].

In addition to motor improvements, advanced control strategies such as dynamic differential pressure control further enhance efficiency under part-load operating conditions. This method continuously adjusts pump speed to maintain optimal differential pressure at critical points within the hydronic system, responding in real time to varying demand. By minimizing unnecessary energy use while maintaining system comfort and stability, dynamic differential pressure control represents a key opportunity for improving pump operation.

High-efficiency pumps available in the U.S. market today typically feature motors that meet or exceed advanced efficiency standards such as IEC IE5, along with VSDs for optimized part-load performance. These pumps often incorporate advanced control strategies, including dynamic differential pressure control, to continuously adjust pump operation based on real-time system demand. This enables hydronic systems to operate at reduced flow rates during periods of lower building loads, noticeably reducing overall energy use while maintaining comfort and performance. Many drive models are compatible with building automation systems, allowing seamless integration and smart diagnostics. Enhanced motor designs—such as synchronous reluctance motors—offer improved reliability and energy savings compared to traditional motors. Taken together, these features allow high-efficiency pumps to reduce both pumping energy and water flow, support stable system performance, and qualify for utility incentives.

This report details the scope of pump upgrades, including performance assumptions based on nominal and part-load efficiencies drawn from published manufacturer data. The study simulates and analyzes the energy and performance impacts of replacing old pumps with modern variable-speed pumps featuring advanced part-load control capabilities. By quantifying these improvements, it aims to provide practical guidance for building owners and engineers seeking to modernize water-based heating and cooling systems for greater energy efficiency and performance.

2 ComStock Baseline Approach

The ComStock™ baseline models simulate pump systems used in various hydronic loops, including heating hot water, chilled water, condenser water, service/domestic water heating, and ground-source heat pump loops. Pump power is modeled based on loop-specific pressure head requirements aligned with American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 standards and incorporates motor efficiencies consistent with those used for fans. ComStock accounts for both primary-only and primary-secondary loop configurations, reflecting common design practices in commercial heating, ventilating, and air-conditioning (HVAC) systems.

In ComStock, all pumps use intermittent control, allowing them to turn off when the loop has no load. Constant-volume pumps follow the ASHRAE 90.1 pump curve, while variable-speed pumps vary speed to modulate flow. Variable-speed pumps are modeled with a 0% minimum flow ratio, which likely underestimates energy use because most systems must maintain roughly 30%–50% flow to keep equipment like chillers and boilers operating properly. These assumptions guide how pumping energy is estimated across different building types and system configurations in the ComStock models. This is also described in detail in the ComStock Reference Documentation [6].

The characteristics of existing HVAC systems in ComStock are primarily determined by building type, as HVAC system types vary by building use. HVAC equipment performance is assumed to comply with the energy code requirements in effect at the time and location of installation, which informs assumptions about system efficiency. Figure 2 presents the heating/cooling type percentage of floor area by building type. It also reflects the proportion of systems that include water pumps for space heating and cooling—specifically, those with boilers, chillers, and district water systems.

Figure 2. ComStock baseline heating and cooling system type percentages of floor area by building type

GSHP = ground-source heat pump; WSHP = water-source heat pump; ASHP = air-source heat pump; DX = direct expansion

3 Modeling Approach

This section outlines the modeling approach for this upgrade or measure, including its applicability (i.e., when and where the upgrade happens), the methodology used for modeling the measure (i.e., how the upgrade pumps are represented), additional modeling details (such as how energy bills are calculated), and the limitations of this measure (i.e., any gaps or constraints in the modeling process).

3.1 Applicability

In this study, the term "applicability" refers to when and where an upgrade is implemented across the building stock. For example, if a baseline building model already includes an energy-efficient system (as is sometimes the case in ComStock), we avoid replacing it with an upgrade that performs equally or worse. Therefore, "applicability" defines the specific conditions under which an upgrade is applied to an existing building model.

For this upgrade, the first step is to determine whether the building model includes any water-based systems that use pumps. These systems may be associated with space heating (e.g., using boilers), space cooling (e.g., using chillers), or service water heating (e.g., water heaters). However, the primary focus of this upgrade is on space heating and cooling systems.

Once it is confirmed that space heating and cooling water systems are present in the existing building model, the measure identifies all pumps associated with those systems. Regardless of whether the existing pumps are constant speed or variable speed, the upgrade attempts to replace all of them according to the specifications outlined in Section 3.2.

However, if the existing pump specifications (e.g., motor efficiency) are already better than those defined by this upgrade, no replacement will be made for those pumps. For detailed information on the pump specifications used in this upgrade, refer to Section 3.2.

Again, the variable-speed pump measure applies to ComStock models that utilize water-based systems for space heating or cooling, representing approximately 31% of the total ComStock floor area (Figure 3). The distribution of HVAC system types in ComStock is based on data from the 2012 and 2018 CBECS. The methodology used to interpret CBECS data and develop HVAC probability distributions for ComStock is detailed in the ComStock Documentation report [6]. As illustrated in Figure 3 (note the logarithmic scale on the *x*-axis), the applicable HVAC systems include components such as chillers, boilers, and district heating and cooling systems.

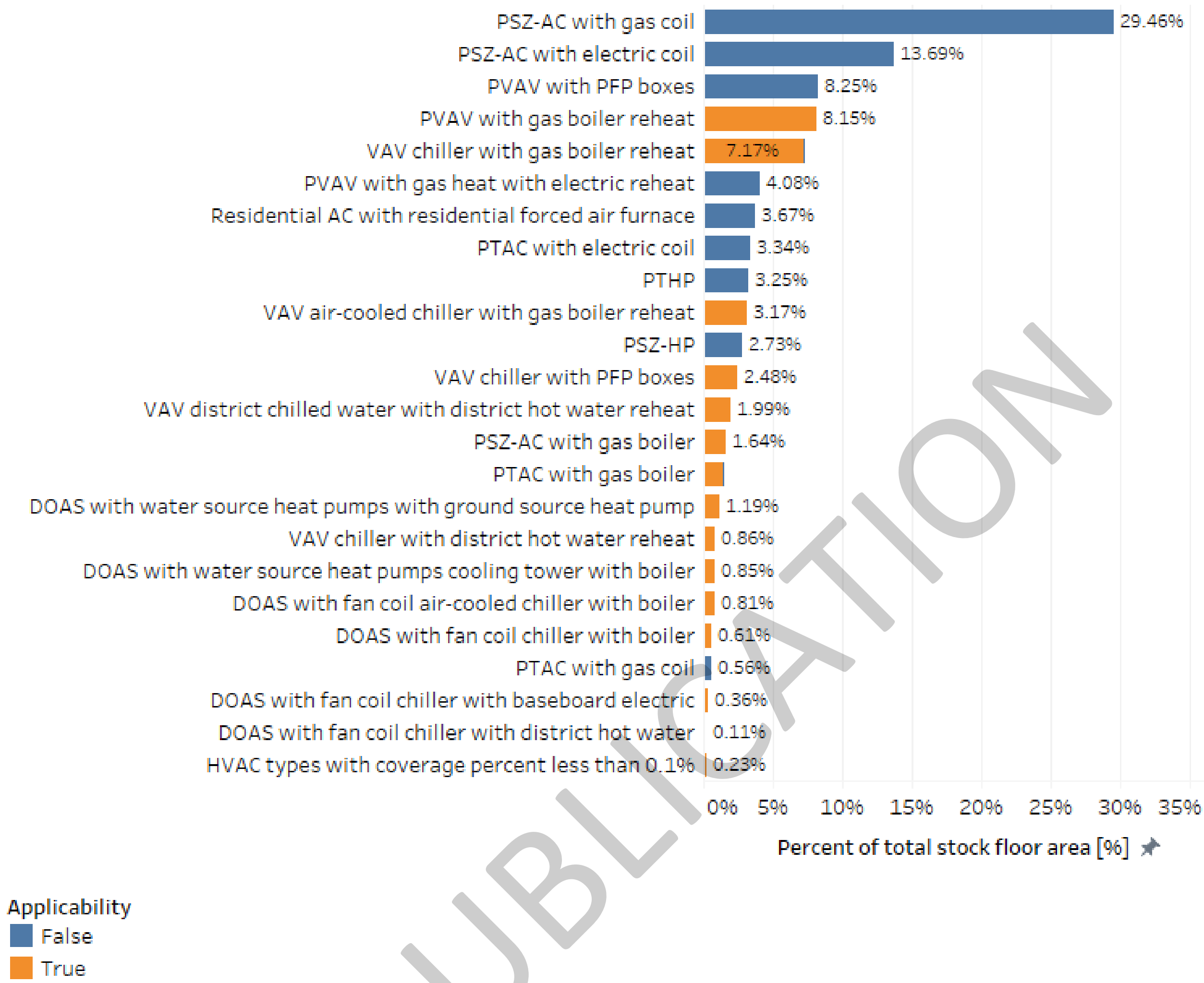


Figure 3. ComStock HVAC system type prevalence by stock floor area.

PSZ-AC = packaged single-zone air conditioner; PTHP = packaged terminal heat pump; PFP = parallel fan power; PTAC = packaged terminal air conditioner; VAV = variable air volume; PVAV = packaged variable air volume; DOAS = dedicated outdoor air system

In real-world applications, variable-speed pumps are often used in both the primary and secondary loops of chilled water and hot water systems to maximize energy efficiency and operational flexibility. While ASHRAE 90.1 appendix G typically assumes a constant-flow primary loop paired with a variable-flow secondary loop for chilled water systems, and often constant-flow configurations for hot water systems, modern designs are increasingly adopting fully variable-flow configurations for both. This shift reduces pumping energy, enhances equipment performance, and maintains optimal temperature differentials across a wide range of load conditions. Additionally, dynamic control strategies such as differential pressure reset and supply temperature reset further improve system responsiveness and lower operating costs. Accordingly, this study explores the use of fully variable-flow pumps in both chilled water and hot water systems.

3.2 Measure Scenario Modeling Methodology

The following sections detail the specific pump technologies and control strategies selected for modeling in this study.

3.2.1 Nominal Efficiencies of Variable-Speed Pumps

Nominal motor efficiency refers to the percentage of electrical energy input to a pump motor that is effectively converted into mechanical energy output under standardized, full-load operating conditions. It represents the motor's ability to minimize energy losses due to heat, friction, and electrical resistance when running at its rated power. This efficiency is typically measured and specified at the motor's nameplate rating and serves as a key indicator of the motor's overall performance and energy consumption. Higher nominal efficiencies correspond to reduced energy waste and lower operating costs, making it an important metric when selecting pumps for energy-efficient building systems.

The IEC defines motor efficiency classes ranging from IE1 (standard efficiency) to IE5 (ultra-premium efficiency), with typical nominal efficiencies increasing progressively across these classes. For example, IE2 motors generally achieve efficiencies around 85%–90%, IE3 motors range around 90%–94%, IE4 motors reach about 94%–96%, and IE5 motors can exceed 96% efficiency under full-load conditions, though actual efficiency within each class varies depending on motor size and specific operating conditions. These IEC classes broadly correspond to NEMA efficiency classifications, where IE2 aligns with NEMA Premium, and IE5 represents an emerging ultra-premium category that is not yet formally standardized by NEMA but reflects the highest efficiency motors currently available. This study focuses on pumps equipped with motors meeting or exceeding the IEC IE5 standard, aiming to capture the energy savings potential and performance benefits associated with these cutting-edge ultra-premium efficiency motors. Figure 4 highlights characteristic differences between different types of motors.

