ComStock Measure Scenario Documentation: Fan Static Pressure Reset for Multizone VAV Systems

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Acknowledgments

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List of Acronyms

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
CDD	cooling degree days
DDC	direct digital controls
DX	direct expansion
EIA	U.S. Energy Information Administration
HDD	heating degree day
HVAC	heating, ventilating, and air conditioning
IES	Illuminating Engineering Society
kBtu	thousand British thermal units
SP	static pressure
TBtu	trillion British thermal units
T&R	trim and respond
URDB	Utility Rate Database
VAV	variable air volume

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—Fan Static Pressure Reset for Multizone Variable Air Volume (VAV) Systems—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 case (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 measure implements a static pressure (SP) reset for air-handling unit fans in multizone VAV systems. An SP reset saves fan energy by allowing fans to operate at a lower SP setpoint during part-load conditions.
Performance Assumptions	• This measure emulates the effects of an SP reset by changing the fan power performance curve as a function of airflow. • The existing fan performance curve is replaced with a curve emulating a “good” SP reset. The “good” SP reset curve is used in OpenStudio® Standards for other systems and was published in the California Energy Commission’s Advanced VAV Design Guide [1].
Applicability	• This measure is applicable to multizone VAV systems in which an SP reset is not already present. This measure is not applicable to fans in dedicated outdoor air systems. • Currently, some multizone VAV systems in ComStock associated with a template of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 2004 or more recent are modeled with an SP reset, depending on fan input power and cooling capacity. No systems modeled with a template older than ASHRAE 90.1 2004 are currently modeled with a reset. • **23% stock floor area applicable**
Release	2025 Release 3: 2025/comstock_amy2018_release_3/

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	Percentage Savings (All Buildings)	Percentage Savings (Applicable Buildings Only)	Absolute Savings (trillion British thermal units [TBtu])
Natural gas	-1.0%	-4.5%	-12.2
Electricity	3.0%	14%	100
Fuel oil	-1.2%	-6.1%	-0.63
Propane	-0.1%	-5.6%	-0.04
Total	**1.9%**	**8.7%**	**92.7**

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	Percentage Savings (All Buildings)	Percentage Savings (Applicable Buildings Only)	Absolute Savings (million USD, 2022)
Electricity	2.9%	13%	3,175
Natural gas	-0.8%	-4.3%	-137.2
Fuel oil	-1.2%	-6.1%	-21.47
Propane	0.0%	-5.8%	-13.43
Total	**2.3%**	**11%**	**3,015**

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1 Introduction

The pressure associated with an air-based heating, ventilating, and air-conditioning (HVAC) system (or other fluid-flow system) has two components: static pressure (SP) and dynamic (or velocity) pressure. Dynamic pressure refers to the pressure the airflow exerts in the direction of flow. SP (also known as “duct static pressure”) reflects the resistance to airflow that ductwork and other system components impose due to friction, turbulence, changes in velocity and obstructions (such as grilles, dampers, etc.) [2]. HVAC fans are typically selected in part based on fan curves, which show the SP that a fan can supply at a given airflow. While the characteristics of pressure-volume curves differ based on fan type, in general, the higher the SP, the lower the airflow for the same power input. [2].

Variable air volume (VAV) systems vary airflow based on zone terminal box damper actuation (which is controlled by the zone thermostat), generally reducing airflow during periods of reduced loads. In VAV systems, SP is typically one element of fan control. In a basic configuration, supply fans can be controlled to a fixed SP setpoint. The setpoint must be adequate to ensure that all VAV terminals can receive their maximum airflow simultaneously as needed [3]. In a VAV system, when a terminal unit damper begins to close, airflow is decreased and pressure in the duct increases. The system curve shifts to the left, as shown in Figure 1. With a constant SP setpoint, the fan now provides less airflow at the same SP. This wastes energy by over-pressurizing the ducts beyond what is needed for the requested airflow. This can be mitigated through the implementation of an SP reset control strategy. Operation at a fixed SP undermines the energy efficiency of VAV systems at part-load conditions [4].

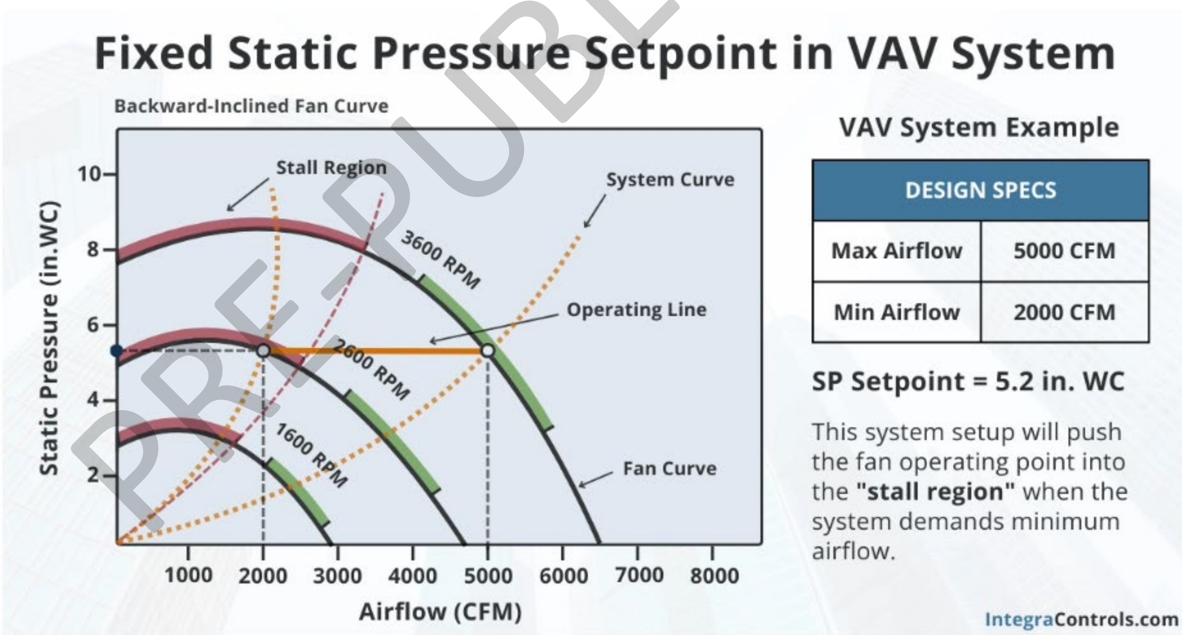

Figure 1. Illustration of fan behavior under fixed static pressure (SP) setpoint as load declines.

VAV dampers close and the system curve shifts left to achieve reduced airflow, since the system is forced to operate at a fixed SP setpoint. Image courtesy of [3].
in. WC = inches of water column; CFM = cubic feet per minute

This measure focuses on an SP setpoint reset in VAV systems, which saves fan energy during periods of reduced loads. With an SP reset, if VAV box dampers close and the system curve shifts left, the SP setpoint and fan speed are reduced, resulting in a new fan curve and system operating point. SP resets can be based on factors that are proxies for load (such as the building's operating schedule) or on direct feedback of VAV box damper position or zone-level airflow. Incorporating direct feedback on zone conditions typically requires direct digital controls (DDC) to the zone level, which is not present in all buildings [4]. SP resets based on programmed daily schedules avoid the need for DDC to the zone, though they will not capture the full potential savings of a modulating reset based on zone conditions [5]. The 2022 American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 90.1 requires that an SP reset must be incorporated in multizone VAV systems with DDC to the zone, and with nameplate fan motor power exceeding 5 horsepower [6]. In systems subject to this requirement, ASHRAE 90.1 also requires that control systems generate alarms to identify "rogue" zones (which have wide-open dampers and may be preventing the reset) and allow operators to remove rogue zones from the determination of the SP reset [6]. Some requirements for SP resets in systems with DDC to the zone have been presented in Guideline 90.1 since 1999 [7].

In a particular building, the need for an SP reset can be observed through VAV box damper positions. If all damper positions are below 50% during occupied periods, the system could likely benefit from an SP reset or a more aggressive reset, if an SP reset is already in place [5]. This measure focuses on "pressure-independent" VAV boxes with airflow sensors that precisely regulate airflow to the zone. "Pressure-dependent" VAV boxes regulate airflow through damper position only, which can complicate implementation of an SP reset [4]. "Pressure-dependent" VAV boxes are generally pneumatically controlled and thus are not suitable candidates for the implementation of an SP reset using zone feedback without an extensive overhaul [8].

Two common approaches for SP reset using zone feedback include a "critical zone" approach and a "trim and respond" (T&R) approach [4] [9]. The "critical zone" approach resets the SP setpoint within a predetermined range using a control loop (typically proportional-integral) to keep the VAV box demanding the most SP close to fully open, often at a threshold of 90% open [4] [1]. "Rogue" zones that continually demand high SP can be ignored, at the risk of providing insufficient airflow [1].[1] (Zones can exhibit "rogue" behavior for multiple reasons, including control faults, or having under-sized VAV boxes. Faults are discussed in a subsequent section. Achieving the best results from an SP reset strategy is generally predicated on all zones having appropriately sized VAV boxes [1] [7]). The maximum and minimum SP setpoints can be determined during balancing and must be sufficient to provide design airflow to all boxes simultaneously, and to provide minimum ventilation airflows to all boxes simultaneously, respectively [1]. Hydeman et al. [1] caution that SP control loops require careful tuning and that the reset control loop should be configured to respond slowly relative to zone airflow control loops, since changing the system SP will immediately affect fan airflow and propagate to zone damper positions [1].

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[1] For this reason, Hydeman et al. [1] recommend oversizing VAV boxes for zones with high cooling loads and without ventilation requirements (such as zones consisting of server rooms), to avoid the box frequently limiting an SP reset [1].

T&R is an approach that can be applied to control for pressure, temperature, and other variables [9]. In the context of SP, T&R incrementally reduces the SP setpoint until a zone is no longer able to meet its airflow demand, generating a “request.” After a given number of requests have been made, the setpoint is increased. When the number of requests drops below the given threshold, the system continues to reduce the SP setpoint. T&R can address complexities in terms of the priority of different zones by assigning weights to their requests [9]. According to the ASHRAE Guideline 36 [9], T&R is easier to tune than other approaches for SP control and provides for faster response. ASHRAE [9] notes that T&R can result in cyclic hunting of control loops, but that it takes place slowly enough to be non-disruptive. T&R avoids the need for explicit damper position feedback from VAV boxes, since it monitors airflow “requests” from zones but still requires DDC to the zone level for implementation [7].

Hydeman et al. [1] performed analysis based on data collected from a real office building in San Jose, California, to evaluate the effects of a “perfect” SP setpoint reset (in which the SP setpoint was controlled to keep the VAV box with the highest damper position at exactly 90% open). Hydeman et al. [1] collected airflow and pressure data from the building and used a fan curve representing the perfect reset to emulate the effects at the monitored airflow values. Depending on the type of fan considered, they found that annual fan energy use can potentially be reduced by as much as 50% with a “perfect” SP reset, relative to a baseline with a constant SP setpoint. This was like results Hydeman et al. [1] obtained through a modeling analysis for a fictious building. Fan energy savings from an SP reset are highly dependent on fan sizing and load, which dictate how often and to what extent the SP can be reset.

