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ComStock Measure Documentation: Thermostat and Lighting Control for Load Shedding

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National Renewable Energy Laboratory

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List of Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
EIA	U.S. Energy Information Administration
HVAC	heating, ventilating, and air conditioning
LED	light-emitting diode
PADD	Petroleum Administration for Defense District
URDB	Utility Rate Database

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 multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual subhourly 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 end-use load shapes that cover high-impact, market-ready (or nearly market-ready) measures. "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 data sets 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 an upgrade package of two ComStock measures—Thermostat Control for Load Shedding and Lighting Control for Load Shedding—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 data set 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. More details on the individual upgrades can be found on the ComStock upgrade measures page.

Table ES-1. Summary of Key Modeling Specifications

Package Title	Thermostat and Lighting Control for Load Shedding
Technology description	• This package combines two measure scenarios: thermostat control for load shedding and lighting control for load shedding. It relaxes thermostat set points (heating and cooling) and dims lighting systems to reduce the building's daily electricity peak demand during demand flexibility events. • Demand flexibility events are dispatched every weekday for 4 hours. The timing of the dispatch window is centered around either the grid peak load or each individual building's peak load for the day, depending on the objective. Dispatch schedule inputs generated by the method "Dispatch Schedule Generation" described in End-Use Savings Shapes Measure Documentation: Dispatch Schedule Generation for Demand Flexibility Measures determine the start and end times of the daily 4-hour windows that cover the peak loads.
Performance assumptions	• The thermostat set points are adjusted −2°C and +2°C for heating and cooling, respectively, during the dispatch window (load shed periods), and ramp back to original set points over 2 hours after the window for rebound control. • The lighting level (the corresponding power) is reduced 30% during the dispatch window (load shed periods), and resumes to the original value after the window.

Package Title	Thermostat and Lighting Control for Load Shedding
	• Control decisions of the two measures are made independently, without consideration of integration of HVAC and lighting systems (e.g., internal heat gain from lighting equipment impacting HVAC operations).
Applicability	• The individual measures share the same applicability for building types, which covers large, medium, and small offices; warehouses; and primary and secondary schools. • The thermostat control measure is applicable electric HVAC (electric heating or cooling or both) systems, which corresponds to 67.26% of the stock floor area. • The lighting control measure is applicable to 68.00% of the stock floor area based on the building types listed above.
Release	• 2025 Release 1: 2025/comstock_amy2018_release_1/

National annual results for site energy, energy bills, and demand flexibility are summarized in Table ES-2 to Table ES-4. Note that the summary table for energy bills uses one of many respective scenarios. Other scenarios are discussed later in the report, with further scenarios available in the ComStock public dataset.

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

Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (trillion British thermal units [TBtu])
With individual peak load reduction objective			
Natural gas	-0.32%	-0.75%	-4.9
Electricity	1.77%	3.53%	56.1
With grid-level peak load reduction objective			
Natural gas	-0.22%	-0.52%	-3.4
Electricity	1.23%	2.47%	39.0

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. Bill savings summary is present with individual peak load reduction objective.

End Use/Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (Million USD, 2022)
Electricity	1.9%	3.0%	2
Natural gas	0.0%	0.0%	0
Fuel oil	0.0%	0.0%	0
Propane	0.0%	0.0%	0
Total	1.6%	2.7%	2

Table ES-4. Summary of Key Results for Monthly Peak Savings

Median Percent Savings (Applicable Buildings Only)	Jan	Fen	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
With individual peak load reduction objective												
Mean daily peak load	6.3%	6.6%	6.0%	6.5%	7.3%	6.9%	6.9%	7.1%	7.3%	6.7%	6.5%	6.1%
Mean daily peak load on grid peak window	0.7%	0.6%	0.5%	0.6%	-0.2%	-0.4%	-1.3%	-1.0%	-0.1%	0.3%	0.5%	0.5%
With grid-level peak load reduction objective												
Mean daily peak load	0.0%	0.0%	0.0%	-0.1%	-0.3%	-0.5%	-0.7%	-0.6%	-0.4%	-0.1%	0.0%	0.0%
Mean daily peak load on grid peak window	13.2%	13.2%	11.7%	12.2%	16.3%	18.5%	20.6%	20.5%	17.2%	12.9%	13.0%	12.8%

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1 Technology Summary

This upgrade package couples these two building components—thermostat and lighting—with technologies focusing on demand flexibility control for load shedding. The upgrade package applies the Thermostat Control for Load Shedding and Lighting Control for Load Shedding upgrades based on the applicability criteria of each individual upgrade. A model will have all, some, or none of the upgrades applied depending on how the model's characteristics align with each upgrade's applicability criteria.

For details about each of the two technologies, reference their individual upgrade documentation: Thermostat Control for Load Shedding and Lighting Control for Load Shedding.