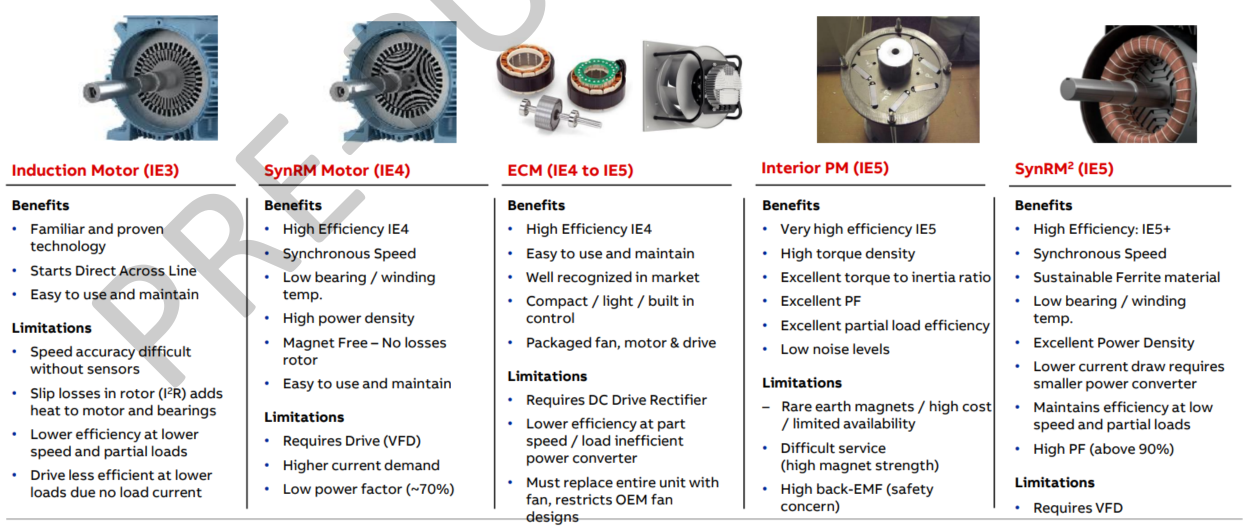


Figure 4. Comparisons of different types of motors [2]

To apply realistic nominal efficiencies from published manufacturer data to EnergyPlus®, we leverage EnergyPlus sizing parameters such as design flow rate and design head pressure to calculate corresponding design power consumption and motor efficiency.[1] While there are many other required input fields for modeling variable-speed pumps in EnergyPlus, these two are chosen to reflect nominal efficiencies of pumps we are interested in. The two inputs (design flow rate and design head pressure) can be used to calculate design power consumption as

$$P_{design} = \frac{Q \times H}{\eta_{pump} \times \eta_{motor}} \quad (1)$$

where:

- P_{design} is design power consumption in watts (W), mapped with manufacturer data
- Q is design flow rate in cubic meters per second (m^3/s), calculated from EnergyPlus sizing algorithm
- H is pump head in pascals (Pa, or N/m^2), calculated from OpenStudio® Standards workflow
- η_{pump} is pump efficiency (decimal, e.g., 0.75), assumed a constant value
- η_{motor} is motor efficiency (decimal, e.g., 0.90), mapped with manufacturer data.

Since motor efficiency (which we are correlating with design power) is already accounted for in the equation, an iterative approach is adopted to estimate design power by leveraging the observed relationship between design power consumption and motor efficiency derived from published manufacturer data. Figure 5 illustrates this relationship using data from two manufacturer catalogs, covering pumps ranging from 0.46 hp to 50 hp, with corresponding motor efficiencies ranging from 89% to 96% [7], [8], all of which meet or exceed the IEC IE5 efficiency standard.

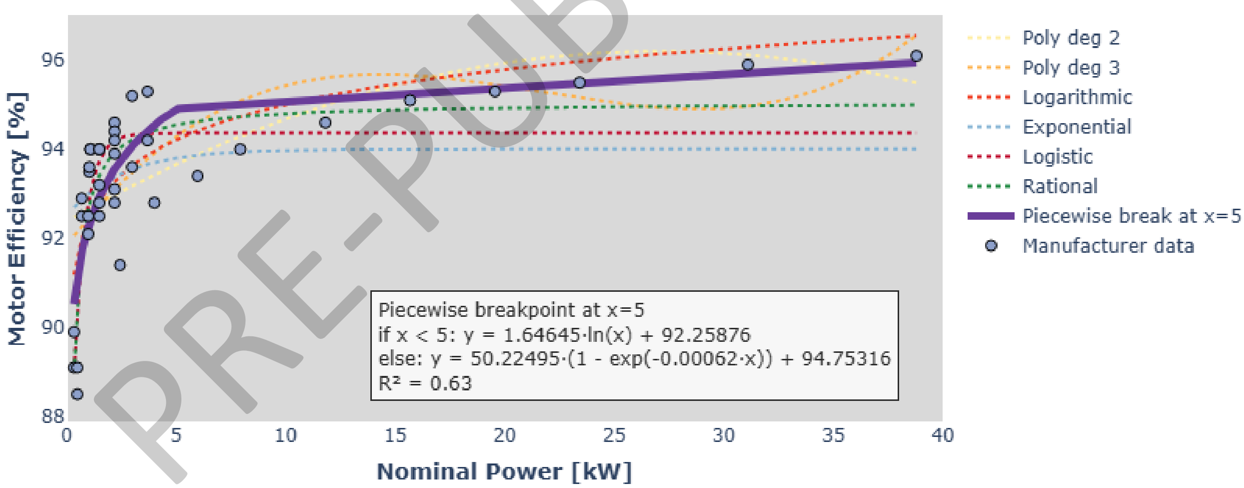


Figure 5. Regression fitting on manufacturer data: motor nominal efficiency

Seven regression models were evaluated, and a piecewise regression curve with a fixed breakpoint at 5 kW was selected for final implementation. This model best captures the steep increase in efficiency at lower power ratings and the gradual rise at higher ratings. While other

[1] Definitions of these terms can be found at https://bigladdersoftware.com/epx/docs/24-2/input-output-reference/group-pumps.html.

models failed to reflect this nonlinear trend adequately, the logarithmic model captured the behavior well. However, it was ultimately unsuitable, as motor efficiency cannot be calculated for power inputs equal to or below 1 kW (e.g., log(1) = 0), limiting its applicability in the lower range.

3.2.2 Part-Load Efficiencies of Variable-Speed Pumps

Part-load efficiency refers to the performance of a pump motor when operating below its full-rated capacity, typically under varying loads common in real-world conditions. Since pumps rarely need to operate at full load design load, part-load efficiency measures how effectively the motor converts electrical energy into mechanical energy during partial operation, such as at reduced flow or pressure demands when building loads are less than design conditions. Efficient part-load performance is critical because it directly influences the overall energy consumption of pumping systems throughout their various operating conditions. Advanced motor designs and control strategies—such as VSDs—improve part-load efficiency by adjusting motor speed and torque to match system requirements, thereby reducing energy waste and lowering operational costs.

Dynamic head optimization (DHO) is an advanced pump control strategy that continuously adjusts the pump setpoint to maintain the minimum required differential pressure across a hydronic system based on real-time demand. Unlike traditional differential pressure reset methods that rely on predefined schedules or fixed sensor locations, DHO uses distributed pressure or flow sensors combined with building automation system feedback to dynamically reduce pump head while ensuring adequate flow to all terminal units. This approach minimizes unnecessary energy consumption caused by overpressurization—especially under part-load conditions—and is often integrated with VSDs or variable-frequency drives to optimize pump efficiency across the entire operating range. DHO is commonly implemented in high-performance HVAC systems and district energy plants aiming to maximize energy savings without compromising comfort or equipment performance.

To develop an advanced part-load performance curve representing DHO control, we leveraged publicly reported energy savings from three peer-reviewed studies. Zhao et al. [9] reported pump energy savings of 11% using an optimal loop-based differential pressure reset strategy compared to conventional differential pressure reset. Additionally, Zhufang [10] evaluated an optimal differential pressure reset and observed about 13% energy reduction relative to the conventional method. Based on these findings, which specifically capture the impact of modern control strategies by holding other variables constant and varying only the control approach, we conservatively applied the minimum reported savings from each study—11% and 13%, respectively. Thus, for curve development, we used the 11% pump energy savings during part-load operation, relative to the standard VSD differential pressure reset strategy (the best-performing curve currently available in OpenStudio Standards).

Figure 6 illustrates the new curve (labeled as VSD DHO) alongside existing curves from the OpenStudio Standards, highlighting the additional power savings (i.e., 11% reduction in fraction of full-load power) under part-load conditions compared to the conventional differential pressure reset (shown as VSD DP reset). The optimization maintains the cubic form while proportionally reducing the area under the curve—which represents total energy consumption—by 11%. The affinity law curve ($y = x^3$), representing ideal lossless performance, is also shown for reference.

The resulting VSD DHO curve performs slightly below the affinity law but better than conventional reset strategy (i.e., VSD DP Reset in Figure 6).

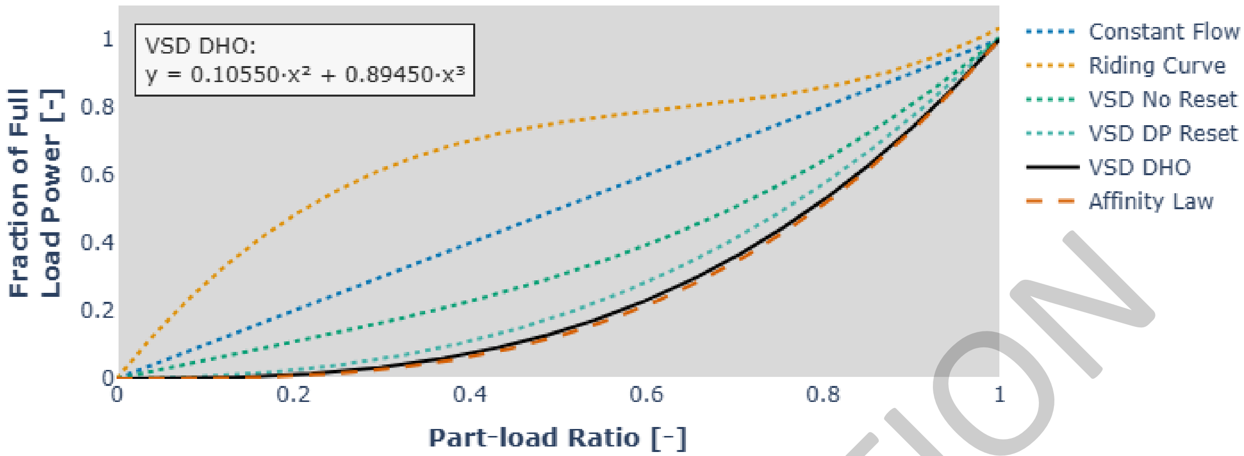


Figure 6. Regression fitting on manufacturer data: pump part-load efficiency

3.2.3 Upgrades in Other Parts of the Water System

Advanced variable-speed pumps with dynamic control strategies such as DHO can achieve significantly greater efficiency when paired with system-level reset strategies. For instance, resetting chilled and hot water supply temperatures based on outdoor air conditions can reduce overall pumping energy during mild weather by enabling pumps to operate at lower speeds and heads, even if flow rates increase due to smaller temperature differentials. Similarly, optimizing condenser water setpoints can lower system lift and flow requirements, further reducing pump energy consumption.