Tukur et al. [10] evaluated a novel SP reset approach incorporating demand-controlled ventilation and fault detection and diagnostics in a real building. Their control sequence used zone carbon dioxide levels to dynamically reset VAV box minimum airflows, and fault detection and diagnostics to ignore “rogue” zones in a T&R-based SP reset. The sequence was configured to ignore zones with a fault (failed thermostats or VAV box dampers stuck in one position) in the determination of the SP setpoint, using fault detection and diagnostics to identify such zones. In an evaluation in an office building of the novel control approach and a baseline control approach with a constant SP setpoint, Tukur et al. [10] found fan energy savings of 25%, with each strategy implemented for two weeks. Tukur et al. [10] adjusted the fan power in the energy calculations to normalize airflow requirements between the two periods.

Walaszczyk and Cichoń [7] compared the performance of critical zone and T&R style SP resets with a constant SP setpoint baseline through a simplified modeling analysis. They considered a T&R approach in which a zone with a greater deviation from its desired airflow setpoint generated more “requests” for pressure. Under their critical zone approach, the SP setpoint was determined so that at least one zone had its VAV box “almost” fully open. Walaszczyk and Cichoń [7] found that the two SP reset methods performed very similarly and reduced fan energy by 22% to 48% (with higher savings at lower outdoor air temperatures), relative to the constant setpoint baseline. They noted that fan energy use was slightly higher under the critical zone approach than under T&R, since the limiting box was maintained at “almost” open—not entirely open—conditions. This is counterbalanced by the fact that under their T&R implementation, airflow requirements in the limiting zone may not have been met, since it was allowed to reach and remain at fully open conditions [7].

Fernandez et al. [11] analyzed and compared the effects of an SP reset at the building stock level by emulating two different implementation methods: an approximation of T&R or critical zone based on the ratio of zone airflow to zone design airflow value, and a time-of-day reset based on building occupancy. The approximation was necessary because of the simplified approach associated with common fan models in EnergyPlus®, with which fan power is modeled as a function of flow, without explicit modeling of fan pressure rise [12].[2] (In these simplified fan models, fan pressure rise at design conditions is an input used to calculate design power draw.) Site energy savings were about twice as high under the approach approximating T&R than under the scheduled SP reset [11]. For medium and large office buildings, site energy savings for the time-of-day-based reset ranged from 0.8% to 2.1%, depending on location [11]. Under the T&R approximation approach, site energy savings for the same set of buildings ranged from 2.1% to 4.6% [11]. Greater savings from the T&R approach are expected because it allows for fan speed reductions during both occupied and unoccupied hours.

SP resets are a proven method for energy savings in existing buildings. SP resets require DDC to the zone level for implementation in their most effective form. (Scheduled SP resets are an alternative if DDC is not present at the zone level.) SP resets require careful loop tuning and identification of "rogue" zones that could drive SP requirements and prevent the reset from taking place. SP resets also have benefits for equipment longevity in addition to energy savings. Stall and surge are fan operation instabilities that can occur when the fan is operating to the left of its peak SP point (as illustrated in Figure 1). An SP reset results in a new fan curve and system operating point when the reset takes place, providing the same airflow with a lower fan speed relative to the same conditions without a reset. This reduces the likelihood that stall or surge will occur, since the surge region generally extends to higher airflows at higher SPs [13]. This measure scenario implements an SP reset in multizone VAV systems that do not already include SP reset controls, in a way that approximates the effects of a T&R or critical-zone-based reset approach.

[2] The Fan:ComponentModel now available in EnergyPlus for central air handling unit fans provides a physics-based model for flow-dependent fan pressure rise [12].

2 ComStock Baseline Approach

Currently, only multizone (not single-zone) VAV systems are represented in the ComStock baseline [14].[3] In the ComStock baseline, VAV fans are modeled with the Fan:VariableVolume object from EnergyPlus, which characterizes fan power draw with a curve representing power as a function of flow, without explicit modeling of fan pressure rise [12]. In EnergyPlus, airflows are dictated based on ventilation requirements and zone loads, and limits on airflow are set in the terminal unit objects rather than in the fan itself. Since duct pressure is not explicitly modeled in ComStock, VAV terminal units are analogous to pressure-independent boxes.

ComStock incorporates the OpenStudio® Standards approach for implementing SP resets, which reflects the applicable version of ANSI/ASHRAE/IES[4] Standard 90.1. Based on the applicable template, multizone VAV fans in ComStock and OpenStudio Standards are modeled with a curve reflective of an SP reset or without an SP reset. The assignment logic is listed in Table 1. Where the criteria for an SP reset are met, an SP reset is implemented in OpenStudio Standards and the ComStock baseline. Where only a fan threshold is listed, any fan with rated motor input power exceeding the threshold will have an SP reset implemented. Where a cooling capacity is also listed, that threshold must also be met for an SP reset to be implemented. For buildings with templates of an older vintage than ANSI/ASHRAE/IESNA Standard 90.1 2004 in the ComStock baseline, no SP resets are implemented.

Table 1. OpenStudio Standards Logic for Fan Curve Assignment

Template	Motor Input Power Threshold (horsepower)	Cooling Capacity Threshold (Btu/h)
DOE Ref Pre-1980	N/A	N/A
DOE Ref 1980-2004	N/A	N/A
ASHRAE 90.1 2004	9.9	N/A
ASHRAE 90.1 2007 and 2010	7.54	N/A
ASHRAE 90.1 2013	DX cooling: 0 Chilled water/evaporative: 0.25	DX cooling: 110,000 Chilled water/evaporative: N/A

Multizone VAV fans in ComStock without an SP reset are modeled with the "Multi Zone VAV with discharge dampers" curve from OpenStudio Standards [15]. Discharge dampers are a means of regulating airflow from VAV fans that reduces the extent to which individual VAV box dampers need to modulate. They are less energy-efficient than an SP reset. A minimum flow fraction of 25% is applied with ComStock's implementation of this fan curve [15]. In EnergyPlus, this minimum flow fraction is used only to calculate power draw, not to calculate

[3] Single-zone VAV systems are not represented in the ComStock baseline but are implemented through some measures [23]. This measure is not applicable to single-zone VAV systems. In single-zone VAV systems, airflow can modulate to meet the load of the zone served, so there is not a need for static pressure control [21].
[4] ANSI = American National Standards Institute; ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers; IES = Illuminating Engineering Society

airflows [12]. Figure 2 shows the fan curve used in multizone VAV models without an SP reset in ComStock, along with curves emulating SP resets.

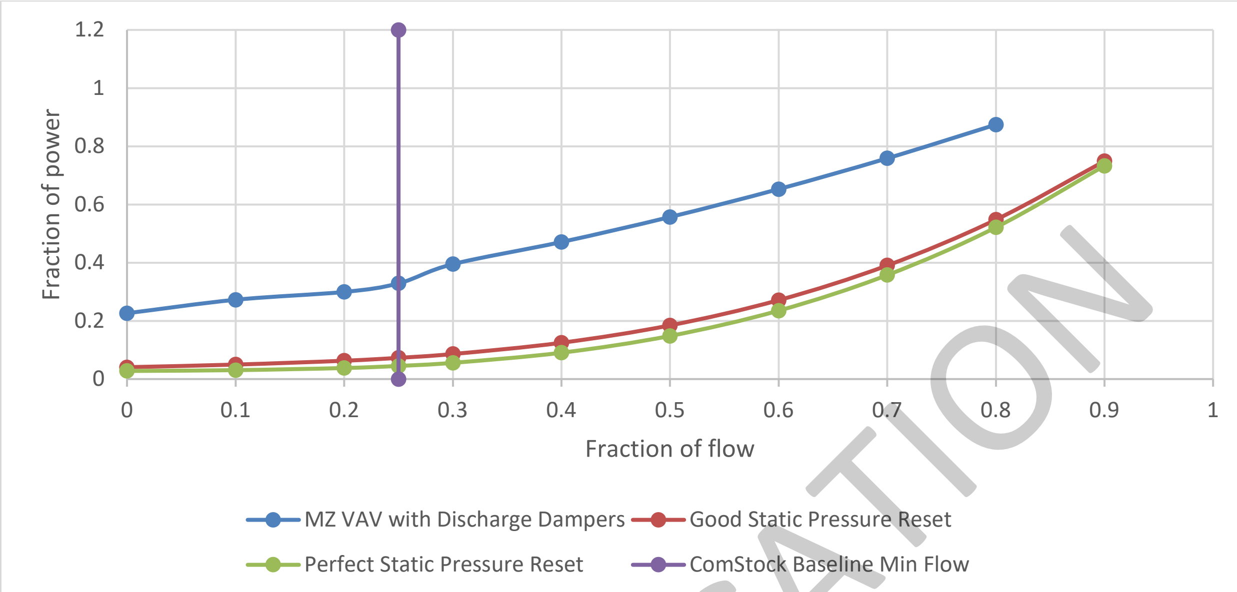


Figure 2. Comparison of VAV fan curve without SP reset from ComStock baseline with curves emulating SP resets

MZ = multizone

3 Modeling Approach

3.1 Applicability

This measure is applicable to multizone VAV systems currently modeled without SP resets in ComStock [16]. This accounts for 23% of the weighted floor area in ComStock (14.6 billion square feet). Figure 3 illustrates the applicability of this measure by HVAC system type.

ComStock HVAC distributions are informed by the Commercial Buildings Energy Consumption Survey (CBECS; the 2012 and 2018 results combined). The methodology for interpreting CBECS data to create HVAC probability distributions for ComStock is discussed in the ComStock Documentation report [14].