2 ComStock Baseline Approach

The following sections provide high-level summaries of the ComStock baseline approach for thermostat and interior lighting. For more detail about how these systems are modeled in the ComStock baseline, including data sources, reference the ComStock documentation [1].

2.1 HVAC/Thermostat

This measure modifies the existing model thermostat set point schedules during the daily peak demand windows (specifically on-peak and post-peak periods) only. For times outside of the event, the existing thermostat schedules in the model are unchanged. The details of the thermostat schedule in the existing ComStock models can be found in Section 4.2 "Hours of Operation and Occupancy," which determines building hours of operation, and Section 4.8.7 "Thermostat Set Points," which describes how thermostat set points/setbacks are applied to the schedule, in the ComStock Documentation [1].

2.2 Interior Lighting

This measure modifies the existing model (interior) lighting schedules during the daily peak demand windows (specifically on-peak periods) only. For times outside of the event, the existing lighting schedules in the model are unchanged. The details of the lighting schedules, technology, and power in the existing ComStock models can be found in Section 4.2 "Hours of Operation and Occupancy" and Section 4.5.1 "Interior Lighting" in the ComStock Documentation [1] for default schedules, and Section 3.3.4 "Interior Lighting Schedule Magnitude Variability" in the End-Use Load Profiles project report [2] for base-to-peak variation applied to the default lighting schedules.

ComStock interior lighting is determined by a lighting technology generation approach, with each generation representing a collection of lighting technologies typically installed during a given time period. ComStock assumes four categories of lighting: general (overhead lighting), task (lights focused on specific areas), supplemental (additional lighting), and wall wash (illuminates vertical surfaces). The lighting technologies used in each category across the ComStock lighting generations are listed in Table 1. Generations 4–8 represent varying efficacy levels of LEDs, with Generation 4 being the first LED technology to market, and Generation 8 being the estimated technology level in 2035.

Table 1. Lighting Generations and Associated Technologies for Each Category

Lighting Generation	General Lighting Technology	General Lighting (High Bay) Technology	Task Lighting Technology	Supplemental Lighting Technology	Wall Wash Lighting Technology
Gen 1	T12 linear fluorescent	High-intensity discharge mercury vapor	Incandescent A-shape	Incandescent decorative	Incandescent decorative
Gen 2	T8 linear fluorescent	High-intensity discharge metal halide	Halogen A-shape	Halogen decorative	Halogen decorative
Gen 3	T5 linear fluorescent	High-intensity discharge metal halide	Compact fluorescent screw	Compact fluorescent pin	Compact fluorescent pin
Gen 4–8	LED linear	LED high bay luminaire	LED general purpose	LED decorative	LED directional

ComStock uses a similar approach to the ASHRAE 90.1 Lighting Subcommittee for determining the lighting power density allowance for a given space type. Table 2 provides the average installed building-level lighting power densities in ComStock by building type and lighting generation.

Table 2. Average Building-Level Lighting Power Density (W/ft^2) by Lighting Generation and Building Type

Building Type	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
full_service_restaurant	1.51	0.96	0.45	0.43	0.39
hospital	1.59	1.07	0.63	0.58	0.52
large_hotel	1.31	0.80	0.29	0.23	0.21
large_office	1.18	0.80	0.50	0.53	0.47
medium_office	1.18	0.80	0.50	0.53	0.47
outpatient	1.27	0.85	0.53	0.52	0.47
primary_school	0.73	0.56	0.48	0.47	0.42
quick_service_restaurant	1.73	1.11	0.56	0.52	0.47
retail	1.17	0.75	0.54	0.47	0.42
secondary_school	0.88	0.58	0.48	0.45	0.40
small_hotel	1.08	0.63	0.28	0.25	0.22
small_office	1.18	0.79	0.50	0.52	0.47
strip_mall	1.59	1.07	0.65	0.64	0.59
warehouse	0.83	0.40	0.39	0.30	0.27

Specifically, the lighting generations and corresponding lighting power densities were assigned to each building model during the sampling process, based on a validated distribution data (Figure 1), and introduced uncertainty representing realistic installation trends of different generations and impact of building sizes. Default interior lighting schedules come from the OpenStudio-standards U.S. Department of Energy prototype building models [3]. The schedules are then adjusted with variational base-to-peak ratios to incorporate impact from characteristics such as building types and operating hours.