While these advanced strategies can enhance system performance, they are not universally standard in pump replacement projects and depend on the capabilities of existing equipment and the readiness of control systems. To account for this variability, our modeling methodology provides options to enable or disable these reset strategies based on specific measure arguments, giving users the flexibility to adapt the analysis to their project's scope and constraints. In this report, the following strategies have been only implemented in the sensitivity study in Section 5.2 in conjunction with the pump replacement:

- Chilled water supply temperature reset based on outdoor air temperature
- Hot water supply temperature reset based on outdoor air temperature.

3.3 Utility Bills

ComStock provides utility bill estimates for several fuel types in buildings: electricity, natural gas, propane, and fuel oil. The current implementation represents utility bills circa 2022, which is the most current year of utility data available from the U.S. Energy Information Administration (EIA). This section provides a high-level overview of the methodology behind utility bills in ComStock; more detailed information is available in the ComStock Reference Documentation [6]. Summary statistics from this implementation are shown in Table 1. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 1. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural gas	$0.007/kBtu ($0.70/therm)[a]	$0.012/kBtu ($1.20/therm)	$0.048/kBtu ($4.80/therm)
Propane	$0.022/kBtu ($2.20/therm)	$0.032/kBtu ($3.20/therm)	$0.052/kBtu ($5.20/therm)
Fuel oil	$0.027/kBtu ($2.70/therm)	$0.033/kBtu ($3.30/therm)	$0.036/kBtu ($3.60/therm)
Electricity	$0.003/kBtu ($0.01/kWh)	$0.035/kBtu ($0.12/kWh)	$3.530/kBtu ($12.04/kWh)

[a] kBtu = thousand British thermal units

Natural gas bills are estimated using 2022 EIA averages by state. 2022 U.S. EIA Natural Gas Prices - Commercial Price and U.S. EIA Heat Content of Natural Gas Delivered to Consumers are used to create an energy price in units of $/kBtu [11].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type and U.S. EIA residential Weekly Heating Oil and Propane Prices (October–March) and EIA assumed heat content for these fuels are used to create an energy price in units of $/kBtu [12]. Residential prices are used because commercial prices are only available at the national resolution. Additionally, most commercial buildings using these fuels are assumed to be smaller buildings where a residential rate is likely realistic. For states where state-level pricing was available, these prices are used directly. For other states, Petroleum Administration for Defense District (PADD)-average pricing is used. For states where PADD-level pricing is not available, national average pricing is used.

The primary resource for ComStock electric utility rates is the Utility Rate Database (URDB), which includes rate structures for about 85% of the buildings and 85% of the floor area in ComStock [13]. The URDB rates include detailed cost features such as time-of-use pricing, demand charges, ratches, etc. ComStock only uses URDB rates that were entered starting in 2013, and a cost adjustment factor is applied such that the rates reflect 2022 U.S. dollars.

URDB rates are assigned to ComStock models at the census tract level. The URDB can include several rate structures for a census tract. Instead of attempting to presume any single rate, multiple rates from the model's census tract are simulated; the ComStock dataset includes the minimum, median, mean, and maximum simulated rates for each model.

Many precautions are implemented to prevent less reasonable rates from being applied. This includes removing non-commercial rates, rates with non-building-load keywords (e.g. Security Light, Irrigation, Snow, Cotton Gin), rates where the load profile does not follow any potential min/max demand or energy consumption qualifiers, and rates that cause suspiciously low (<$0.01/kWh) or high (>$0.45/kWh) blended averages. Additionally, any bill that is lower than 25% of the median or higher than 200% of the median is eliminated to avoid extreme bills.

For buildings with no URDB electric utility assigned, or for buildings where none of the stored rates are applicable, the annual bill is estimated using the 2022 EIA Form-861 average prices based on the state each model is located in [14]. While this method does not reflect the detailed rate structures and demand charges, it is a fallback for the 15% of buildings in ComStock with no utility assigned.

3.4 Limitations and Concerns

Comprehensive pump performance maps across many different manufacturers, which are required for detailed energy modeling, are not publicly available. Consequently, we must make engineering judgments to closely reflect products in the current market. The work presented here attempts to use the most informative data available and makes documented assumptions about chiller operation and performance. These will notably impact results. Please consider these assumptions.

- Figure 5 presents our assumptions for modeling motor efficiencies of pumps meeting or exceeding the IEC IE5 standard. While relevant data points were collected from two different manufacturers, this dataset is not comprehensive and does not capture the full range of products available on the market. Therefore, it should be noted that our basis assumptions for motor efficiencies are based on information from these specific manufacturers.
- Electric motors can be applied across a wide range of systems, including fans and pumps in HVAC applications. However, during the data collection stage, it was not always clear whether the motor products examined were specifically representative of those commonly used in HVAC pump systems. Although direct case studies documenting the use of one of the synchronous motors (shown in Figure 5) in HVAC water pumping applications are not currently available, their deployment in other high-demand environments—such as clean-in-place systems, conveyor systems, and food processing facilities—demonstrates their suitability for continuous-duty, variable-load operation. Given that electric motors are fundamentally modular components, their applicability is primarily determined by compatibility with system performance requirements (e.g., torque, speed, power), environmental constraints (e.g., ingress protection, thermal ratings), and control integration (e.g., variable-frequency drive compatibility, feedback systems). Based on these considerations, we made an engineering judgment to assume that such motors are applicable to water pumps used in building HVAC systems.

4 Output Variables

Table 2 includes a list of output variables that are calculated in ComStock. These variables are important for understanding the differences between buildings with and without the Variable-Speed Pumps measure applied. These output variables can also be used for understanding the economics of the upgrade (e.g., return on investment) if cost information is available (i.e., material, labor, and maintenance costs for technology implementation).

Table 2. Output Variables Calculated From the Measure Application

Variable Name	Description
out.params.pump_flow_weighted_avg_motor_efficiency	Rated flow weighted average motor efficiency of pumps
out.params.pump_flow_weighted_avg_motor_efficiency_const_spd	Rated flow weighted average motor efficiency of constant-speed pumps
out.params.pump_flow_weighted_avg_motor_efficiency_var_spd	Rated flow weighted average motor efficiency of variable-speed pumps
out.params.pump_count_hvac_const_spd	Total count of constant-speed pumps in HVAC systems
out.params.pump_count_hvac_var_spd	Total count of variable-speed pumps in HVAC systems
out.params.pump_count_swh_const_spd	Total count of constant-speed pumps in service water heating systems
out.params.pump_count_swh_var_spd	Total count of variable-speed pumps in service water heating systems
out.params.pump_total_constant_speed_pump_power_w	Total power of constant-speed pumps in watts
out.params.pump_total_variable_speed_pump_power_w	Total power of variable-speed pumps in watts

5 Results

In this section, results are presented both at the stock level and for individual buildings through savings distributions. Stock-level results include the combined impact of all the analyzed buildings in ComStock, including buildings that are not applicable to this measure. Therefore, they do not necessarily represent the energy savings of a particular or average building. Stock-level results should not be interpreted as the savings that a building might realize by implementing the measure.

Total site energy savings are also presented in this section. Total site energy savings can be a useful metric, especially for quality assurance/quality control, but this metric on its own can have limitations for drawing conclusions. Further context should be considered, as site energy savings alone do not necessarily translate proportionally to savings for a particular fuel type (e.g., gas or electricity), source energy savings, or cost savings. This is especially important when a measure impacts multiple fuel types or causes decreased consumption of one fuel type and increased consumption of another. Many factors should be considered when analyzing the impact of a strategy, depending on the use case.

While Sections 5.1 and 5.2 present results of two upgrade scenarios—(1) pump replacement only and (2) pump replacement with chilled water/hot water reset control—the stock-level results presented in Section **Error! Reference source not found.** and beyond, as well as in the published dataset, reflect only the pump-replacement-only scenario.

5.1 Single-Building Measure Tests

In this section, we analyze the performance of a medium office building model—equipped with a variable air volume system connected to water-cooled chiller, cooling tower, and natural gas boiler—located in Montgomery, Alabama (climate zone 3A) to demonstrate the application of the measure scenario to a single building.

In this building, the HVAC system includes four pumps: one for the primary chilled water loop, one for the secondary chilled water loop, one for the cooling tower condenser loop, and one for the hot water loop. In the baseline model, variable-speed pumps are used in the secondary chilled water and hot water loops while constant-speed pumps are used in the other two loops. In the upgrade scenario, both constant and variable-speed pumps are replaced with variable-speed pumps featuring higher motor efficiency and improved part-load performance. However, because pump operation is governed by system controls—such as the method used to regulate chilled water temperature setpoints— the efficiency improvement in the simulation will result solely from the enhanced motor efficiencies of the new pumps if the control system cannot modulate pump speeds under part-load conditions.

Figure 7 and Figure 8 present the results of pump-replacement-only scenario—one with pump replacements (labeled “Upgrade”) and one without (labeled “Baseline”). Key metrics related to the pump replacement are shown as annual average daily profiles, differentiated by cooling and heating seasons for this location.

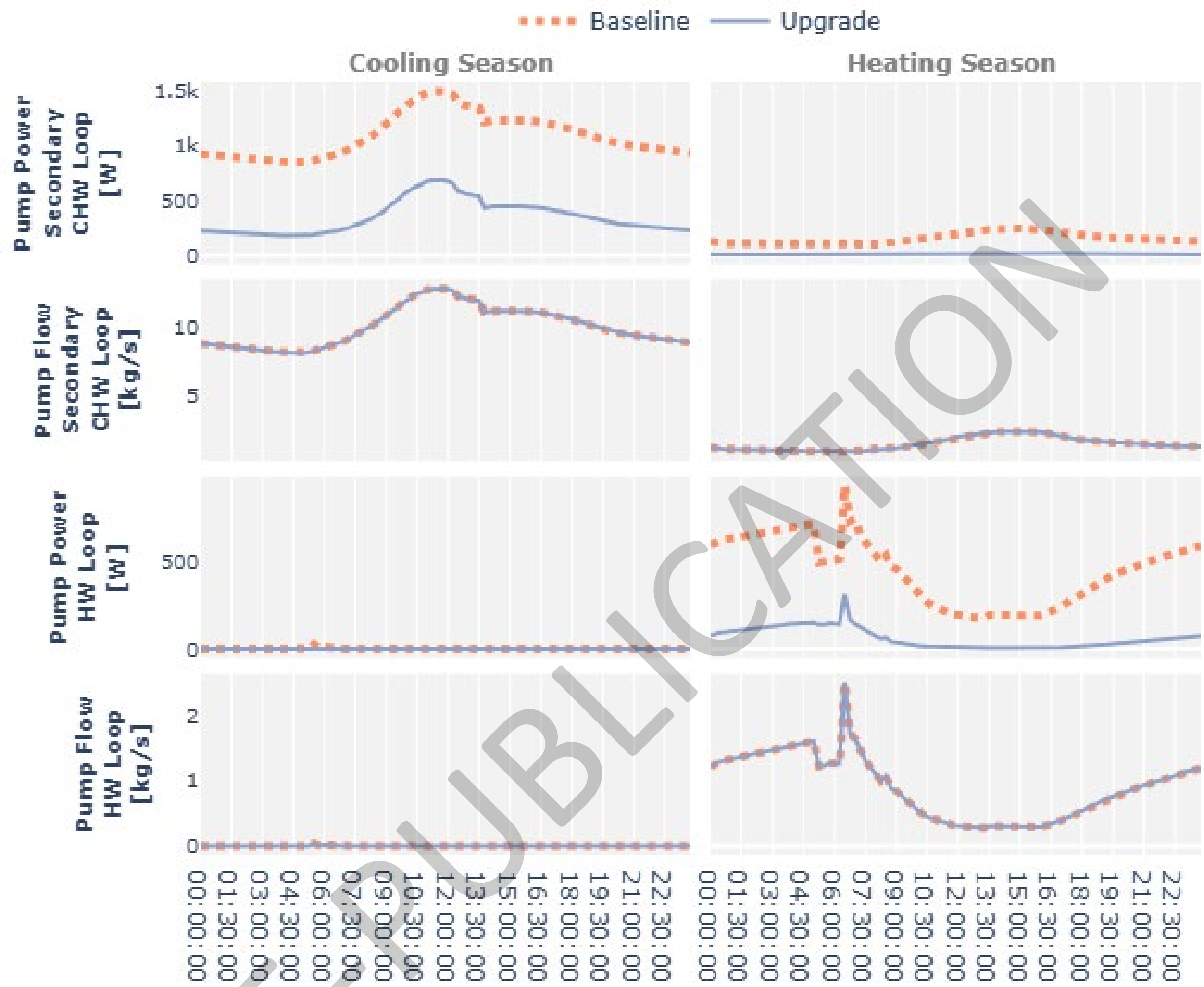


Figure 7. Pump replacement test: replacing existing variable-speed pumps.