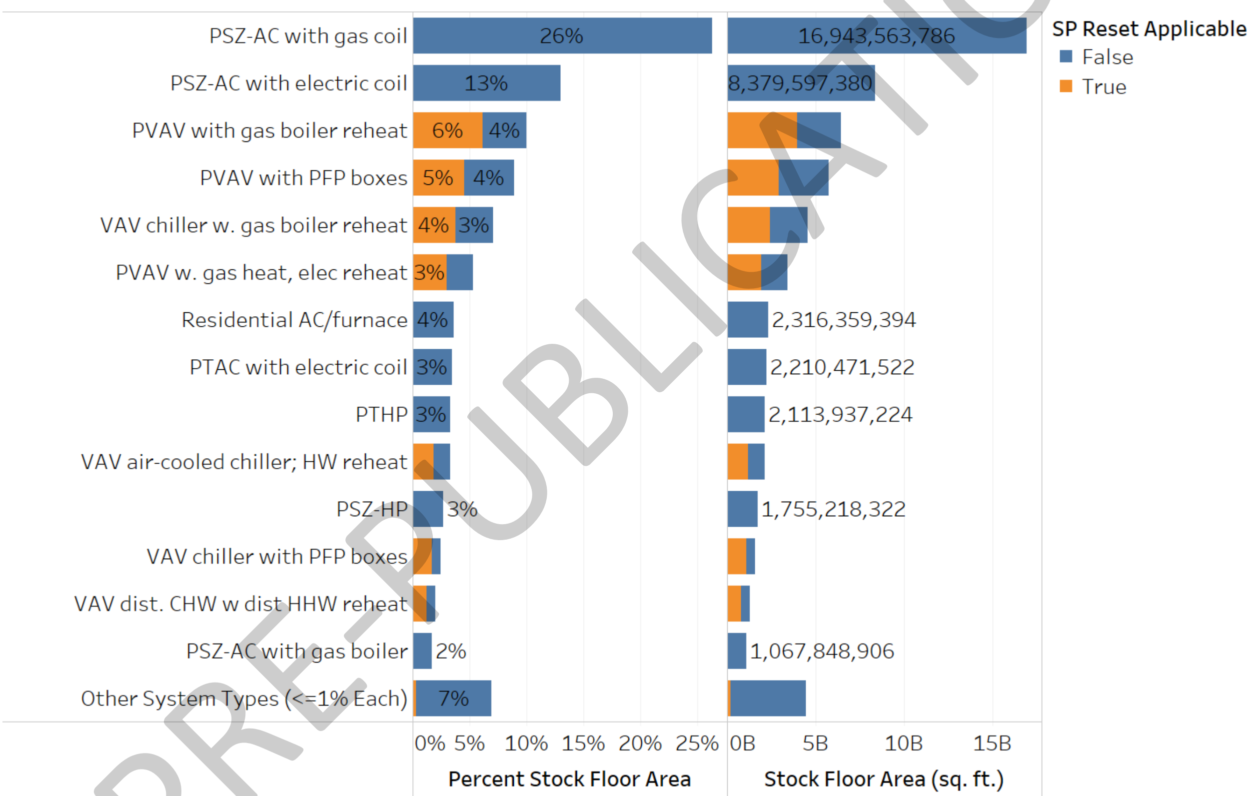


Figure 3. Measure applicability by HVAC system type

PSZ-AC = packaged single zone air conditioner; PVAV = packaged variable air volume; VAV = variable air volume; PFP = packaged fan-powered (boxes); PTAC = packaged terminal air conditioner; PTHP = packaged terminal heat pump; PSZ-HP = packaged single zone heat pump; CHW = chilled water; HHW = heating hot water

3.2 Measure Scenario Modeling Methodology

This measure is implemented by replacing the existing power vs. airflow fan curve with a curve representing the effects of an SP reset for systems that do not already use SP reset. The new curve represents a “good” (fairly effective) SP reset published in the Advanced VAV Design

Guide, which is also used to represent an SP reset in OpenStudio Standards [1] [15]. Figure 2 compares the two fan curves, along with a curve representing a "perfect" SP reset. The "good" and "perfect" SP reset curves are quite similar. As shown in Figure 2, the Good SP Reset curve results in lower power at all levels of flow less than 100% relative to the baseline curve. (At 100% flow, the curves coincide.)

Minimum variable frequency drive speed, corresponding in this context to minimum airflow fraction, is an important consideration. Totally enclosed fan-cooled motors are generally the most sensitive to minimum speeds to ensure adequate motor cooling; they are generally intended to operate at a minimum speed of 25% [17]. Some sources recommend a minimum speed of only 10% for HVAC fan motors equipped with variable frequency drives [1]. To avoid the need for motor replacement in some applications, this measure will assume a 25% minimum speed, consistent with the existing VAV fan implementation in ComStock without an SP reset.[5] The effects on energy savings of a 25% minimum speed vs. a 10% minimum speed are expected to be minimal, given the low slope of the "good" SP reset power vs. flow curve in this region.

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, but more detailed information is available in the ComStock Reference Documentation [14]. Summary statistics from this implementation are shown in Table 2. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 2. 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 [18].

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 [7]. 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

[5] OpenStudio Standards assumes a minimum speed of 10% on several VAV fan curves [15].

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 [8]. The URDB rates include detailed cost features such as time-of-use pricing, demand charges, ratchets, 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 unrealistically 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 in [19]. 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

ComStock, along with many building energy modeling workflows, uses simplified zoning approaches, which can result in airflow rates at the system level that diverge from what might occur in an actual building. This influences the energy savings calculated for this measure. The ComStock baseline also presents a limitation in evaluating energy savings from this measure. For buildings with templates of an older vintage than ANSI/ASHRAE/IESNA Standard 90.1 2004 in the ComStock baseline, no SP resets are implemented. This may not fully capture the extent of buildings in which SP resets have been implemented as part of retro-commissioning.

The "good" SP reset curve that will be used (and is currently used in other applications in OpenStudio Standards) reflects an assumption regarding the effectiveness of the reset, corresponding to the SP associated with zero flow in the underlying system curve (0.5" of static) [1]. This assumption is intended to reflect common conditions and is not reflective of every application. In practice, phenomena such as rogue zones and other faults can undermine the effectiveness of an SP reset. (Reset strategies can be programmed to ignore certain rogue zones, potentially at the expense of comfort in those spaces.) This means that the aggregate energy savings evaluated through this analysis represents an "upper bound" on attainable savings.

The fan modeling approach implemented in ComStock, using curves to characterize power draw as a function of flow without explicit modeling of pressure rise, is a simplification that ignores some nuances of pressure drop through the distribution system. Using an alternative, more detailed approach in EnergyPlus would require a traditional fan curve representing pressure rise as a function of flow. Identifying an appropriate fan curve for each modeled fan would not be tractable in ComStock.

As discussed previously, in systems that currently lack zone-level DDC, implementation of an SP reset would require an extensive controls retrofit to enable zone-level feedback to the building management system. Implementation of DDC to the zone in such systems would also create opportunities for implementation of other energy efficiency measures and improve fault detection and diagnostics capabilities.

4 Output Variables

Table 3 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 Fan SP Reset 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 3. Output Variables Calculated From the Measure Application

Variable Name	Description
SP_reset_applied	SP reset applied (true) or not (false)
air_system_vav_avg_flow_ratio	Average air flow ratio (air flow as a fraction of design airflow) across VAV systems

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 an energy efficiency strategy, depending on the use case.

5.1 Single-Building Measure Tests

In this section, we describe the operation of a hospital in Hattiesburg, Mississippi, climate zone 3A, to demonstrate the measure scenario application on a single building. The baseline model uses VAV systems with central hot water and chilled water coils and terminals with hot water reheat. Chilled water is supplied by an air-cooled chiller, and heating hot water is supplied by a natural-gas-fired boiler.

The building is served by two air-handling units, each with one supply fan. One of the two supply fans (SF-1) operates at or below 40% of design airflow for almost 75% of the year, and the other fan (SF-2) operates at or below that threshold for 86% of the year. Figure 4 shows the distribution of fan airflow fraction for SF-1.

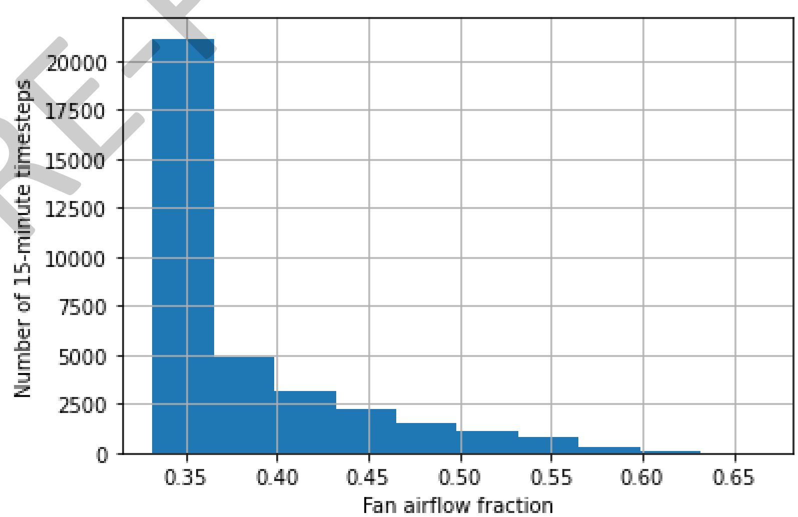


Figure 4. Distribution of fan airflow fraction over 15-minute time steps of year for SF-1

The fan power reduction follows the expected trend based on the reset curve. At an airflow fraction of 40%, the fraction of design power is reduced from about 40% under the baseline curve for these models in ComStock, to 12% under the "good" SP reset curve. As a result of the substantial fraction of the year with the fan operating at low loads, implementation of the SP reset in this model results in a large reduction in fan energy use. Figure 5 shows total building-level fan power draw under the baseline and with the SP reset and, as a reference, calculated fan power draw based on a fixed 40% airflow fraction under the two cases. The SP reset results in a 59% reduction in building-level fan energy use. Figure 6 shows power fraction as a function of flow fraction for SF-1 in the base and SP reset cases, superimposed on the modeled fan curves for the two cases. Table 4 summarizes energy savings by relevant end uses for this building.

Table 4. Summary of Energy Savings by End Use

End Use/Fuel Type	Baseline	SP Reset	Absolute Savings	Percentage Savings (%)
Heating (therms)	16,634	17,487	-853	-5.1%
Cooling (electric, kWh)	650,278	593,889	56,389	8.7%
Fans (electric, kWh)	246,806	100,611	146,195	59.2%

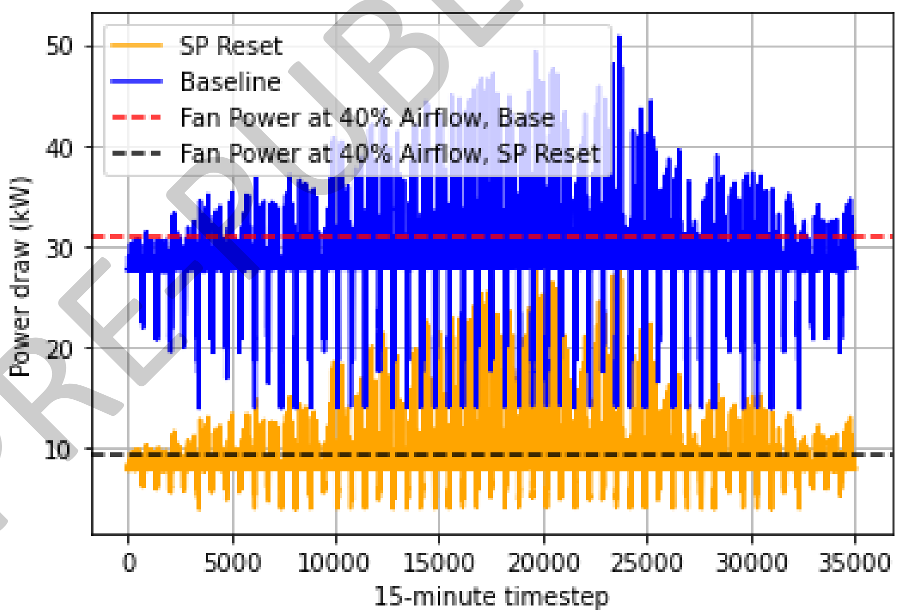


Figure 5. Total fan power draw for SP reset and baseline

Red dashed line shows fan power at 40% airflow under the baseline fan curve. Black dashed line shows fan power at 40% airflow under the reset curve.