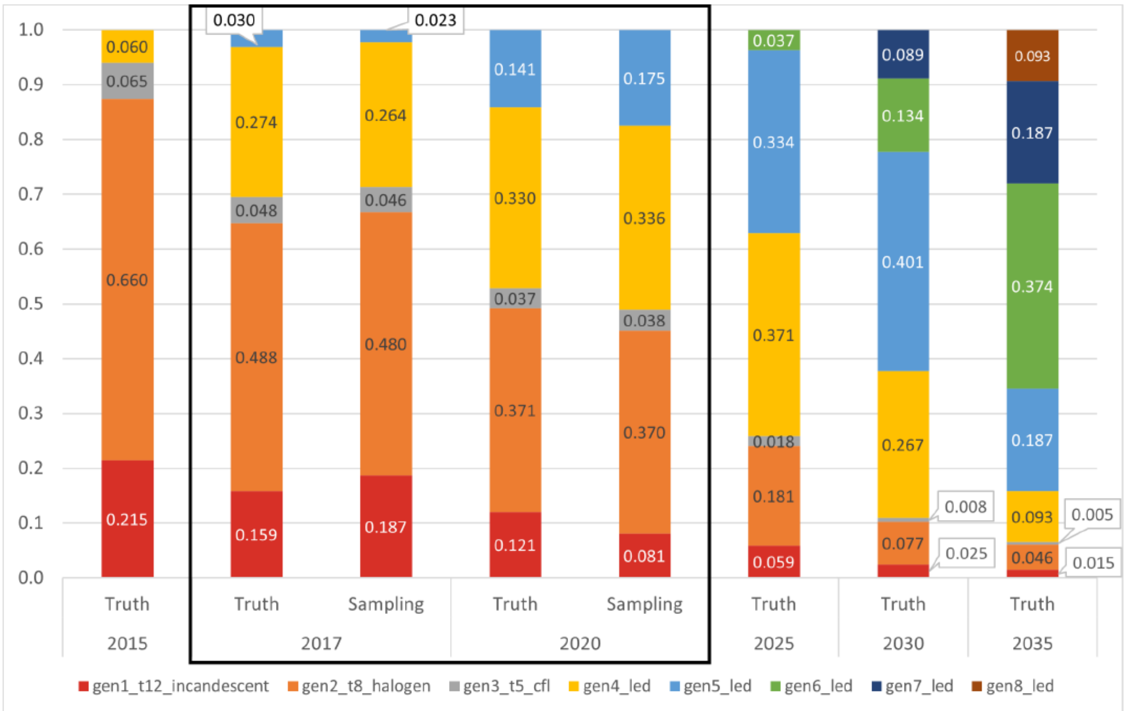

Figure 1. "Truth" lighting generation distribution (0–1) from validated data and comparison of 2017 and 2020 ComStock sampling results

3 Modeling Approach

The following sections summarize the applicability and modeling approaches for the Thermostat Control for Load Shedding and Lighting Control for Load Shedding upgrades included in this upgrade package. For more detailed descriptions of each individual measure, reference the individual upgrade documentations.

3.1 Applicability

The two upgrades share the same building types—office buildings (small, medium, and large), warehouses, and schools (primary and secondary). However, while the lighting control upgrade assumes all the lighting systems in the applicable buildings are controllable for the measure to be applied (some existing old lighting systems may require additional retrofitting/controls to implement the measure), the thermostat control measure will only affect thermostats associated with electric HVAC equipment in a building, as shown in Figure 2. Overall, the package is applicable to 67.26% of the stock floor area.

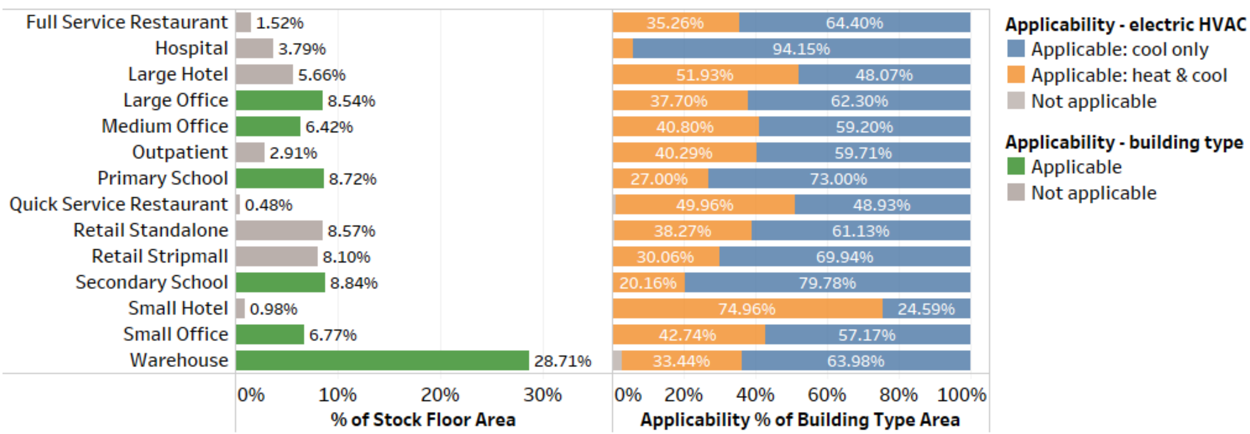

Figure 2. Prevalence of building types and applicability for each building type (for both scenarios) and HVAC fuel type (for thermostat control scenario)

Both upgrade measures will identify the building types for each ComStock baseline model, with the same building type applicability criteria. If the building type passes the applicability check, the thermostat control measure will then extract all the thermostats of the model and check the fuel sources of associated HVAC systems. The measure will identify and adjust the temperature set point schedules of the thermostats controlling electric heating systems or electric cooling systems.