CHW = chilled water; HW = hot water

Figure 7 compares the baseline and upgrade scenarios, focusing on the replacement of existing variable-speed pumps with higher-performing variable-speed models. Since these pumps were already capable of reducing speed under part-load conditions, the water flow rates in the secondary chilled water and hot water loops remain unchanged between the baseline and upgrade scenarios. However, as highlighted in Figure 6, the upgraded pumps exhibit improved part-load efficiencies, resulting in lower pump power consumption as shown in Figure 7. For reference, the baseline pump in the secondary chilled water loop used the “VSD No Reset” curve shown in Figure 6, while the baseline pump in the hot water loop used the “Riding Curve.”

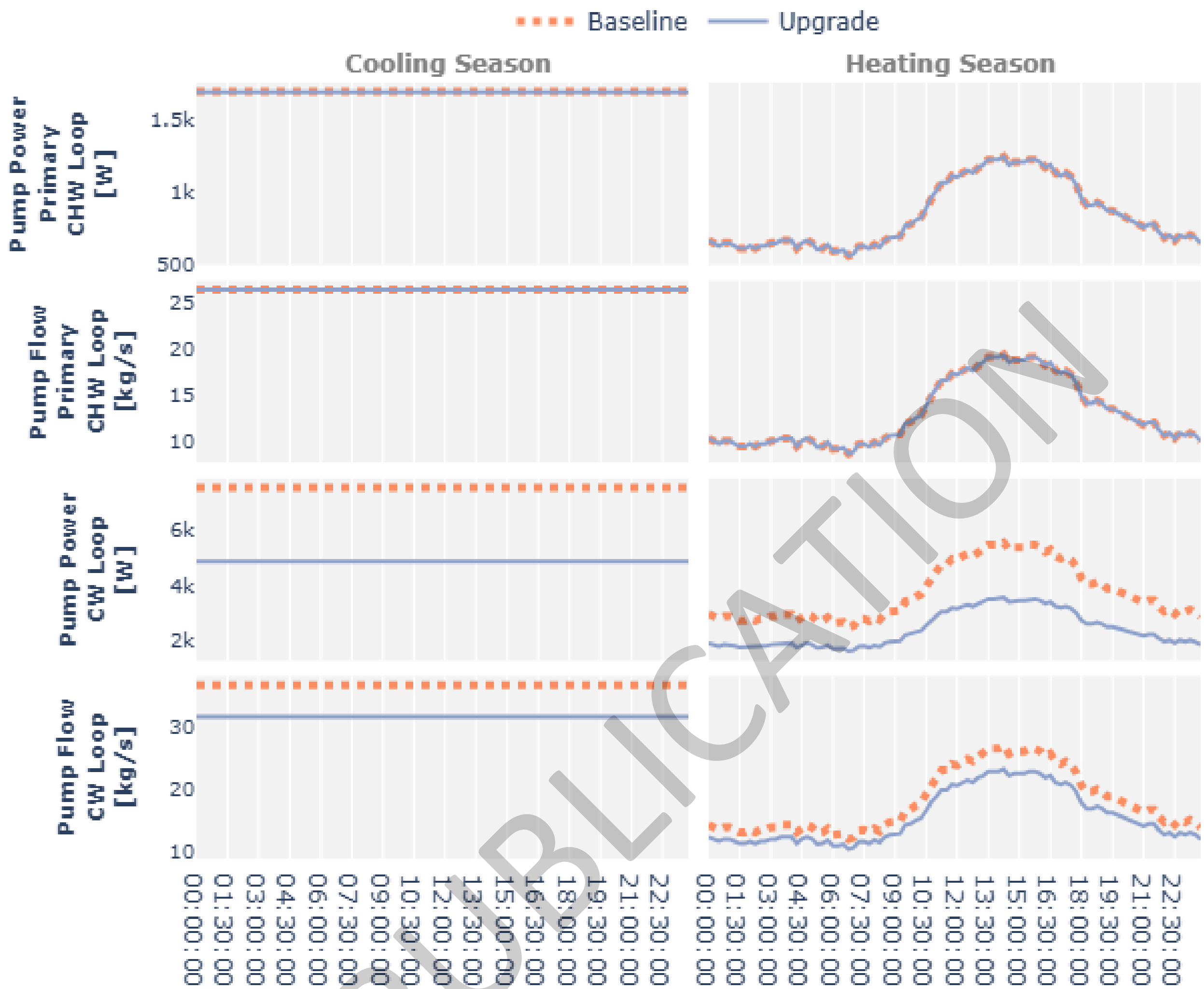


Figure 8. Pump replacement test: replacing existing constant-speed pumps.

Figure 8 presents similar plots, this time focusing on the replacement of existing constant-speed pumps with higher-efficiency variable-speed models. Since the pump flow control logic remains unchanged in this upgrade scenario, the primary chilled water loop pump—which operates at a constant speed while the chiller modulates capacity based on load—shows no variation in water flow rate between baseline and upgrade. However, due to a roughly 3% improvement in motor efficiency with the new variable-speed pump, the upgrade scenario results in slightly (i.e., not noticeable in the plot) lower pump power compared to the baseline constant-speed pump in the primary chilled water loop.

In Figure 8, the upgraded condenser water pump shows a noticeable reduction in flow rate under part-load conditions. This behavior is expected because the condenser water loop is operated under temperature-based control, in which cooling tower fan speed and condenser water flow are modulated to maintain the condenser leaving water temperature setpoint. As outdoor conditions improve or chiller load decreases, the variable-speed condenser pump can therefore slow down and reduce flow. Despite this modulation, the condenser water pump exhibits a higher absolute power level than the chilled and hot water pumps. This is primarily due to its larger design flow rate and comparable or higher design head, reflecting the need to reject both the building cooling load and the chiller compressor heat. In the upgraded model, the condenser pump is sized for approximately 40% higher flow than the chilled water pumps and operates against a substantially higher head, resulting in a larger design pump power (approximately 7,000 W). In contrast, the chilled water primary loop is configured for constant-flow operation and therefore does not benefit from speed modulation, while the secondary chilled water loop experiences the lowest pump power due to both lower flow demand and load-based flow control. As a result, most of the overall pump power savings observed in the upgraded case are driven by reduced condenser water pump operation rather than by the chilled or hot water loops.

Figure 9 presents another simulation scenario that incorporates chilled and hot water temperature reset strategies based on outdoor air temperature. As shown in the figure, which reflects the impacts on the chiller and boiler, the chilled water supply temperature increases and the hot water supply temperature decreases under milder outdoor conditions in the upgrade scenario. This approach effectively relaxes the supply temperature requirements, allowing the chiller and boiler to operate under more favorable part-load conditions and resulting in additional energy savings for both systems.

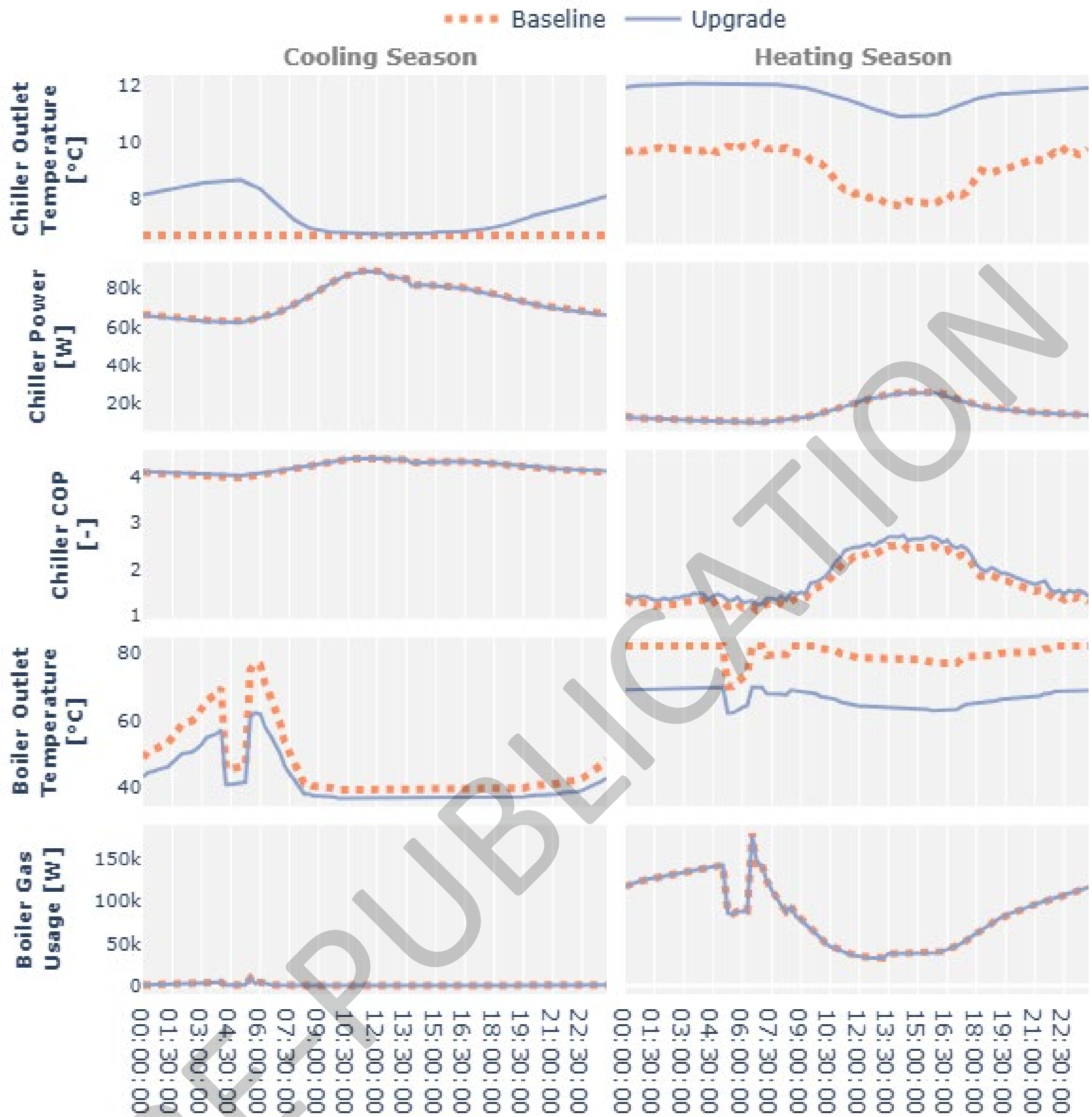


Figure 9. Pump replacement and chilled water/hot water reset test: impact on chiller and boiler

For the pump replacement scenario with chilled and hot water temperature reset, Figure 10 presents plots similar to those in Figure 7, highlighting the pumps affected by the reset strategy. As shown, the relaxed chilled and hot water temperature controls influence the water flow and power in both the secondary chilled water loop and the hot water loop pumps. The hot water loop pump demonstrates power savings primarily during the heating season, while the secondary chilled water loop pump achieves savings during the cooling season but shows increased power use during the heating season.