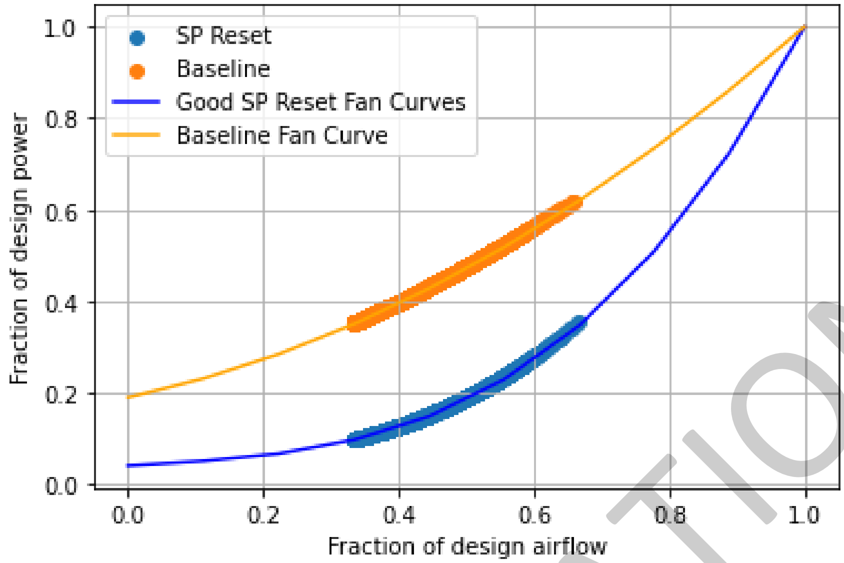


Figure 6. Power fraction as a function of airflow fraction for SF-1 for base and SP reset cases and modeled fan curves

Plotted points represent pairs of observed flow fraction and power for SF-1 in the model, and solid lines represent the modeled fan curves.

5.2 Stock Energy Impacts

The Fan SP Reset measure demonstrates 1.9% total site energy savings (92.7 TBtu) for the U.S. commercial building stock modeled in ComStock (Figure 3) and 8.7% site energy savings among applicable buildings only. The savings contributions by end use and fuel type are summarized in Table 5 and are illustrated in Figure 7.

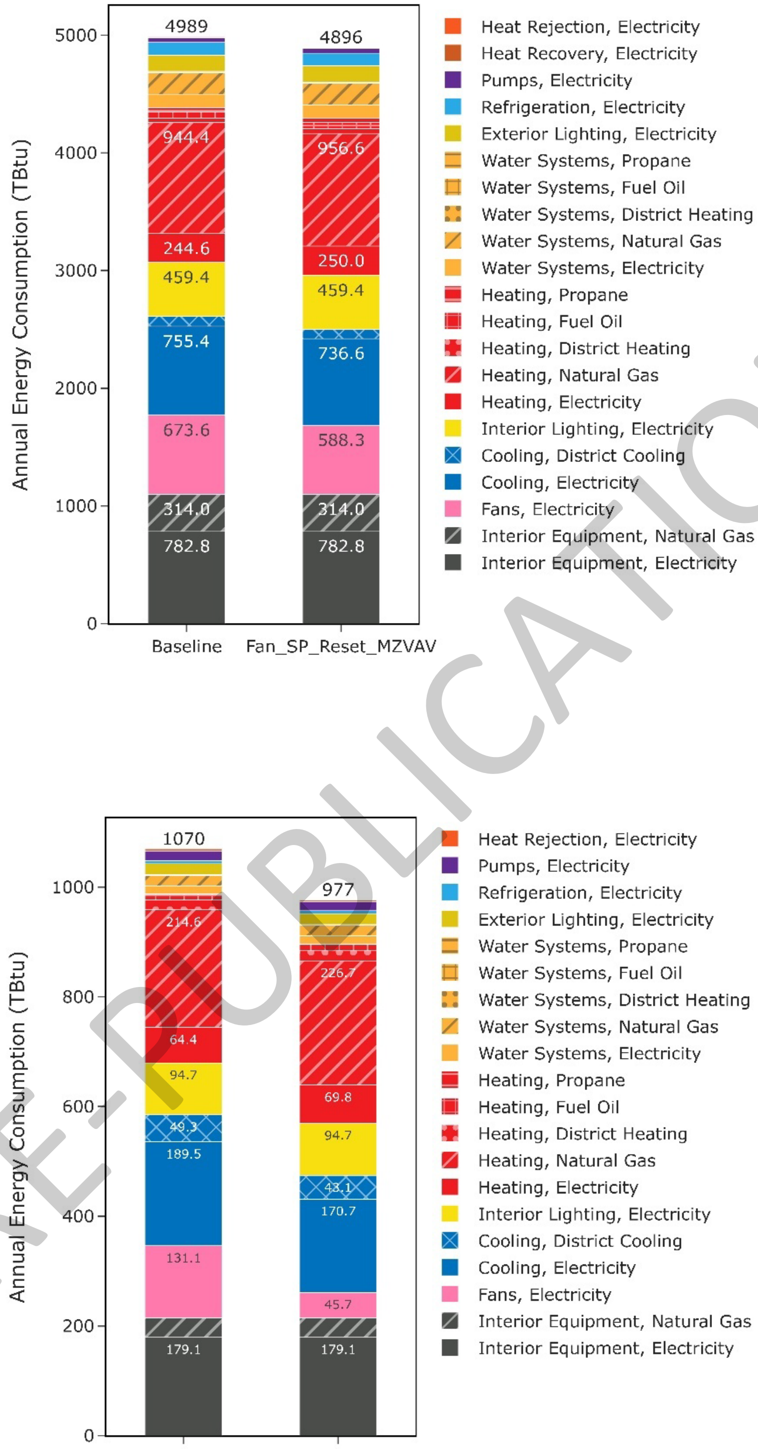
Table 5. Summary of Site Energy Savings From Upgrade Measure Application vs. the ComStock Baseline

End Use/Fuel Type	Percentage Site Energy Savings (All Buildings)	Percentage Site Energy Savings (Applicable Buildings Only)	Absolute Site Energy Savings (TBtu)
Total natural gas	-0.8%	-4.5%	-12.2
Total electricity	3.0%	14.0%	100.0
Total heating	-1.3%	-5.7%	-17.6
Gas heating	-1.3%	-5.7%	-12.2
Electric heating	-2.2%	-8.3%	-5.4
Electric fans	12.7%	65.0%	85.4
Electric cooling	2.5%	9.9%	18.8

Figure 7 shows a disaggregation by end use of the effects of applying the Fan SP Reset measure. Figure 7a shows the effects for the full building stock sample, and Figure 7b shows the effects for only those buildings to which the measure was applicable. Energy savings primarily result from a reduction in fan electricity energy use, since the SP reset reduces fan power during periods of low load. The fraction of fan energy savings in applicable buildings (65%) is consistent with expectations for a fan operating at low load, based on the fan curve used to model the impacts of this measure. This is examined in more detail in Section 4.6. Past studies of SP resets implemented in real buildings have reported fan energy savings from 25% to 50% [10] [1].

The penalty for heating end uses results from a reduction in fan heat, which at times would have provided useful heating to the airstream. The reduction in fan heat also explains the reduction in cooling energy. The expected magnitude of these impacts on heating and cooling energy use depends on the amount of time the reduction in fan heat results in creating a heating demand, reducing the cooling demand, or neither (if zones are operating in the deadband) across the ComStock sample. As a high-level check, the aggregate fan energy reduction was compared to the magnitude of the heating penalty and cooling energy savings, adjusted for the typical natural gas heating efficiency in ComStock (80%), and a typical direct expansion (DX) minimum cooling efficiency in ComStock (an energy efficiency ratio of 8.2 and COP of 2.4) [14]. (The electric heating energy penalty was not adjusted, since electric heating coils operate with an effective efficiency of 1.0.) DX cooling serves 81% of the floor area in ComStock. The sum of the estimated reduction in useful fan heat, based on the heating penalty converted to a heating load (9.7 TBtu), and the estimated reduction in fan heat imposing a cooling penalty (based on the cooling energy savings converted to a cooling load) (45 TBtu) is 55 TBtu, equal to about 64% of the overall reduction in fan electricity (about 85 TBtu). This is consistent with expectations, since much of the time fan heat will either provide useful heating or result in a cooling requirement. The only periods in which the fan heat is not useful or imposing a cooling requirement are those in which the unit is ventilating but not heating or cooling (e.g., inside the thermostat deadband).

Past studies assessing the impacts of fan SP resets have done so through both modeling analyses and with data from real buildings. Past studies of SP resets implemented in real buildings have reported fan energy savings from 25% to 50% [10] [1]. Fan energy savings from an SP reset is highly dependent on the relationship between fan sizing and relative loads. Another U.S. building stock-level analysis of fan SP resets found 4.6% site energy savings from implementation of a T&R style SP reset (and lower percentage savings from a scheduled reset) [11]. The reset implemented in this study more closely approximates a T&R style reset than a scheduled reset. The energy savings reported in this study exceed both the fan energy savings and site energy savings proportions reported in past studies (65% and 8.7% among applicable buildings in this study, respectively). This reflects the load conditions under which fans typically operate in ComStock, which is discussed in more detail in Section 4.6.



a)

b)

Figure 7. Comparison of annual site energy consumption between the ComStock baseline and the Fan SP Reset measure scenario.

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

5.3 Stock Utility Bill Impacts

The stock-level impacts of the Fan SP Reset measure on utility bills are summarized in Table 6 and Figure 8. Note that ComStock considers all potential electricity rates for a given location; thus, the results are presented based on maximum, mean, and minimum electricity rates. Across all three scenarios, the Fan SP Reset measure results in 2% utility bill savings, reflecting the net effect of a reduction in electricity use, and a small increase in use of heating fuels. The percentage bill savings by end-use generally tracks the percentage energy savings by that end use. Figure 9 highlights these effects by showing distributions of utility bill impacts by fuel type. Bill savings are achieved for the overall bill and for the electricity bill (with the bill under the mean rate shown), and an increase occurs for natural gas and fuel oil bills. The fact that the distribution of the overall utility bill savings closely mirrors that of the electricity bill savings, shifted slightly lower, reflects the fact that electricity makes up most of the utility bill in many commercial buildings, and the penalties on the fuel bills have the effect of reducing the net savings slightly. A very small fraction of the sample (about 1.4%) sees a slight increase in utility bills. Forty-one percent of this small set of buildings (223 buildings) use fuel oil for heating and have a higher-than-average fuel oil heating penalty from the measure. Fuel oil is generally more expensive per unit than natural gas, and this drives the slight overall utility bill penalty for these buildings.