3.2 Technology Specifics

3.2.1 Determining Dispatch Windows for Demand Flexibility

By applying the method "Dispatch Schedule Generation" described in End Use Savings Shapes Measure Documentation: Dispatch Schedule Generation for Demand Flexibility Measures, a daily load dispatch schedule is generated based on the demand flexibility objective.

When the objective is individual building peak load reduction, the daily dispatch windows correspond to the daily peak building loads. When the objective is grid-level peak load reduction, the daily dispatch windows correspond to the daily grid peak loads extracted from the Cambium load data [4].

The schedule will then be used as the input of both upgrades to determine the periods when lighting level and thermostat set points should be adjusted. Specifications of parameters for generating the peak schedule are defined in detail in the supplemental documentation.

3.2.2 Thermostat Control

The Thermostat Control for Load Shedding upgrade applies heating and cooling temperature set point offsets (setbacks) on applicable thermostats in models to reduce the heating and cooling load during the peak windows. Following every peak window, the upgrade applies a rebound period for set points to ramp back to the original values, to mitigate the rebound (snapback) effect. This gradual restoration of the set point reduces the potential of creating a new peak load with immediate restoration, which was observed in simulation tests applying thermostat adjustment for peak demand periods.

3.2.3 Lighting Control

The Lighting Control for Load Shedding upgrade applies lighting dimming control to reduce the lighting load during the peak windows. After the peak window, the lighting levels resume to the values following the original schedules.

3.2.4 Input Parameters

The default input parameters for the upgrades in this package are summarized in Table 3.

Table 3. Default Options and Values for Measure Parameters

Parameter	Thermostat Control for Load Shedding	Lighting Control for Load Shedding
Objective	Peak load reduction / Grid peak load reduction	
Load prediction method	Perfect prediction (full baseline simulation)	
Peak window determination method	Centered with peak	
Length of peak window	4 hours	
Control actions during peak window	±2°C	30% reduced
Lighting adjustment method	N/A	Absolute percentage change (compared to fully ON)
Length of rebound control (thermostat)	2 hours	N/A

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* [1]. Summary statistics from this implementation are shown in Table 4. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 4. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural gas	$0.007/kBtu ($0.7/therm)	$0.012/KBtu ($1.2/therm)	$0.048/kBtu ($4.8/therm)
Propane	$0.022/kBtu	$0.032/kBtu	$0.052/kBtu
Fuel oil	$0.027/kBtu	$0.033/kBtu	$0.036/kBtu
Electricity	$0.003/kBtu ($0.01/kWh)	$0.035/kBtu ($0.12/kWh)	$3.530/kBtu ($12.04/kWh)

Natural gas bills are estimated using 2022 EIA averages by state. 2022 EIA natural gas prices (commercial price) and EIA heat content of natural gas delivered to consumers are used to create an energy price in dollars per thousand Btu [5].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 distillate prices by sales type, 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 dollars per thousand Btu [6]. 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 [7]. The URDB rates include detailed cost features such as time-of-use pricing, demand charges, and ratches. 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 noncommercial 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 minimum/maximum 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 [8]. 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

- This measure is less mature compared to conventional upgrades, which are easily implemented through established contractor services and market practices. On one hand, the proposed control strategies build on straightforward extensions of existing temperature setbacks and lighting controls, suggesting a relatively low barrier to implementation once controllable and dimmable systems are in place. On the other hand, the methodology relies heavily on load prediction, and the modeled performance is likely to exceed what can be achieved in current real-world applications. Furthermore, practical barriers remain for novel HVAC and lighting controls, particularly those that are model- or predictive-based, including occupant acceptance, integration complexity, and the absence of standardized contractual frameworks between utilities, building owners, and aggregators. Together, these factors indicate that while the measure appears simple in theory, its real-world deployment can be complex.

- There are many possible estimation functions and reduction strategies that could be implemented, and this study chooses a single set of parameters that we consider to be reasonable and generalizable, but these choices will have an impact on results. First, this measure relies on the user-provided inputs of dispatch schedule, for which several options are developed and provided in the "Dispatch Schedule Generation" method. Different options yield distinctive dispatch time windows: perfect match to daily peak load (perfect prediction), a mimic of advanced application with uncertainty (bin sampling), or fixed dispatch schedules by season and region (fixed schedule). The differences in performance of different options and the limitations and concerns of the dispatch window generation method described in End Use Savings Shapes Measure Documentation: Dispatch Schedule Generation for Demand Flexibility Measures also apply to the implementation of this measure. For example, the objective function of generating daily dispatch windows could vary depending on measure, such as utility cost savings. The input parameters of a selected dispatch schedule generation method also play a significant role in the performance, such as dimming percentage value and length of peak window, and the impact may vary depending on building properties and weather conditions. We applied simple parametric analysis on the input parameters to justify the selection of default values, but detailed fine-tuning and other practical considerations are needed to determine the best parameter set(s).