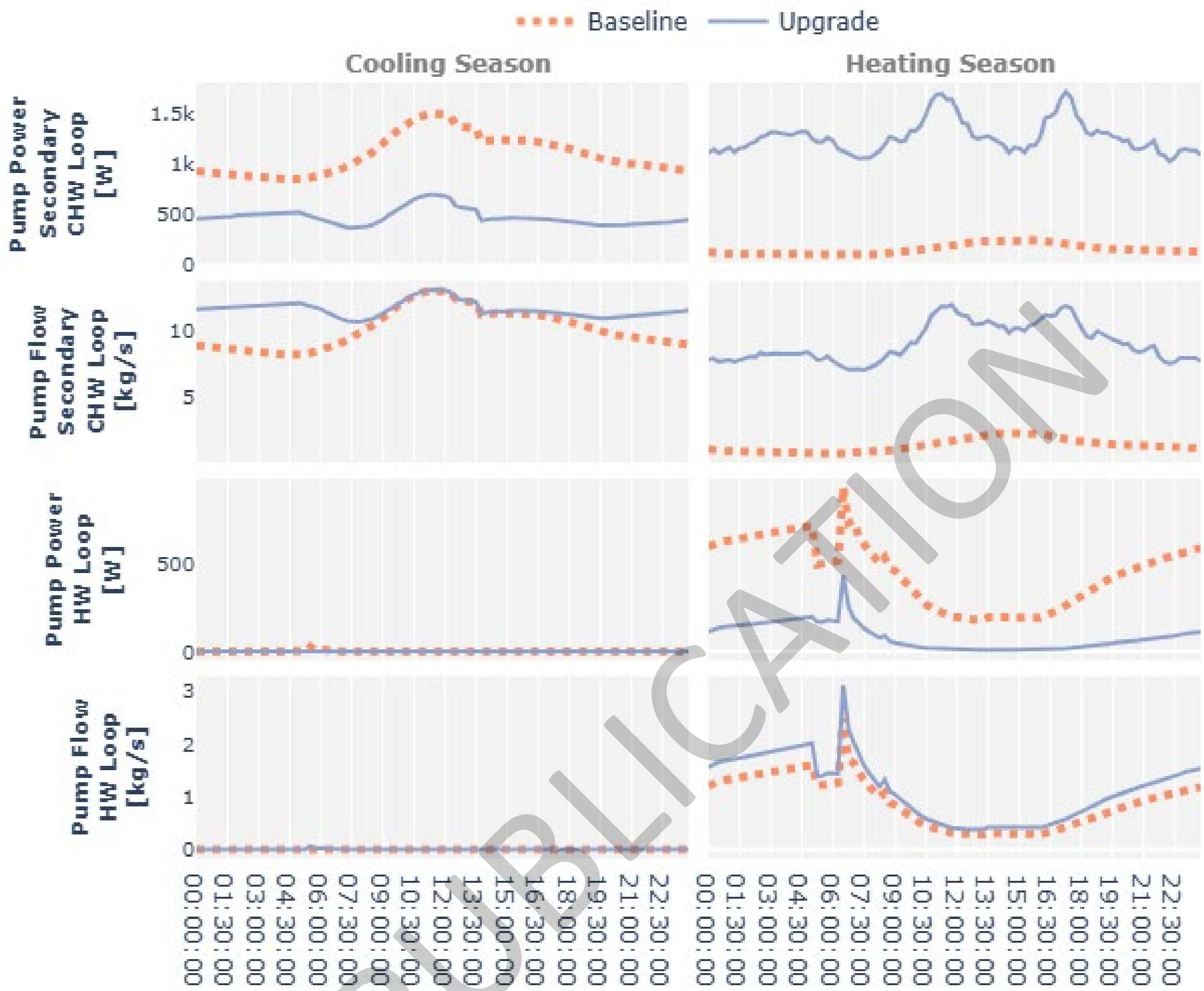


Figure 10. Pump replacement and chilled water/hot water reset test: replacing existing variable-speed pumps

As the supply temperature is relaxed, the temperature difference (ΔT) between supply and return water can decrease, particularly if the return temperature does not shift proportionally. This behavior depends on several factors, including the characteristics of terminal equipment (e.g., coils), control strategies, and system load. In many cases, a reduced ΔT results, which, for a constant thermal load, requires an increase in flow rate to maintain the same capacity. However, the corresponding rise in pump power is typically modest and is expected to be more than offset by the improved efficiency of chiller and boiler operation enabled by the reset strategy.

Table 3 presents the annual summary of one baseline and two upgrade scenarios illustrated in Figure 7 and Figure 10. As indicated in Table 3, reductions in pump energy consumption are the primary contributors to total site energy savings, resulting in approximately 2.2%–2.7% savings in site electricity use. In the pump-replacement-only scenario, the improved pump efficiency introduces less heat into the water loop, leading to a slight increase in heating energy and a corresponding decrease in cooling energy. However, these changes are minor relative to the overall energy savings from the pumps. In the combined pump replacement and chilled water/hot water reset control scenario, additional efficiency gains from chillers and boilers lead to further, albeit modest, reductions in site energy consumption for heating and cooling.

Table 3. Single-Building Model Test: Annual Energy Consumption Comparisons

	Electricity (MWh)			Natural Gas (MWh)		
	Baseline	**Pump**	**Pump + Chilled Water/Hot Water Reset**	**Baseline**	**Pump**	**Pump + Chilled Water/Hot Water Reset**
Heating	0	0	0	304	306	304
Cooling	370	370	367	0	0	0
Interior lighting	64	64	64	0	0	0
Exterior lighting	49	49	49	0	0	0
Interior equipment	292	292	292	0	0	0
Exterior equipment	0	0	0	0	0	0
Fans	57	57	57	0	0	0
Pumps	69	46	53	0	0	0
Heat rejection	26	24	24	0	0	0
Humidification	0	0	0	0	0	0
Heat recovery	0	0	0	0	0	0
Water systems	22	22	22	0	0	0
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
Total end uses	**949**	**923**	**928**	**304**	**306**	**304**
Savings	**-**	**2.7%**	**2.2%**	**-**	**-0.5%**	**0.09%**

5.2 Sensitivity Analysis With Reduced Stock Model

We conducted a sensitivity analysis by (1) considering two different upgrade scenarios around pumps and (2) applying these different upgrades to ComStock with reduced stock models (i.e., ~10,000 instead of ~100,000 models that reasonably represent variations of the commercial building stock). This section includes the results of this sensitivity analysis to provide partial snapshots of how these different upgrade scenarios propagate to the stock of building models.

Note that because the sensitivity analysis in this section uses far fewer models to represent the building stock than a full ComStock run, results should be used for understanding generalized and conceptual trends only. Results with the full ComStock run in Section **Error! Reference source not found.** and after might show slightly different trends because they include the remaining ~90,000 models. More detailed analyses should always utilize the available scenarios in the full published ComStock datasets.

Figure 11 illustrates the impacts of two upgrade scenarios analyzed in this sensitivity study: (1) pump replacements only, and (2) pump replacements combined with a chilled/hot water supply temperature reset based on outdoor air temperature. The figure also breaks down four different end-use energy categories to show how each HVAC subsystem is affected. As expected, replacing all existing pumps with high-efficiency variable-speed models led to a 35% reduction in pump electricity use. However, when the control system is upgraded to include outdoor air temperature-based supply water temperature reset, pump electricity usage increased slightly, though it remained below the baseline level.

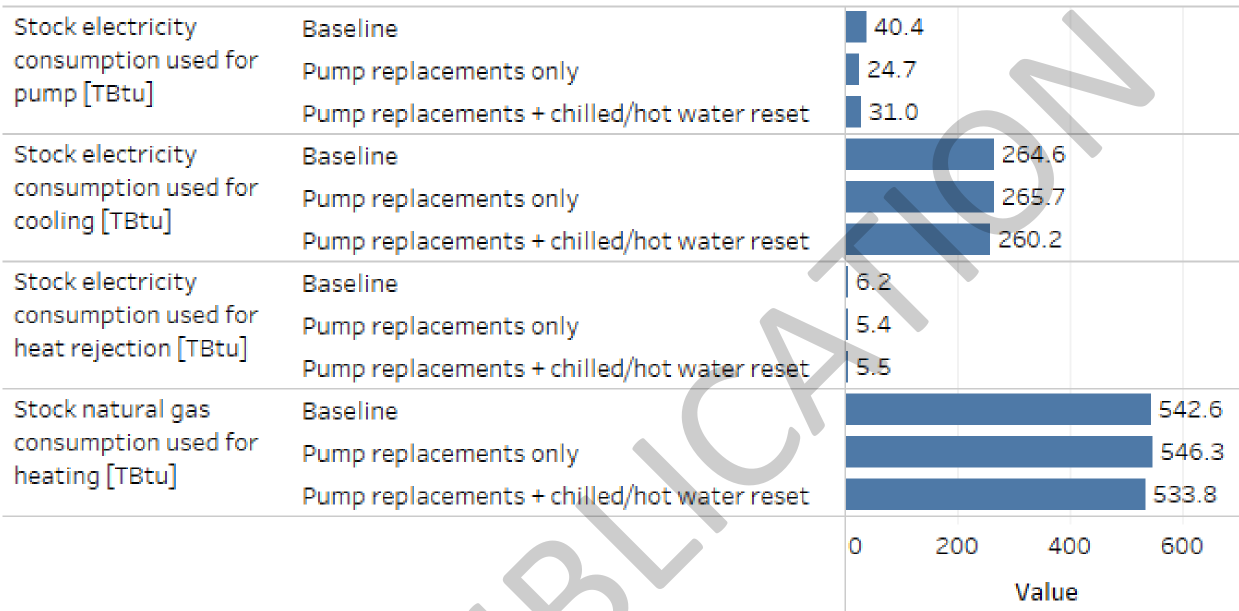


Figure 11. Sensitivity analysis on different upgrade scenarios around pumps

The temperature reset strategy adjusts the chilled and hot water supply temperatures during mild weather, raising the chilled water supply temperature and lowering the hot water supply temperature when thermal loads are lower. This allows chillers and boilers to operate under more favorable part-load conditions, improving their overall efficiency and resulting in additional energy savings. However, as the chilled (or hot) water supply temperature increases (or decreases), the temperature difference (ΔT) between supply and return water narrows. To deliver the same cooling or heating output, this reduced ΔT can necessitate a higher flow rate, leading to an increase in pump energy consumption, as shown in Figure 11. Nonetheless, the modest increase in pump energy use (approximately 7 TBtu) is offset by the greater energy savings from improved chiller and boiler performance, which amount to 5.5 TBtu in cooling and 12.5 TBtu in heating savings (measured in site energy), also depicted in Figure 11.