Table 6. 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	Percentage Savings (All Buildings)	Percentage Savings (Applicable Buildings Only)	Absolute Savings (Million USD, 2022)
Electricity	2.9%	13%	3,175
Natural gas	-0.8%	-4.3%	-137.2
Fuel oil	-1.2%	-6.1%	-21.47
Propane	0.0%	-5.8%	-13.43
Total	**2.3%**	**11%**	**3,015**

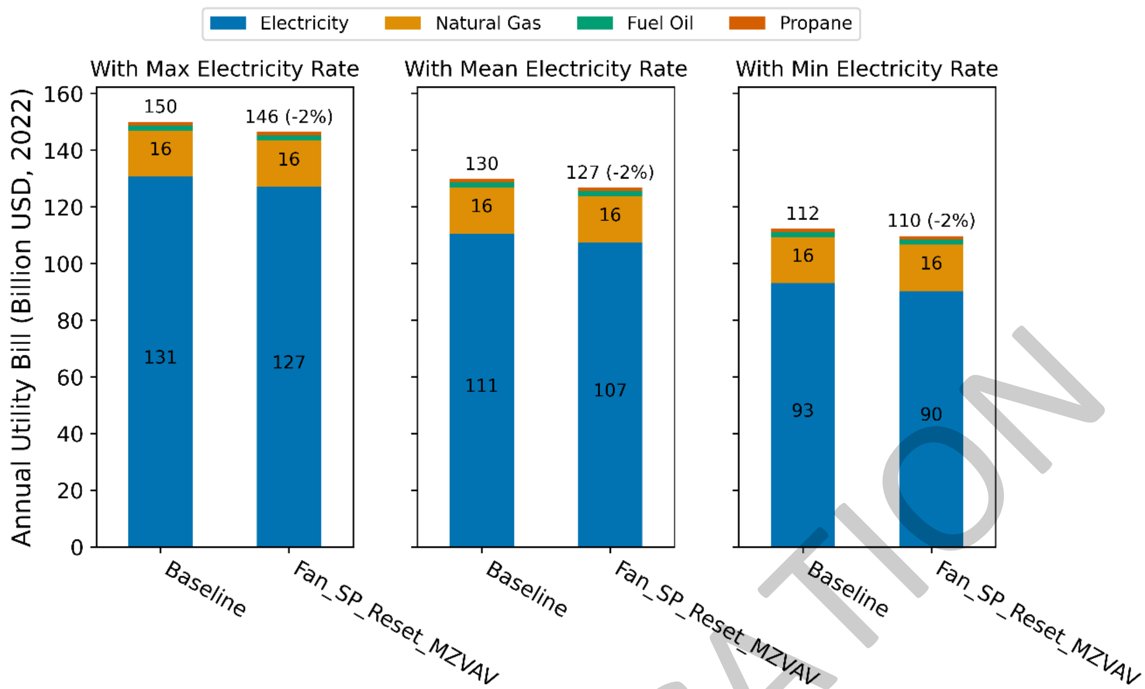


Figure 8. Annual utility bill impacts using the max, mean, and minimum bills across available rate structures for buildings for both the Fan SP Reset and baseline scenarios.

Includes buildings not applicable to the Fan SP Reset measure scenarios.

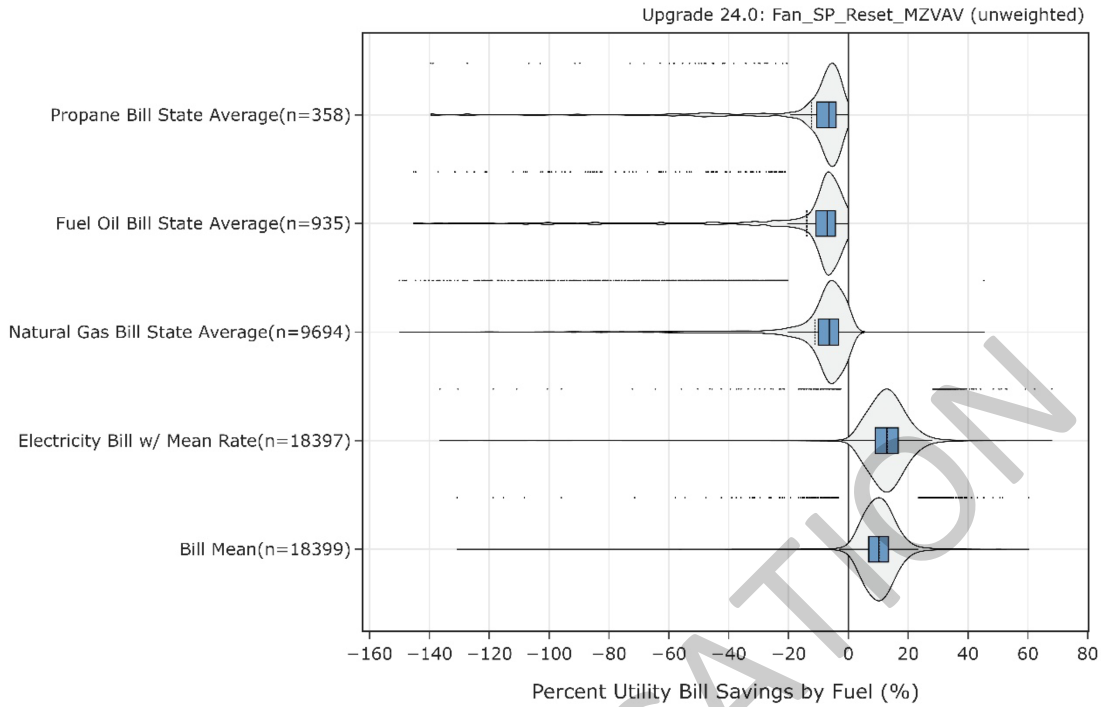


Figure 9. Percentage annual utility bill savings distribution for ComStock models with the Fan SP Reset measure scenario by fuel type.

Results shown in this plot are the savings for the average available utility rate per building. 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 unweighted ComStock models that were applicable for energy savings for the fuel type category.

Figure 10 shows distributions of utility bill savings by climate zone. Climate zones 6A, 6B, and 7 have lower 25th percentile, median, and 75th percentile utility bill savings than climate zones such as 2A, 3B, and 3C. This generally tracks the relative site energy savings distributions for these climate zones, shown in Figure 11. Utility bill savings from this measure are also affected by the relative magnitudes of electricity and heating fuel rates, since the measure results in electricity savings, and a heating fuel penalty. Note the very small number of buildings in climate zone 8 with this measure applicable in the sample (only 19 buildings).

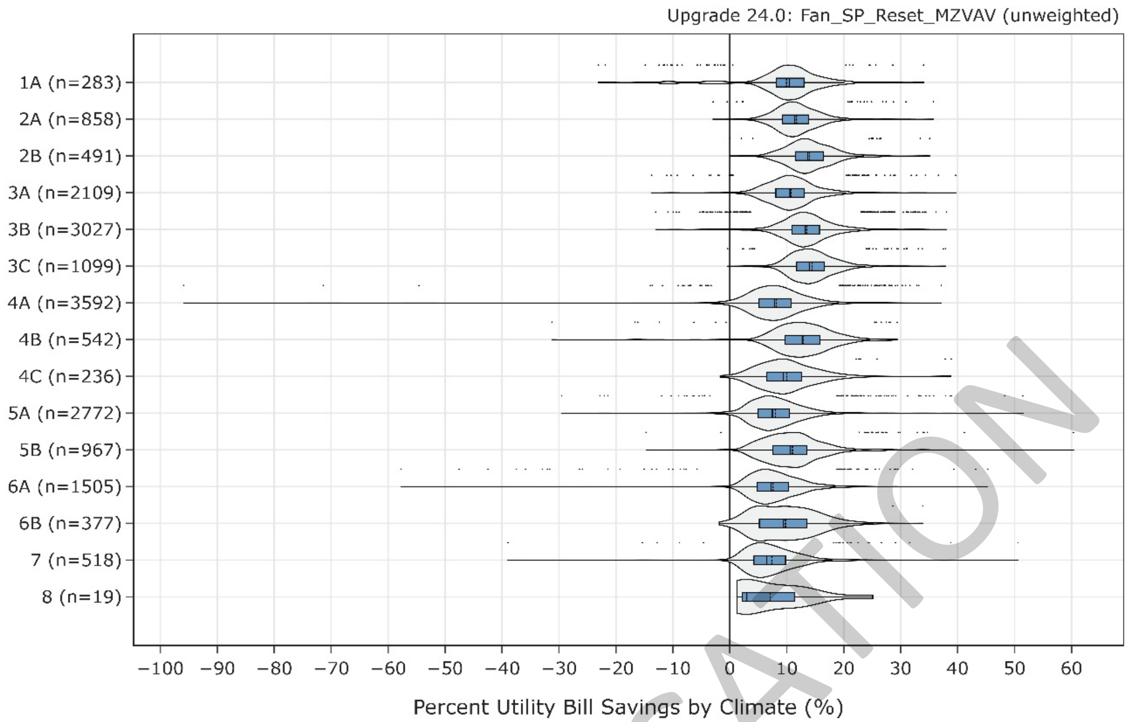


Figure 10. Percentage annual utility bill savings distribution for ComStock models with the Fan SP Reset measure scenario by climate zone.

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 unweighted ComStock models that were applicable for energy savings for the fuel type category.

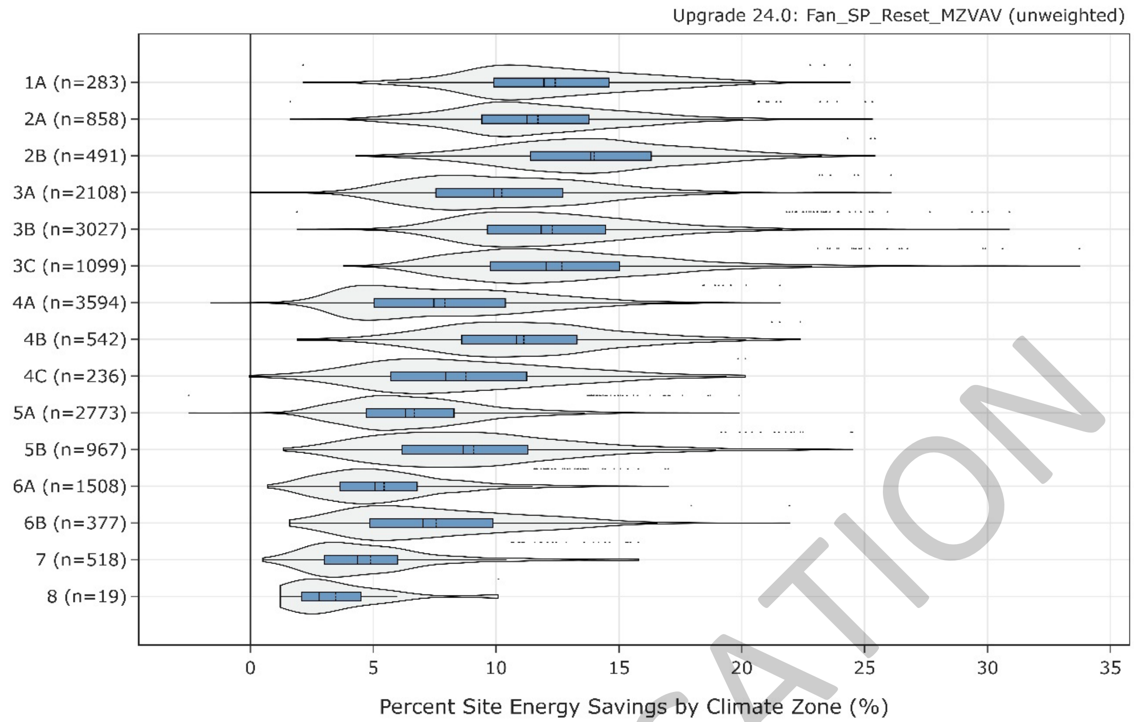


Figure 11. Percentage annual site energy savings distribution for ComStock models with the Fan SP Reset measure scenario by climate zone.