- The current scope of applicable building types is limited to offices, schools, and warehouses, with a simplified control strategy—uniform relative change throughout the building. As discussed in Section 3.1, different building types can have different practical concerns when applying demand flexibility strategies. For example, lighting controls in warehouses could have minimal impact on occupants if the warehouse has low occupancy, while the occupancy distributions in schools are much more complicated and dynamic, and the ranges of acceptable visual environment vary depending on the functions of spaces and real-time occupancy status. Such distinctions require careful and comprehensive research to transform the proposed strategy into practical applications, such as integration with occupancy sensor-based control (e.g., prioritizing comfort criterion in occupied space and turning lights off in unoccupied area). We have chosen applicability of building types with assumed dimming in all contained space types, and upgraded lighting technology to make demand flexibility control possible and generalizable, which at this time is subjective due to a lack of technical references and standardizations (in stock level).

- This measure uses individual building-level daily peak load reduction or grid-level peak reduction as the objective function. There are many other objective functions that have different, possibly conflicting goals, such as eco-friendly goals, grid-level operating cost reductions, and building-level utility bill reductions. We plan to add the objective of utility bill cost reduction in the future to align the demand control of buildings with the grid demand management strategy through the medium of utility rates.

- We do not limit the number of days (events), and we fix the duration of daily dispatch window for demand response control, as we are investigating the maximum potential of applying demand flexibility measures in the stock level. However, actual implementation of demand flexibility strategy may be far less frequent than daily, such as 10–15 events per season in typical demand response programs, which would impact results.

4 Output Variables

Table 5 includes a list of output variables that are calculated in ComStock. These variables are important in terms of understanding the differences between buildings with and without the Thermostat and Lighting Control for Load Shedding upgrade package applied. These output variables can also be used for understanding the economics of the upgrade (e.g., return on investment) if cost information (i.e., material, labor, and maintenance costs for technology implementation) is available.

Table 5. Output Variables Calculated From the Measure Application

Variable Name	Description
minimum_daily_peak_jan_kw	Minimum of daily electric peak loads (in kW) in January
minimum_daily_peak_feb_kw	Minimum of daily electric peak loads (in kW) in February
minimum_daily_peak_mar_kw	Minimum of daily electric peak loads (in kW) in March
minimum_daily_peak_apr_kw	Minimum of daily electric peak loads (in kW) in April
minimum_daily_peak_may_kw	Minimum of daily electric peak loads (in kW) in May
minimum_daily_peak_jun_kw	Minimum of daily electric peak loads (in kW) in June
minimum_daily_peak_jul_kw	Minimum of daily electric peak loads (in kW) in July
minimum_daily_peak_aug_kw	Minimum of daily electric peak loads (in kW) in August
minimum_daily_peak_sep_kw	Minimum of daily electric peak loads (in kW) in September
minimum_daily_peak_oct_kw	Minimum of daily electric peak loads (in kW) in October
minimum_daily_peak_nov_kw	Minimum of daily electric peak loads (in kW) in November
minimum_daily_peak_dec_kw	Minimum of daily electric peak loads (in kW) in December
maximum_daily_peak_jan_kw	Maximum of daily electric peak loads (in kW) in January
maximum_daily_peak_feb_kw	Maximum of daily electric peak loads (in kW) in February
maximum_daily_peak_mar_kw	Maximum of daily electric peak loads (in kW) in March
maximum_daily_peak_apr_kw	Maximum of daily electric peak loads (in kW) in April
maximum_daily_peak_may_kw	Maximum of daily electric peak loads (in kW) in May
maximum_daily_peak_jun_kw	Maximum of daily electric peak loads (in kW) in June
maximum_daily_peak_jul_kw	Maximum of daily electric peak loads (in kW) in July
maximum_daily_peak_aug_kw	Maximum of daily electric peak loads (in kW) in August
maximum_daily_peak_sep_kw	Maximum of daily electric peak loads (in kW) in September
maximum_daily_peak_oct_kw	Maximum of daily electric peak loads (in kW) in October
maximum_daily_peak_nov_kw	Maximum of daily electric peak loads (in kW) in November
maximum_daily_peak_dec_kw	Maximum of daily electric peak loads (in kW) in December
median_daily_peak_jan_kw	Median of daily electric peak loads (in kW) in January
median_daily_peak_feb_kw	Median of daily electric peak loads (in kW) in February
median_daily_peak_mar_kw	Median of daily electric peak loads (in kW) in March