The observed reduction in cooling tower fan energy use can be explained by improved system performance. Replacing constant-speed condenser water pumps with variable-speed models enables better flow modulation and reduced water flow during part-load conditions. This decreases the amount of heat that needs to be rejected by the cooling tower at any given moment, as shown in Figure 11. As a result, the cooling tower fans can operate at lower speeds or for shorter periods, leading to a measurable reduction in their electricity consumption.

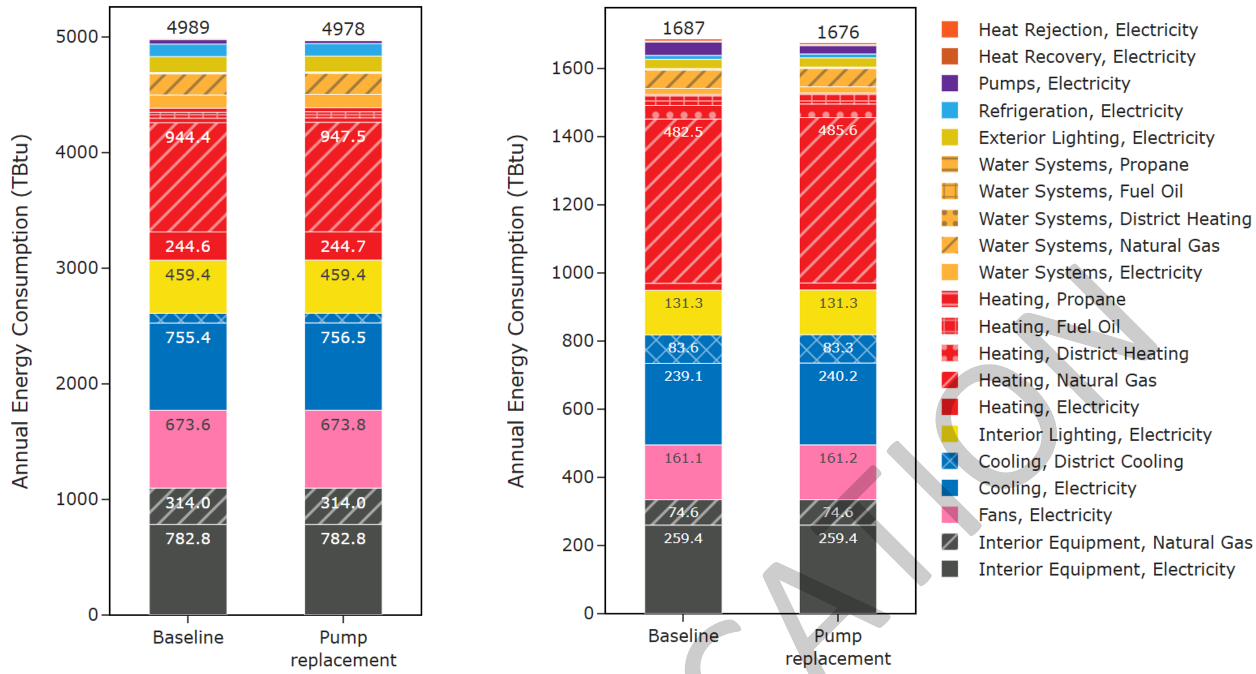
For the remaining subsections, the pump-replacement-only scenario will be examined to highlight the differences in their respective impacts.

5.3 Stock Energy Impacts

Table 4 and Figure 12 show the comparison of annual site energy consumption between the baseline and upgrade scenarios for the entire building stock and buildings that are only applicable to the upgrade, respectively. The pump replacement upgrade measure demonstrates 0.2% total site energy savings (11 TBtu) for the U.S. commercial building stock modeled in ComStock, including both applicable and inapplicable (e.g., buildings without pump) buildings for this upgrade. The savings of the pump-replacement-only scenario are primarily attributed to 38% stock pump electricity savings (15 TBtu), 12% stock heat rejection electricity savings (0.8 TBtu), 0.4% stock district cooling savings (0.3 TBtu), -0.4% stock district heating savings (-0.2 TBtu), and -0.3% stock heating natural gas savings (-3 TBtu).

Table 4. Summary of Site Energy Savings From Upgrade Measure Application vs. the ComStock Baseline

End Use/Fuel Type	Percent Site Energy Savings (All Buildings)	Percent Site Energy Savings (Applicable Buildings Only)	Absolute Site Energy Savings (TBtu)
Total natural gas	-0.22%	-0.51%	-3.1
Total electricity	0.43%	1.6%	14.4
Electric pumps	37.6%	38%	14.9
Electric heat rejection	12.4%	12.4%	0.78
District cooling	0.39%	0.39%	0.32
District heating	-0.43%	-0.43%	-0.17
Natural gas heating	-0.33%	-0.64%	-3.1



(a) Entire building stock (b) Applicable models only

Figure 12. Comparison of annual site energy consumption between the ComStock baseline and the pump replacement measure scenario.

Energy consumption is categorized both by fuel type and end use. (a) The entire building stock modeled in ComStock; (b) only models applicable to the measure.

As highlighted in Sections 5.1 and 5.2, the savings presented in Table 4 and Figure 12 exhibit similar patterns when extrapolated to the stock level. At this scale, the overall energy savings are relatively modest; however, notable reductions in the end-use level include a 38% decrease in pump energy consumption and a 12% reduction in cooling tower fan energy consumption. Additionally, there are marginal but positive/negative impacts on cooling/heating loads, arising from the reduced heat added to the water loop associated with higher pump efficiency.

5.4 Stock Utility Bill Impacts

This section includes a comparison of annual utility bills for buildings using different energy sources (i.e., electricity, natural gas, propane, fuel oil) and for the entire building stock. Because we apply many electricity utility rate structures that are available for a building located in a certain geographical location, our data include many annual utility bills per building model. Table 3 shows a comparison among two scenarios: baseline and pump replacement upgrade. For detailed information regarding utility rate implementation, refer to the ComStock Reference Documentation [15]. Site energy savings and utility bills savings do not necessarily align due to cost differences between fuel types as well as primary energy conversion factor differences.

Figure 12 shows aggregated "site" energy consumption, which does not reflect the "primary" energy perspectives. Thus, the annual aggregated cost comparisons, shown in Table 3, can also tell us the primary energy consumption comparisons between different scenarios.

Table 5. Summary of Key Results for Annual Utility Bill Savings

Electricity bill savings in this table are calculated using the mean available electricity rate available for each building. Other electricity rate structures are available in this report and in the public dataset. "Applicable" buildings are those that receive the upgrade based on criteria defined for this study.

End Use/Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (million USD, 2022)
Electricity	0.37%	1.4%	0.41
Natural gas	-0.21%	-0.5%	-0.034
Fuel oil	-0.39%	-0.71%	-0.0069
Propane	-0.091%	-0.85%	-0.0011
Total	**0.28%**	**0.96%**	**0.37**

In Table 3, electricity bills showed the highest percentage savings, with 1.3% savings among applicable buildings and absolute annual savings of $0.4 million per year. In contrast, natural gas, fuel oil, and propane all exhibited negative savings percentages, primarily due to slight penalties in space heating—specifically, less heat added to the water loop because of more efficient pump operation—leading to increased costs. Nevertheless, the total combined savings across all fuel types resulted in a net gain of 0.9% for applicable buildings, equating to $0.37 million in annual savings.

5.5 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes. Site energy savings can be useful for these (and possibly other) purposes, but additional factors should be considered when drawing conclusions, as site energy savings do not necessarily translate proportionally to source energy savings or energy costs, which vary widely across the United States. Savings shown in this section are based on comparisons between the baseline and pump-replacement-only scenarios on the HVAC system (including chilled water, condenser water, and hot water loops).

Figure 13 to Figure 16 show distributions of the applicable baseline ComStock models versus the upgrade scenario for percentage site energy or site energy use intensity savings with different HVAC types, fuel types, or end uses. Percentage savings provide relative impact of the measure at the individual building level while site energy use intensity savings provide absolute (or aggregated) scale of impact. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for *n* indicates the number of ComStock models that were applicable for energy savings for the fuel type category. It should also be noted that these pairwise comparisons represented with distributions only calculate percentage savings for buildings where the baseline included some prevalence of end use/fuel type. Thus, the electric heating savings only show buildings that originally used some amount of electric heating and do not represent buildings where natural gas was the only heating fuel.

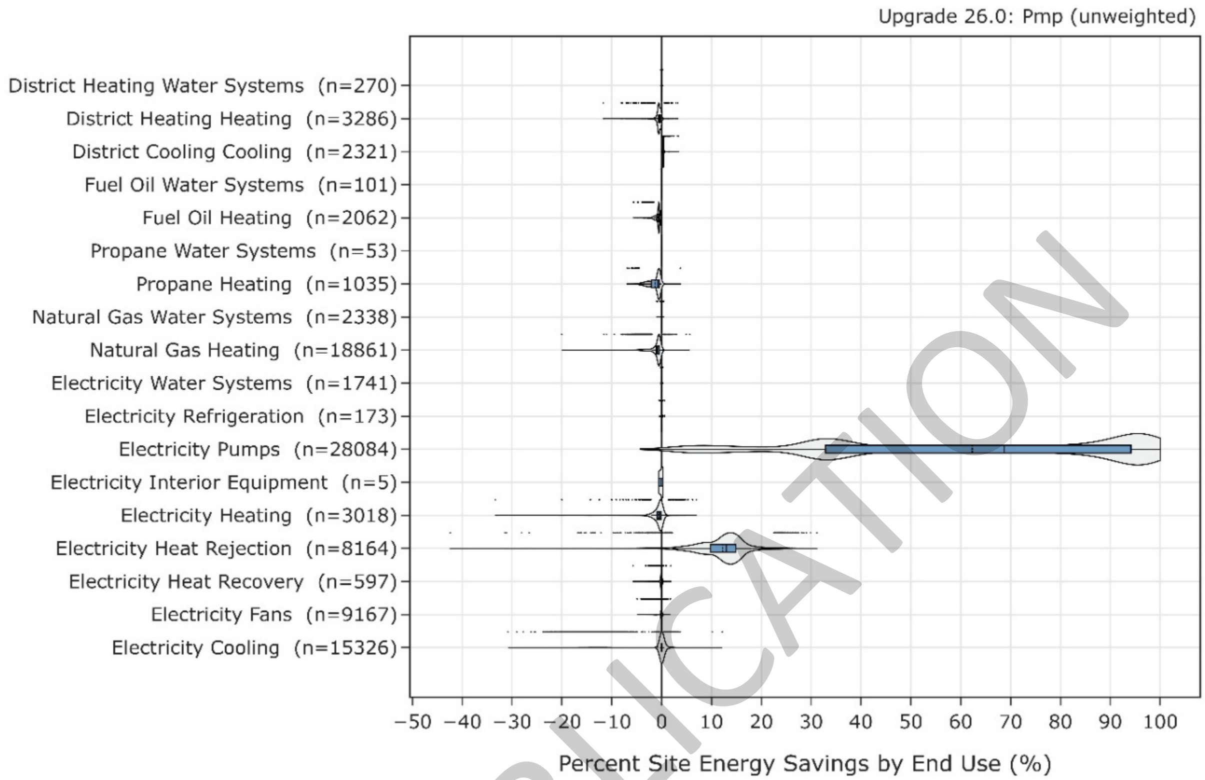


Figure 13. Percentage site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type