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 unweighted ComStock models that were applicable for energy savings for the fuel type category.

5.4 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes for the Fan SP Reset measure. Note that while site energy savings can be informative for these purposes, it does not always correspond directly to outcomes of greater practical significance, such as source energy savings or reduced energy bills. It is important for a decision maker to consider which metrics best align with their specific goals or context.

Figure 12 shows distributions of energy savings by fuel type and end use for buildings to which the Fan SP Reset measure was applied. As expected, fans have the highest values of energy savings, followed by cooling (electric and district cooling), and heat rejection. Fan energy savings reflect fan operation at a lower SP setpoint due to the reset. The median fan energy savings value is 68%. As discussed previously, this is higher than reported in other studies but consistent with the fan operation conditions observed in ComStock. (Past studies have generally not quantified effects of SP resets on specific end uses other than fans.) The effect of operating conditions on fan energy savings is discussed in detail in Section 4.6. Cooling energy savings reflects a reduction in fan heat that would have otherwise produced a cooling load. Energy savings in heat rejection reflects reduced load on cooling towers in buildings with water-cooled chillers because of reduced load on the chiller.

As expected, energy penalties are observed in space heating for all space heating fuel types. The reduction in fan heat through the reset results in a heating energy penalty when the fan heat would otherwise have provided useful heating to the airstream. The magnitude of the cooling energy savings and heating penalty depends on the climate and the building's other thermal loads, which influence whether a building would otherwise have required cooling or heating at a given set of conditions. As discussed previously, the magnitudes of the aggregate cooling energy savings and heating energy penalty across the sample are reasonable given the magnitude of fan energy savings.

The relatively wide distribution of pump energy savings, roughly centered at 0, reflects the fact that in buildings with hydronic systems, both cooling and heating have associated distribution pump energy use. The net effect on pump energy use from the Fan SP Reset measure is a consequence of the balance of the heating and cooling energy impacts, which varies from building to building based on climate and space loads. This is discussed in more detail in Section 5.5.

The small change in interior equipment energy use in a few buildings (four) is the result of a known bug in ComStock regarding schedules for elevator operation (https://github.com/NREL/ComStock/issues/350) [20]. This has very minimal impact on the overall energy savings distributions.

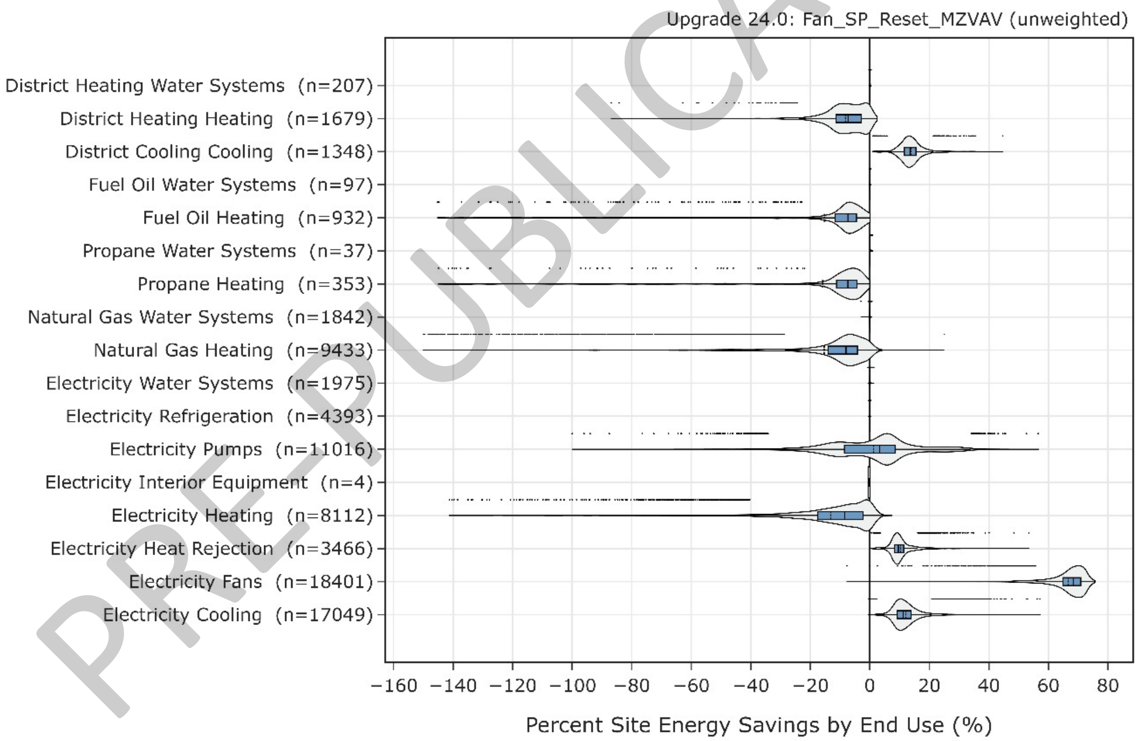


Figure 12. Percentage site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type.

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.

Figure 13 shows the distribution of energy savings by fuel type. As expected, and for the reasons discussed previously, application of the measure results in electricity savings and net site energy savings, as well as savings for district cooling. The measure results in penalties for fuels used solely for heating: natural gas, fuel oil, propane, and district heating.

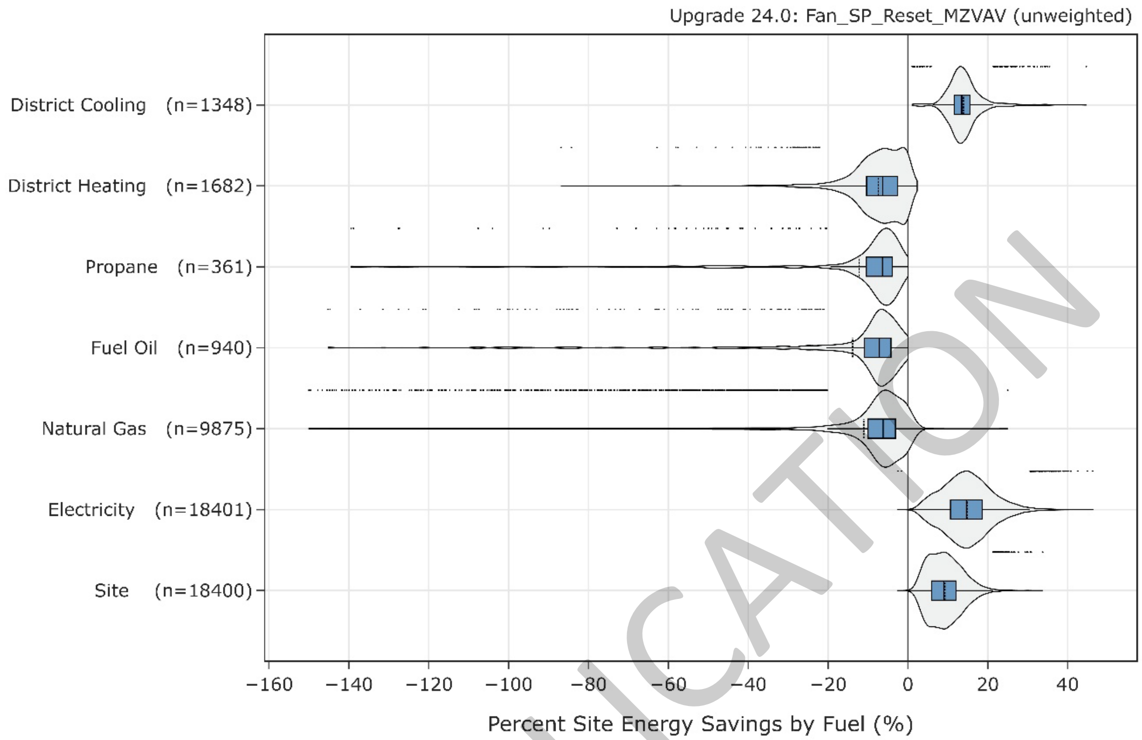


Figure 13. Percentage site energy savings distribution for ComStock models with the applied measure scenario by fuel type.

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.

5.5 Pump Energy Impacts

Figure 14 illustrates the factors driving pump energy impacts in more detail. For buildings with hydronic heating systems, Figure 14 shows that two distinct trends drive effects on pump energy from the SP reset, depending on whether the building has a hydronic cooling system. In buildings with hydronic heating systems and no hydronic cooling, there is a pump energy penalty, which reduces in magnitude as the natural gas heating penalty reduces. This is because in these buildings, the hydronic heating load is the primary driver of circulation pump energy, since hydronic cooling systems are not present. In buildings with both hydronic heating and cooling systems, there are generally pump energy savings, reflecting the reduced load on hydronic cooling systems, which exceeds the penalty from increased pump operation in heating. These two effects explain the distribution roughly centered at zero of pump energy savings from this measure.