Variable Name	Description
median_daily_peak_apr_kw	Median of daily electric peak loads (in kW) in April
median_daily_peak_may_kw	Median of daily electric peak loads (in kW) in May
median_daily_peak_jun_kw	Median of daily electric peak loads (in kW) in June
median_daily_peak_jul_kw	Median of daily electric peak loads (in kW) in July
median_daily_peak_aug_kw	Median of daily electric peak loads (in kW) in August
median_daily_peak_sep_kw	Median of daily electric peak loads (in kW) in September
median_daily_peak_oct_kw	Median of daily electric peak loads (in kW) in October
median_daily_peak_nov_kw	Median of daily electric peak loads (in kW) in November
median_daily_peak_dec_kw	Median of daily electric peak loads (in kW) in December
mean_daily_peak_jan_kw	Mean of daily electric peak loads (in kW) in January
mean_daily_peak_feb_kw	Mean of daily electric peak loads (in kW) in February
mean_daily_peak_mar_kw	Mean of daily electric peak loads (in kW) in March
mean_daily_peak_apr_kw	Mean of daily electric peak loads (in kW) in April
mean_daily_peak_may_kw	Mean of daily electric peak loads (in kW) in May
mean_daily_peak_jun_kw	Mean of daily electric peak loads (in kW) in June
mean_daily_peak_jul_kw	Mean of daily electric peak loads (in kW) in July
mean_daily_peak_aug_kw	Mean of daily electric peak loads (in kW) in August
mean_daily_peak_sep_kw	Mean of daily electric peak loads (in kW) in September
mean_daily_peak_oct_kw	Mean of daily electric peak loads (in kW) in October
mean_daily_peak_nov_kw	Mean of daily electric peak loads (in kW) in November
mean_daily_peak_dec_kw	Mean of daily electric peak loads (in kW) in December
mean_daily_peak_grid_window_jan_kw	Mean hourly daily electric load peak during grid peak window in January
mean_daily_peak_grid_window_feb_kw	Mean hourly daily electric load peak during grid peak window in February
mean_daily_peak_grid_window_mar_kw	Mean hourly daily electric load peak during grid peak window in March
mean_daily_peak_grid_window_apr_kw	Mean hourly daily electric load peak during grid peak window in April
mean_daily_peak_grid_window_may_kw	Mean hourly daily electric load peak during grid peak window in May
mean_daily_peak_grid_window_jun_kw	Mean hourly daily electric load peak during grid peak window in June
mean_daily_peak_grid_window_jul_kw	Mean hourly daily electric load peak during grid peak window in July
mean_daily_peak_grid_window_aug_kw	Mean hourly daily electric load peak during grid peak window in August

Variable Name	Description
mean_daily_peak_grid_window_sep_kw	Mean hourly daily electric load peak during grid peak window in September
mean_daily_peak_grid_window_oct_kw	Mean hourly daily electric load peak during grid peak window in October
mean_daily_peak_grid_window_nov_kw	Mean hourly daily electric load peak during grid peak window in November
mean_daily_peak_grid_window_dec_kw	Mean hourly daily electric load peak during grid peak window in December
q_1_daily_peak_jan_kw	First quartile of daily electric peak loads (in kW) in January
q_1_daily_peak_feb_kw	First quartile of daily electric peak loads (in kW) in February
q_1_daily_peak_mar_kw	First quartile of daily electric peak loads (in kW) in March
q_1_daily_peak_apr_kw	First quartile of daily electric peak loads (in kW) in April
q_1_daily_peak_may_kw	First quartile of daily electric peak loads (in kW) in May
q_1_daily_peak_jun_kw	First quartile of daily electric peak loads (in kW) in June
q_1_daily_peak_jul_kw	First quartile of daily electric peak loads (in kW) in July
q_1_daily_peak_aug_kw	First quartile of daily electric peak loads (in kW) in August
q_1_daily_peak_sep_kw	First quartile of daily electric peak loads (in kW) in September
q_1_daily_peak_oct_kw	First quartile of daily electric peak loads (in kW) in October
q_1_daily_peak_nov_kw	First quartile of daily electric peak loads (in kW) in November
q_1_daily_peak_dec_kw	First quartile of daily electric peak loads (in kW) in December
q_3_daily_peak_jan_kw	Third quartile of daily electric peak loads (in kW) in January
q_3_daily_peak_feb_kw	Third quartile of daily electric peak loads (in kW) in February
q_3_daily_peak_mar_kw	Third quartile of daily electric peak loads (in kW) in March
q_3_daily_peak_apr_kw	Third quartile of daily electric peak loads (in kW) in April
q_3_daily_peak_may_kw	Third quartile of daily electric peak loads (in kW) in May
q_3_daily_peak_jun_kw	Third quartile of daily electric peak loads (in kW) in June
q_3_daily_peak_jul_kw	Third quartile of daily electric peak loads (in kW) in July
q_3_daily_peak_aug_kw	Third quartile of daily electric peak loads (in kW) in August
q_3_daily_peak_sep_kw	Third quartile of daily electric peak loads (in kW) in September
q_3_daily_peak_oct_kw	Third quartile of daily electric peak loads (in kW) in October
q_3_daily_peak_nov_kw	Third quartile of daily electric peak loads (in kW) in November