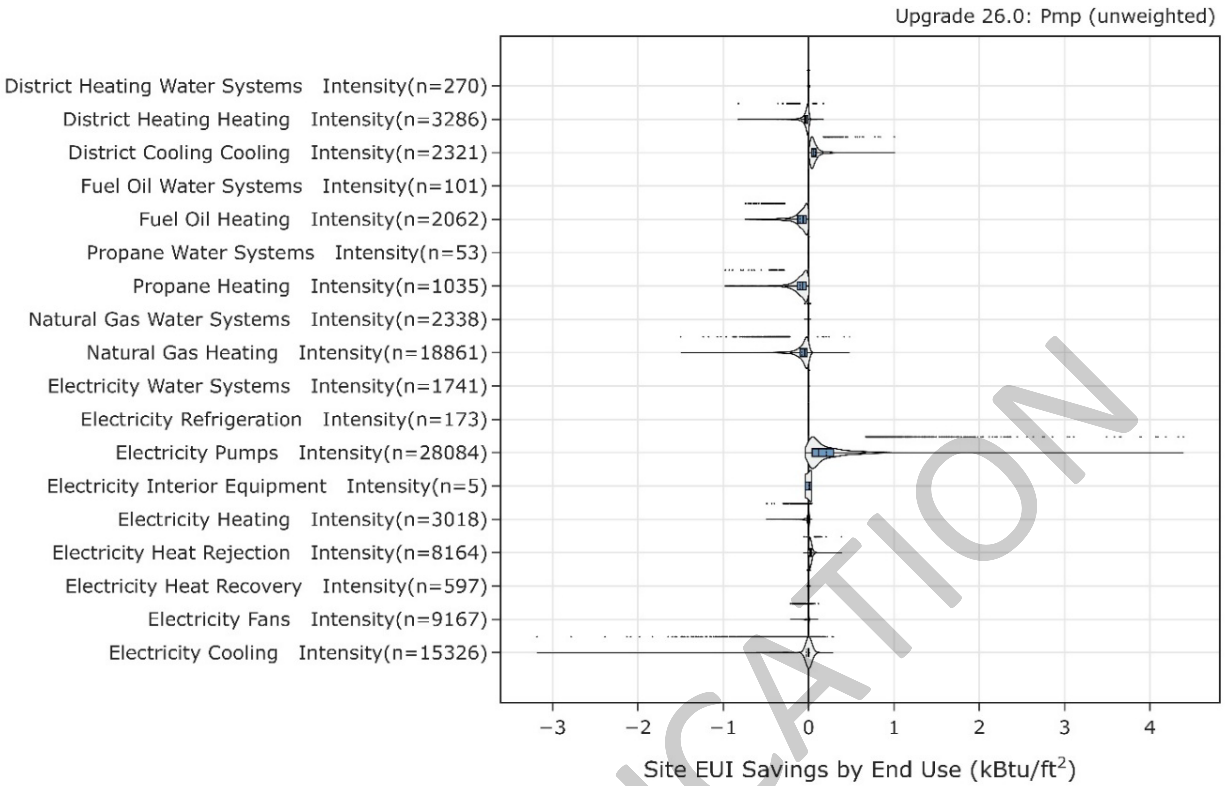


Figure 14. Site energy use intensity savings distribution for ComStock models with applied measure scenario by end use and fuel type

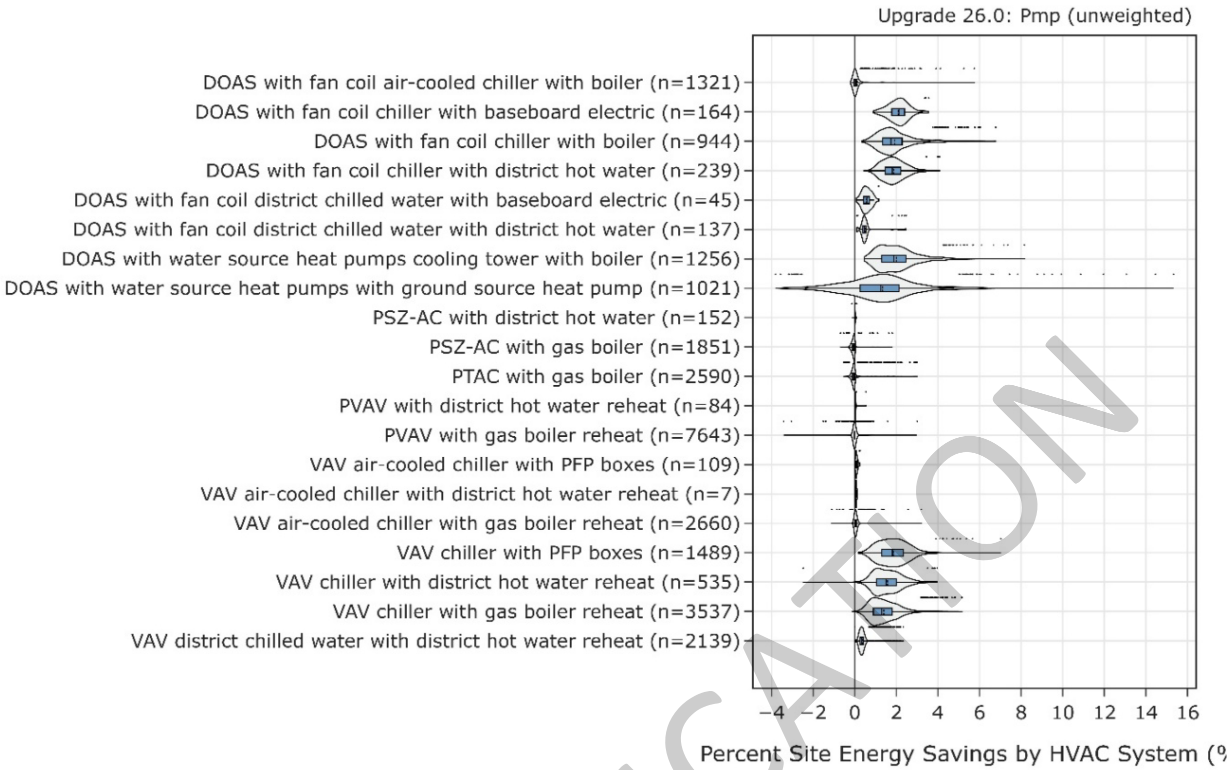


Figure 15. Percentage site energy savings distribution for ComStock models with the applied measure scenario by HVAC type

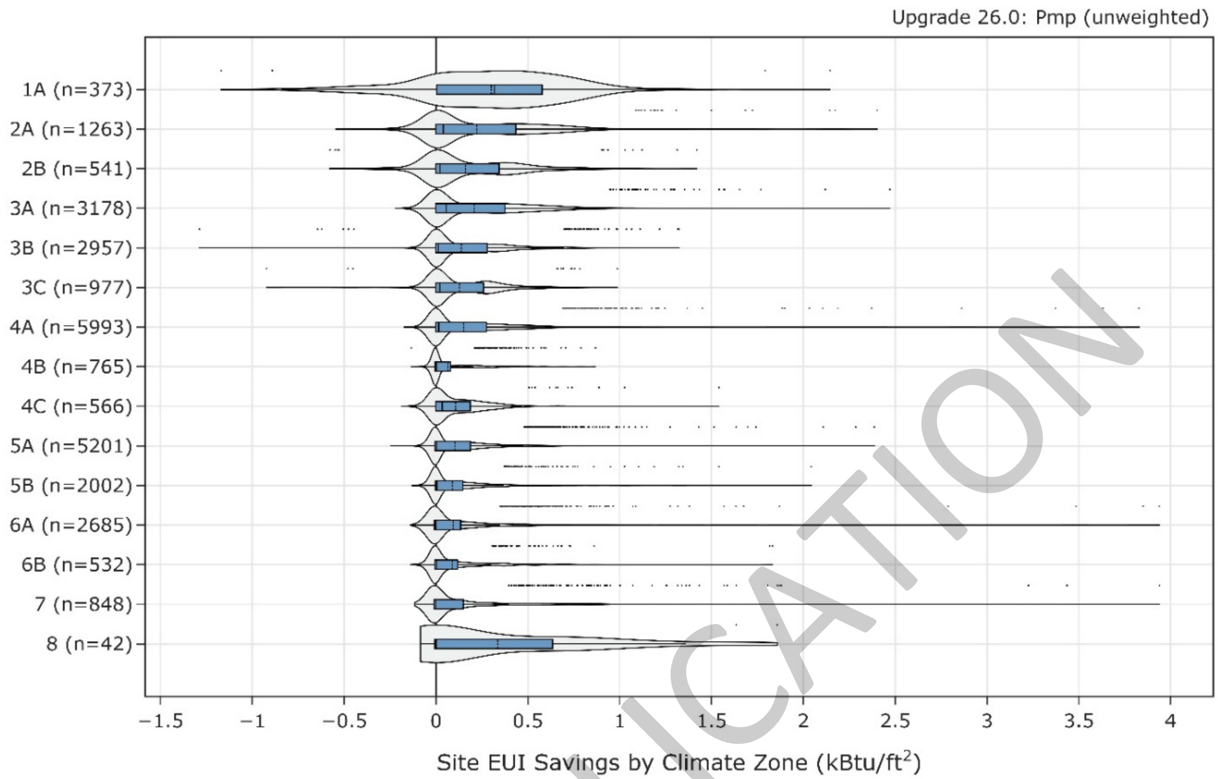


Figure 16. Percentage site energy savings distribution for ComStock models with the applied measure scenario by climate zone

Highlights of conclusions drawn from Figure 13 through Figure 16 include:

- Positive electricity pump savings (Figure 13):
  - The primary savings result from replacing old pumps with newer, more efficient models.
  - The observed 100% electricity savings for pumps are attributed to buildings with minimal annual heating and cooling demands. Due to their inherently low thermal loads, pump operation in these buildings is infrequent. When these pumps are replaced with high-efficiency models featuring improved part-load performance, the resulting energy consumption is extremely low, often below measurable thresholds (e.g., <0.1 kWh). In simulation outputs, this low consumption is rounded to zero, especially when compared to significantly higher energy use from other end uses.
  - Regarding the interquartile range of pump electricity savings, the higher end (e.g., >80% savings) corresponds to cases where constant-speed pumps are replaced with variable-speed pumps, resulting in bigger efficiency gains. Conversely, the lower end of the range (e.g., <40% savings) typically reflects scenarios where older variable-speed pumps are upgraded to newer models, offering more modest improvements due to the better part-load capabilities.