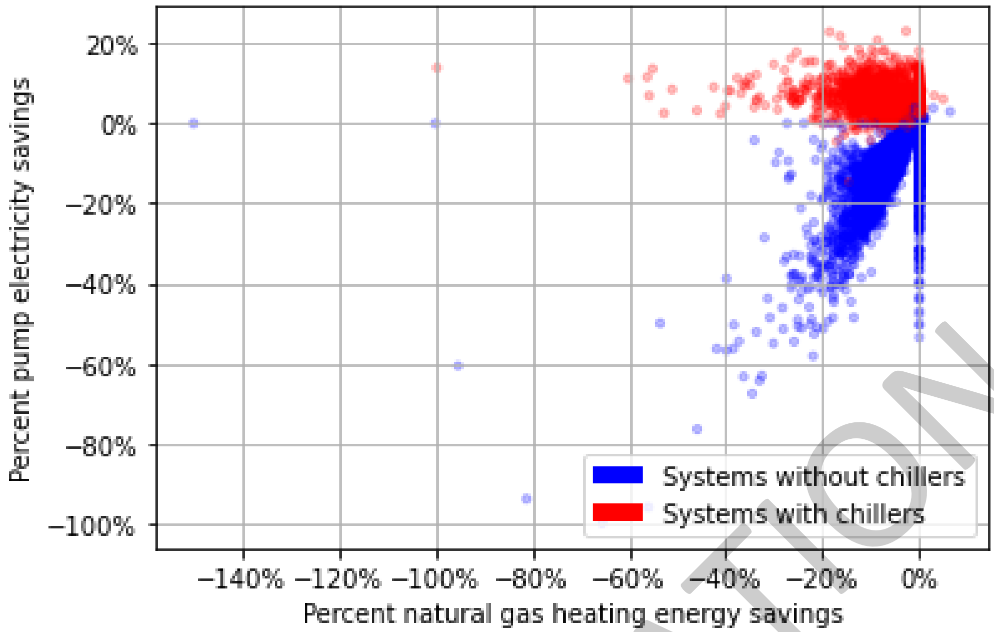


Figure 14. Pump electricity savings vs. natural gas heating energy savings for buildings with hydronic heating systems

5.6 Average Fan Airflow Ratios

In real buildings, the airflow and SP required from a fan are highly influential on the potential impact from an SP reset. In the modeling approach applied through EnergyPlus in this study, SP is not explicitly modeled, and fan power curves are expressed as a function of the airflow ratio, which is the ratio between the fan's current operating airflow and design airflow. The average annual airflow ratios of VAV systems among buildings to which this measure was applicable were investigated to confirm that the energy savings results were reasonable. Note that the fan power curve used in EnergyPlus is a cubic polynomial, and thus an annual average of airflow ratio cannot be perfectly extrapolated to energy savings through the reset.[6] However, the annual average airflow ratio provides an informative proxy for the fan's operating conditions throughout the year.

Figure 15 shows a distribution of average annual airflow ratios among VAV systems in buildings to which the SP reset was applicable. The vast majority (90%) of buildings to which the measure was applicable have an average VAV airflow ratio of less than or equal to 0.4. As illustrated in the fan power curves in Figure 6, a fan operating at an airflow ratio of 0.4 under the SP reset curve uses about 30% of the power of a fan operating at the same airflow ratio under the baseline curve. Given the variation in fan airflow ratio throughout the year, this is generally consistent with the aggregate fan energy savings of 65% observed among applicable buildings. Figure 16 shows a scatterplot of annual fan energy savings through the SP reset as a function of the average VAV airflow ratio. There is a higher density of data points and more variation in fan energy

[6] Some engineers analyzing fan performance in real buildings treat fan power curves as being quadratic, rather than cubic [24].

savings at lower ranges of airflow ratio (less than 0.4). As discussed, an annual average airflow ratio is not a perfect indicator of fan energy savings due to the cubic nature of the fan curve. However, the general shape of the distribution of fan energy savings as a function of airflow ratio bears out expectations in approximating the inverse of the fan power as a function of airflow curve. These results confirm that the relatively high fraction of fan energy savings observed in the ComStock sample through the SP reset are as expected, given the large portion of the sample with low fan airflow ratios. The extent to which these low airflow ratios are representative of conditions in real buildings is an area for further investigation.

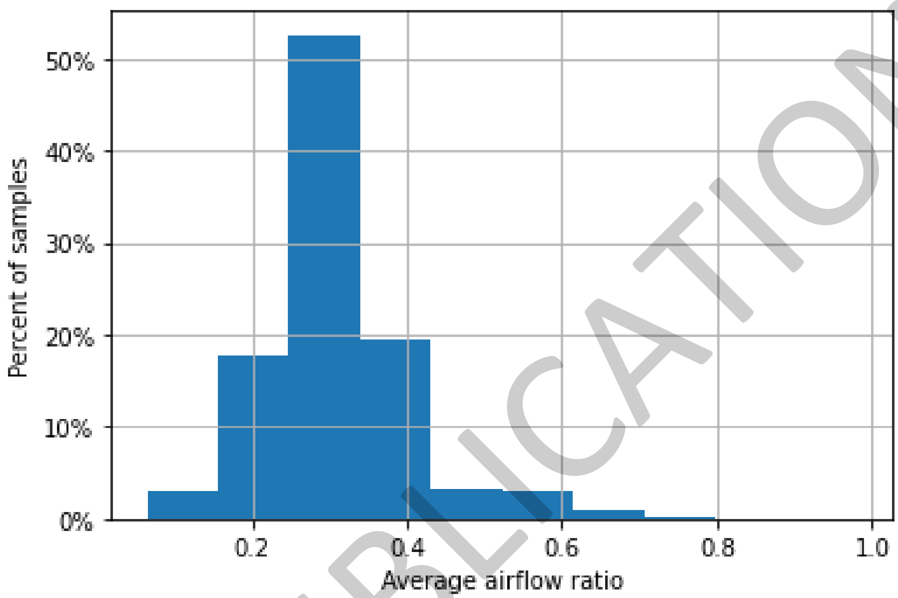


Figure 15. Distribution of average annual airflow ratio among VAV systems in buildings to which this measure was applicable

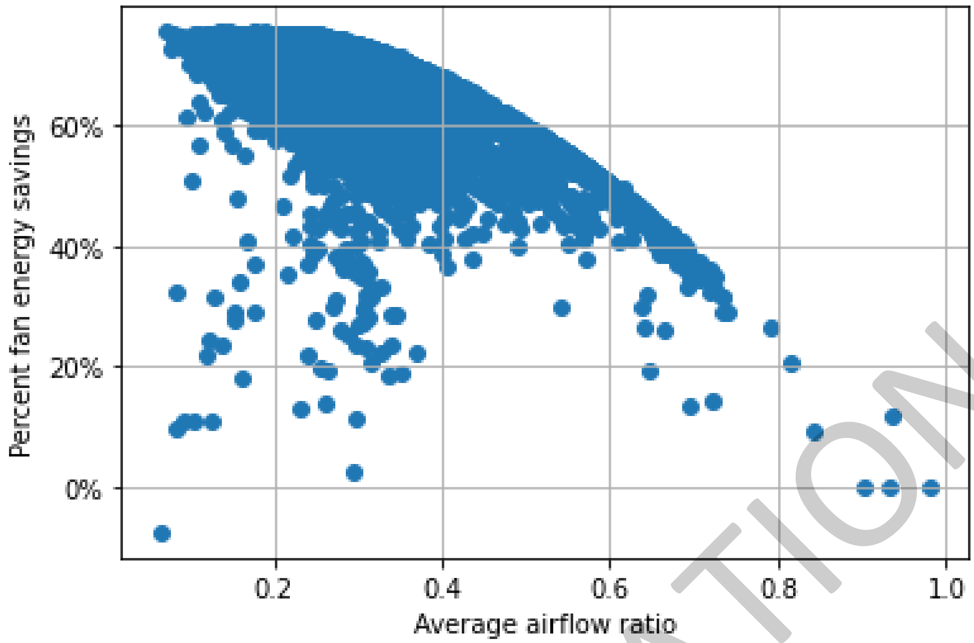


Figure 16. Distribution of annual fan energy savings through SP reset as a function of average airflow ratio among applicable buildings

The relationship between heating and cooling degree days and average fan airflow ratio was also investigated, to determine if climate was a significant factor in influencing airflow ratio. Degree days quantify the heating or cooling demand expected in a given location. Annual heating degree days (HDD) are calculated from days with an average temperature below a given threshold (the base temperature), as the sum of the differences between those averages and the base temperature. Annual cooling degree days (CDD) are calculated from days with an average temperature above a given base temperature (which may be different than the one for HDD), as the sum of the differences between those averages and the base temperature. In ComStock, design fan airflow is determined based on heating and cooling design days, system operating parameters, and ventilation requirements. Operating fan airflow at any given point is influenced by the building's internal thermal loads, outdoor conditions, and ventilation requirements. Among buildings with more than 1,000 HDD with a base of 50°F (HDD 50), a tighter range, and lower maximum, fan airflow ratio was observed. Since commercial buildings are typically cooling dominated, it was hypothesized that this could reflect buildings in cooler climates tending to operate closer to their balance point temperature with less cooling load-driven airflow, as illustrated in Figure 17.

To investigate this possible trend further, the interaction between heating and cooling degree days was considered. Among a subset (about 24% of the applicable sample) of buildings from more "mild" climates (with fewer than 2,000 per year of both HDD 50 and CDD base 65°F [CDD 65]), a limited trend was observed of lower and more tightly clustered fan airflow ratios with buildings with more than 1,200 HDD 50, as illustrated in Figure 18. This may reflect buildings with higher internal load densities that are operating closer to their balance point temperature and have lower space-conditioning-driven airflow requirements in these locations.