Variable Name	Description
q_3_daily_peak_dec_kw	Third quartile of daily electric peak loads (in kW) in December
median_daily_peak_timing_jan_hour	Median hour of daily electric peak loads in January
median_daily_peak_timing_feb_hour	Median hour of daily electric peak loads in February
median_daily_peak_timing_mar_hour	Median hour of daily electric peak loads in March
median_daily_peak_timing_apr_hour	Median hour of daily electric peak loads in April
median_daily_peak_timing_may_hour	Median hour of daily electric peak loads in May
median_daily_peak_timing_jun_hour	Median hour of daily electric peak loads in June
median_daily_peak_timing_jul_hour	Median hour of daily electric peak loads in July
median_daily_peak_timing_aug_hour	Median hour of daily electric peak loads in August
median_daily_peak_timing_sep_hour	Median hour of daily electric peak loads in September
median_daily_peak_timing_oct_hour	Median hour of daily electric peak loads in October
median_daily_peak_timing_nov_hour	Median hour of daily electric peak loads in November
median_daily_peak_timing_dec_hour	Median hour of daily electric peak loads in December
total_electricity_use_jan_kwh	Total electricity energy consumption in January
total_electricity_use_feb_kwh	Total electricity energy consumption in February
total_electricity_use_mar_kwh	Total electricity energy consumption in March
total_electricity_use_apr_kwh	Total electricity energy consumption in April
total_electricity_use_may_kwh	Total electricity energy consumption in May
total_electricity_use_jun_kwh	Total electricity energy consumption in June
total_electricity_use_jul_kwh	Total electricity energy consumption in July
total_electricity_use_aug_kwh	Total electricity energy consumption in August
total_electricity_use_sep_kwh	Total electricity energy consumption in September
total_electricity_use_oct_kwh	Total electricity energy consumption in October
total_electricity_use_nov_kwh	Total electricity energy consumption in November
total_electricity_use_dec_kwh	Total electricity energy consumption in December
average_of_top_ten_highest_peaks_timing_shoulder_hour	Average hour of top 10 highest daily electric peak loads during shoulder season
average_of_top_ten_highest_peaks_timing_summer_hour	Average hour of top 10 highest daily electric peak loads during summer season
average_of_top_ten_highest_peaks_timing_winter_hour	Average hour of top 10 highest daily electric peak loads during winter season
average_of_top_ten_highest_peaks_use_shoulder_kw	Average peak load of top 10 highest daily electric peak loads during shoulder season
average_of_top_ten_highest_peaks_use_summer_kw	Average peak load of top 10 highest daily electric peak loads during summer season

Variable Name	Description
average_of_top_ten_highest_peaks_use_winter_kw	Average peak load of top 10 highest daily electric peak loads during winter season
annual_peak_electric_demand_kw	Building annual peak electric demand
out.utility_bills.electricity_energycharge_bill_mean	Mean utility bill result for applicable utility rates. Energy charge cost only
out.utility_bills.electricity_demandcharge_flat_bill_mean	Mean utility bill result for applicable utility rates. Flat demand charge cost only
out.utility_bills.electricity_demandcharge_tou_bill_mean	Mean utility bill result for applicable utility rates. TOU demand charge cost only
out.utility_bills.electricity_fixedcharge_bill_mean	Mean utility bill result for applicable utility rates. Fixed charge cost only

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 Results from the Individual Building Peak Load Reduction Objective

5.1.1 Demand Flexibility Performance

Figure 3 shows the distribution of savings percentages of mean daily peak load during the whole day, by month for the upgrade scenario with individual peak reduction objective compared to the baseline model. The result shows overall positive monthly peak reduction patterns. The negative peak reductions are likely caused by two factors—increased electric (HVAC) heating load resulted from decreased heat emission from lighting equipment during peak hours, which takes place in the lighting control scenario, and the generated higher peak demand resulting from rebound effects of HVAC systems when resetting to original set points after peak windows, which takes place in the thermostat control scenario. The combined impact of the two scenarios does not show clear seasonal or monthly patterns. Overall, the median savings in all months are positive, ranging roughly from 5% to 7%, indicating consistent peak reduction performance across the year, while the variability highlights building-specific characteristics and/or regional constraints that may limit or enhance peak shaving potential.