    - Figure 15 illustrates energy use intensity savings, which enables more meaningful comparisons across buildings of different sizes by normalizing energy savings relative to floor area.
- Positive electricity heat rejection savings (Figure 13):
    - These savings stem from reduced electricity usage by cooling towers in water-cooled chiller systems.
    - Constant-speed condenser water pumps are upgraded to variable-speed pumps, enabling enhanced modulation and reduced flow during part-load conditions. This decreases the heat rejection load on the cooling tower, allowing the tower fan to operate at lower speeds or for shorter durations, ultimately reducing fan energy consumption.
- Negative heating savings (Figure 13):
    - With more efficient pumps adding less heat to the water loop, the demand for heating increases, resulting in higher usage of heating with electricity, natural gas, fuel oil, propane, or district heating.
    - However, the increase in heating energy use is outweighed by the overall site energy savings achieved through pump efficiency improvements.
- Various HVAC system types leveraging water systems with pumps (Figure 15):
    - Water-cooled chiller systems, which include cooling tower fans, tend to show relatively higher savings compared to air-cooled systems that lack cooling towers.
    - HVAC systems equipped with boilers but no chillers (e.g., packaged terminal air conditioners with gas boilers) tend to show marginally negative savings. This occurs because the reduced heat added to the water stream—due to improved pump efficiency—increases the heating load, which can outweigh the pump energy savings, particularly in buildings with already low heating demand.
- Impacts on climate zones (Figure 16):
    - Hotter climates, which require more energy for chiller systems, tend to experience greater savings from these upgrades compared to the same systems operating in colder climates.

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Appendix A.

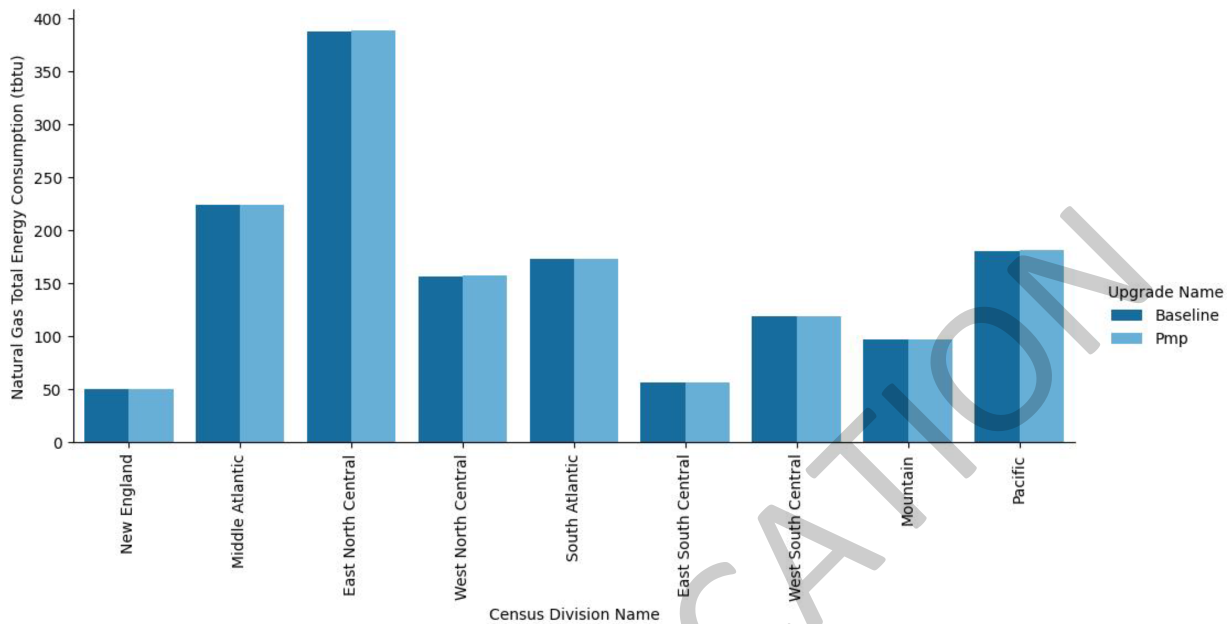

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

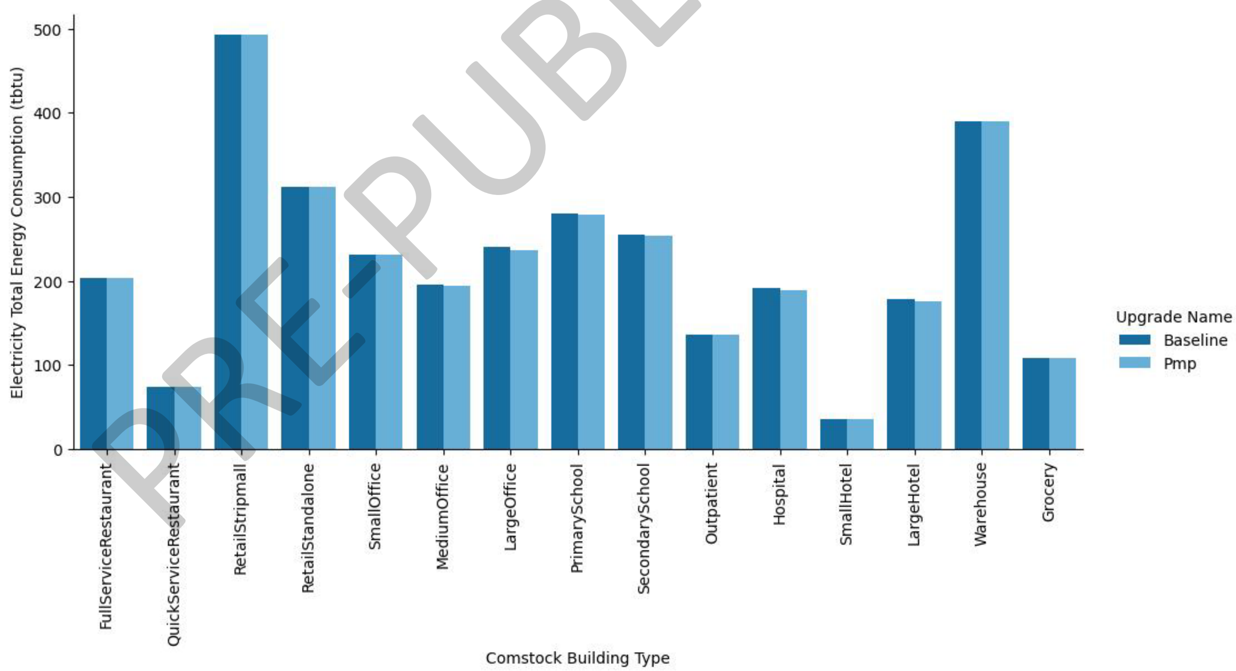

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

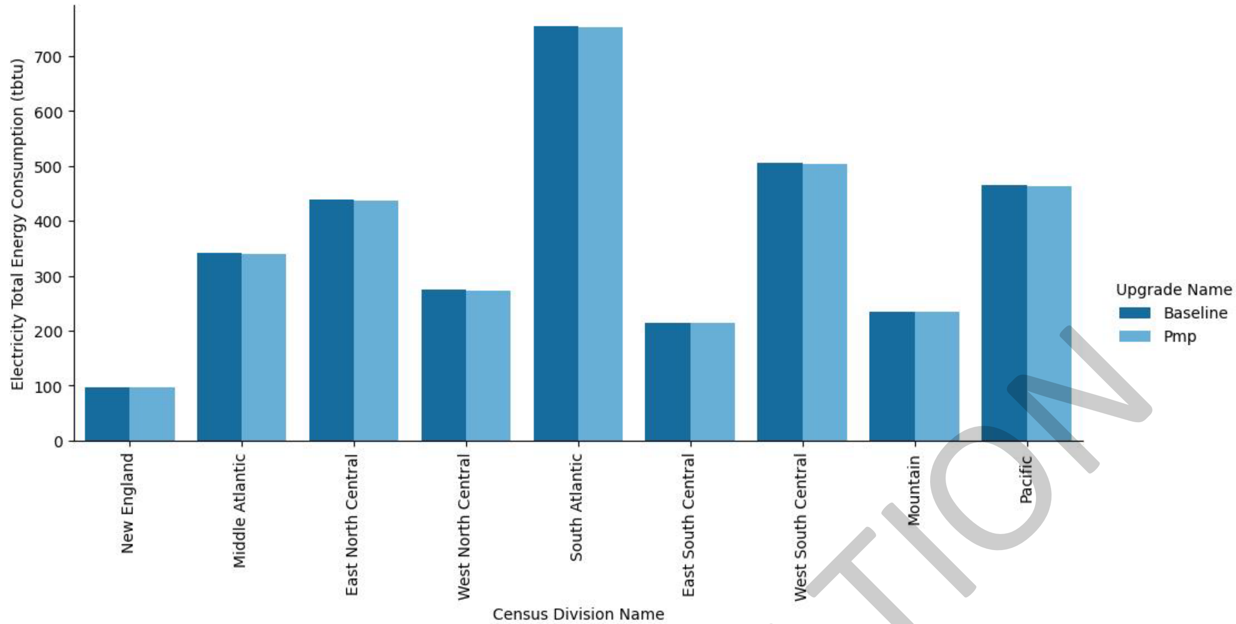

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division

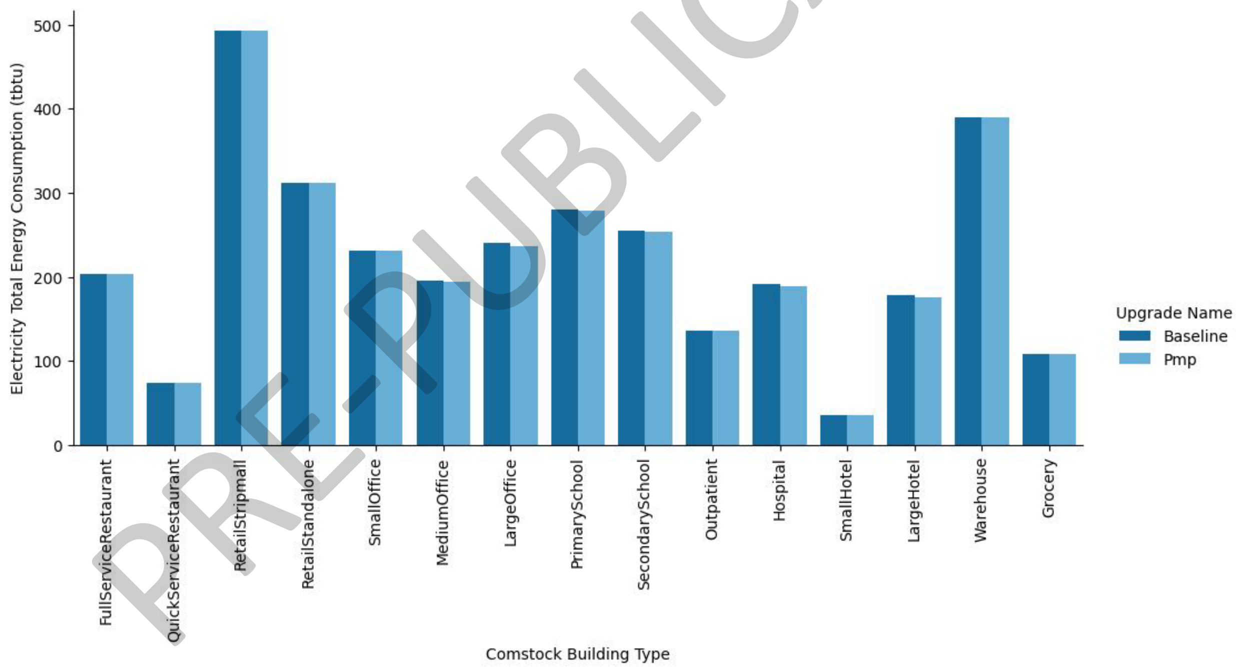

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type