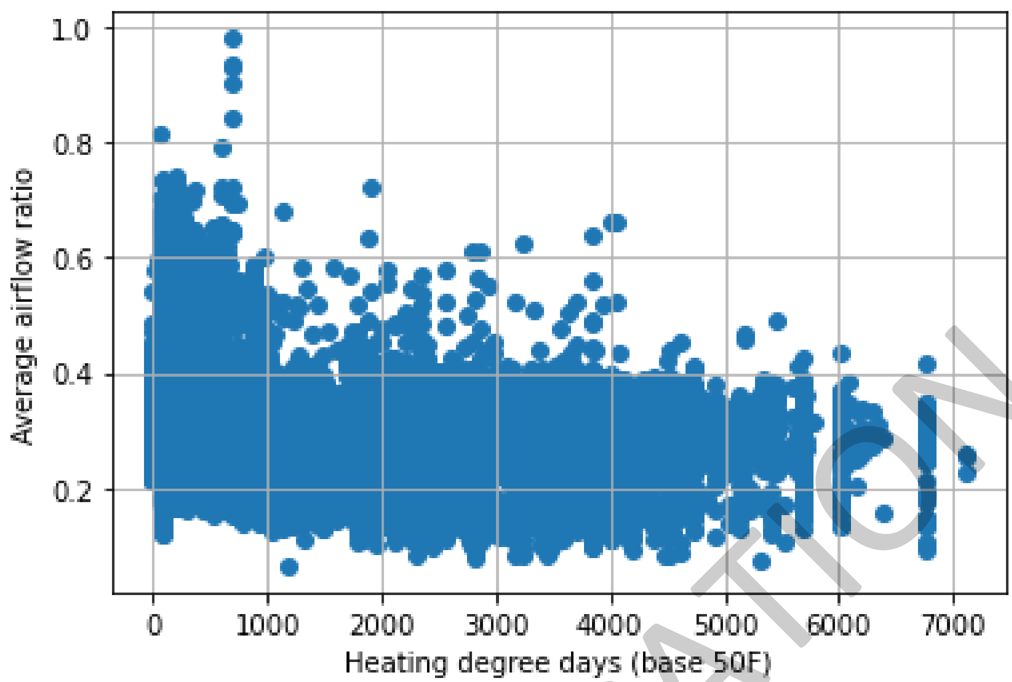


Figure 17. Average fan airflow ratio vs. HDD 50 for all applicable buildings

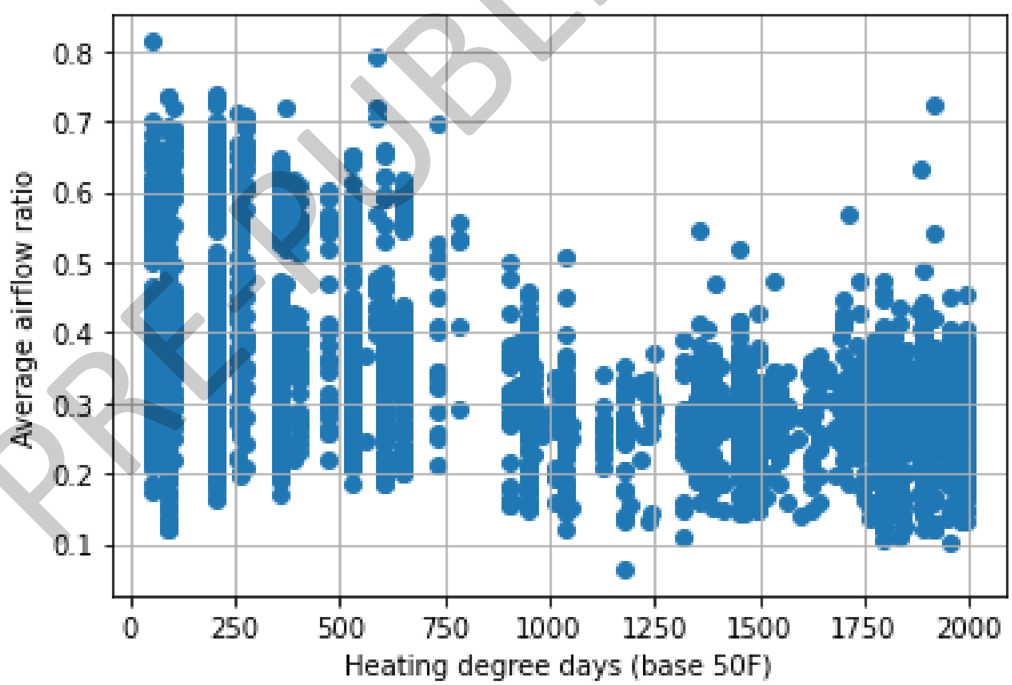


Figure 18. Average fan airflow ratio vs. HDD 50 for applicable buildings in more "mild" climates (<2,000 HDD 50, <2,000 CDD 65)

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Appendix A.

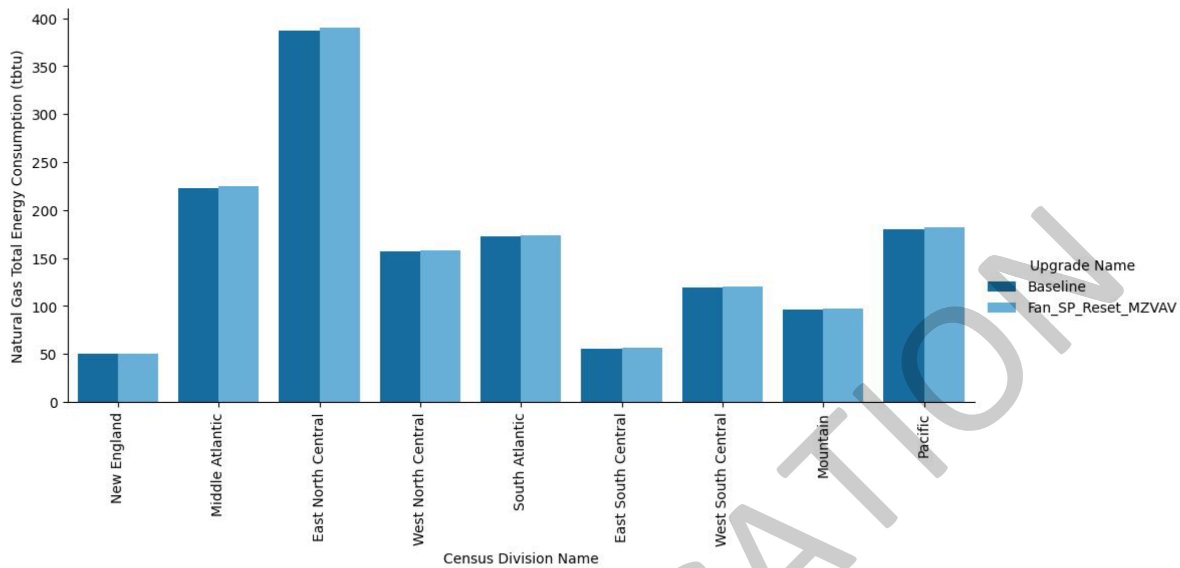

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

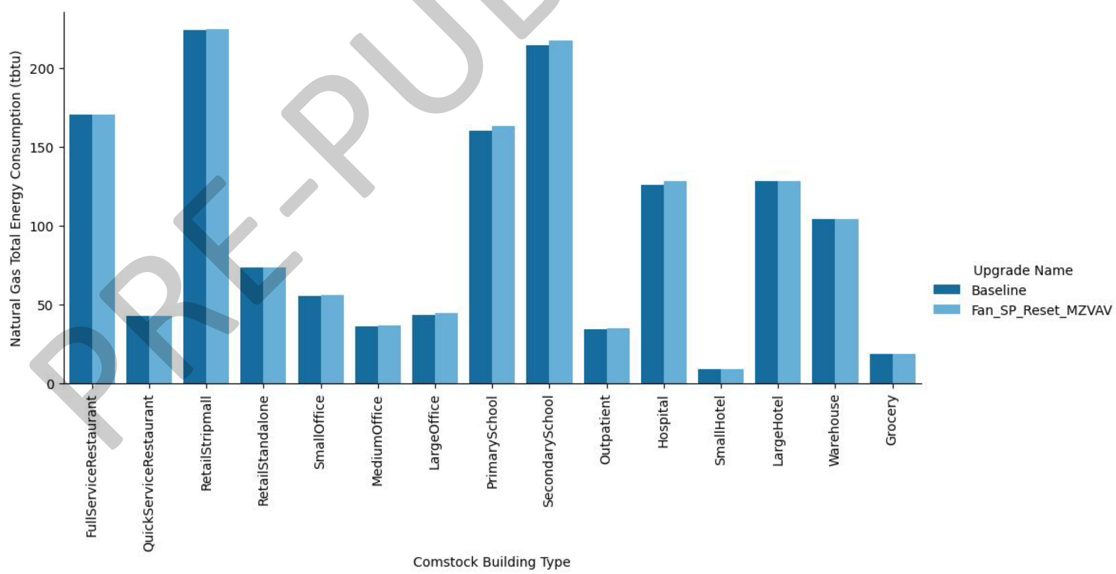

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

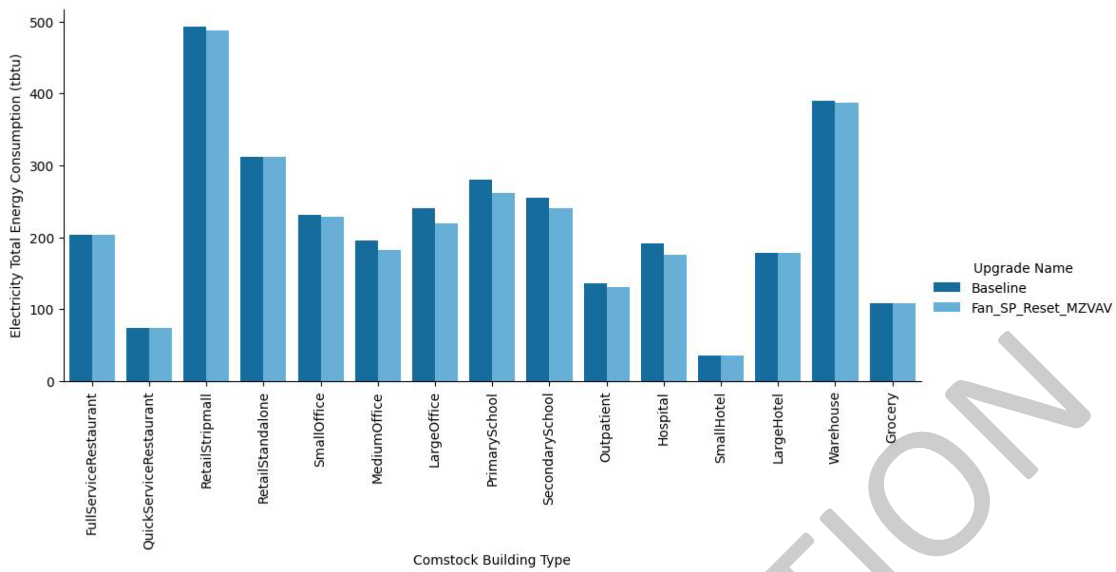

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

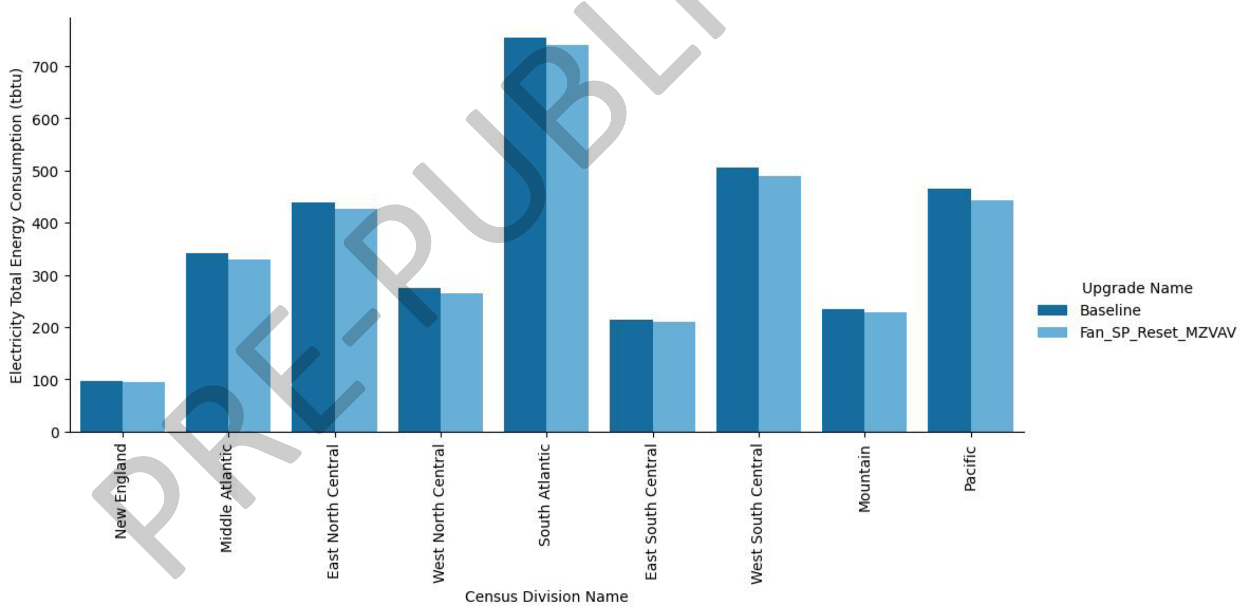

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division