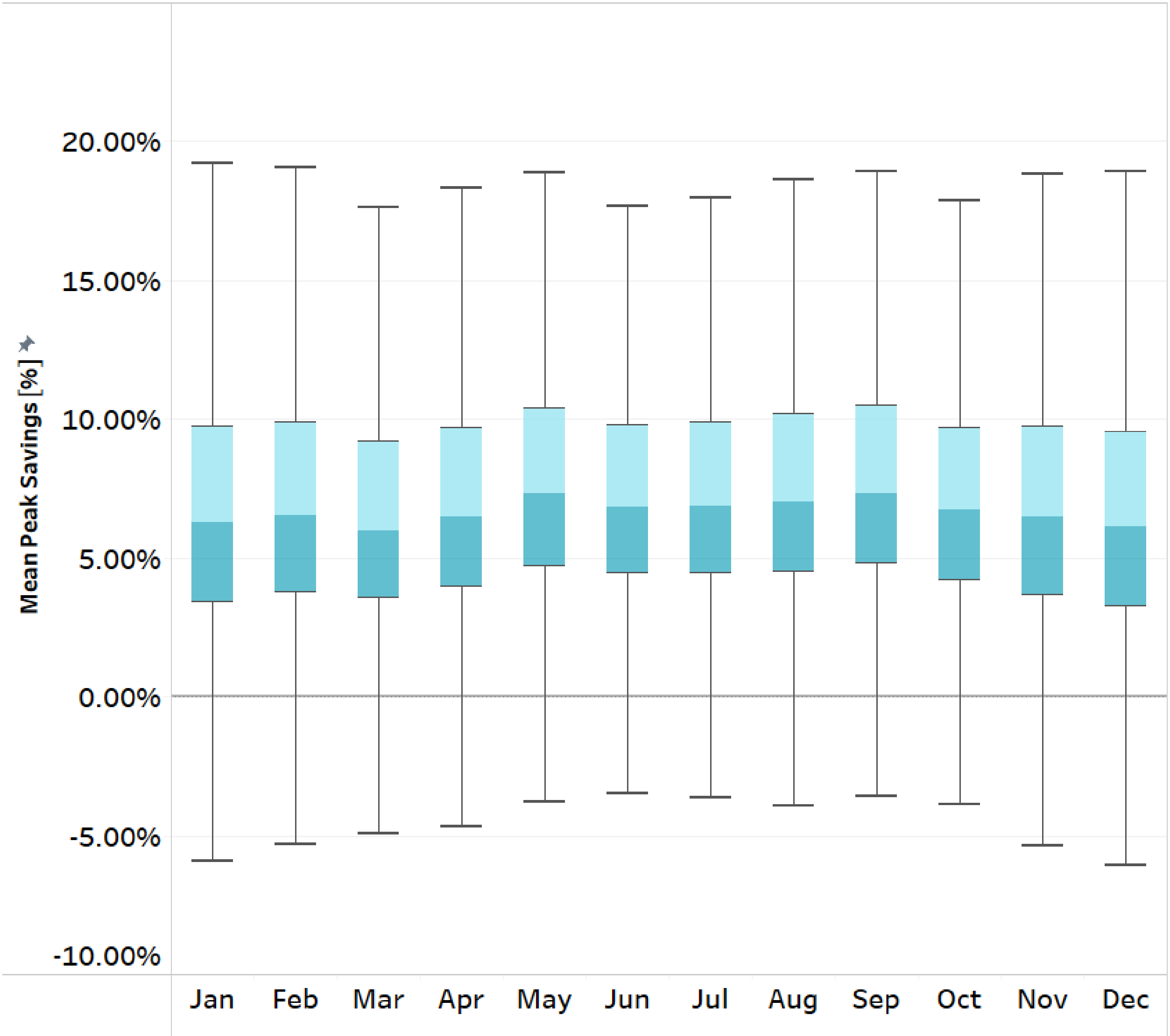

Figure 3. Distribution of the percentage of mean daily peak load reduction by month compared to the baseline model, with individual building peak reduction objective

5.1.2 Stock Energy Impacts

The annual energy impacts are presented in this section Although DF strategies are designed to reduce or shift peak loads rather than minimize total energy consumption, they can still influence overall energy use. Specifically, load shed strategies presented in this package may incidentally reduce annual electricity consumption, resulting in energy savings alongside the intended peak demand reduction. The Thermostat and Lighting Control for Load Shedding package with individual building peak objective demonstrates 1.05% total site energy savings (51.1 trillion Btu [TBtu]) for the U.S. commercial building stock modeled in ComStock, with 2.22% savings for applicable buildings only. The savings contributions by end use and fuel type are summarized in Table 6 and illustrated in Figure 4.

Table 6. Summary of Site Energy Savings From Upgrade Measure Application, With Individual Building Peak Reduction Objective 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 Energy	1.05%	2.22%	51.1
Total Electricity	1.77%	3.53%	56.1
Total Natural Gas	-0.32%	-0.75%	-4.9
Natural Gas Heating	-0.51%	-0.82%	-4.9
Electric Heating	2.54%	4.43%	6.6
Electric Cooling	2.59%	5.24%	18.8
Electric Fans	0.86%	1.83%	4.9
Interior Lighting	5.84%	11.42%	25.7

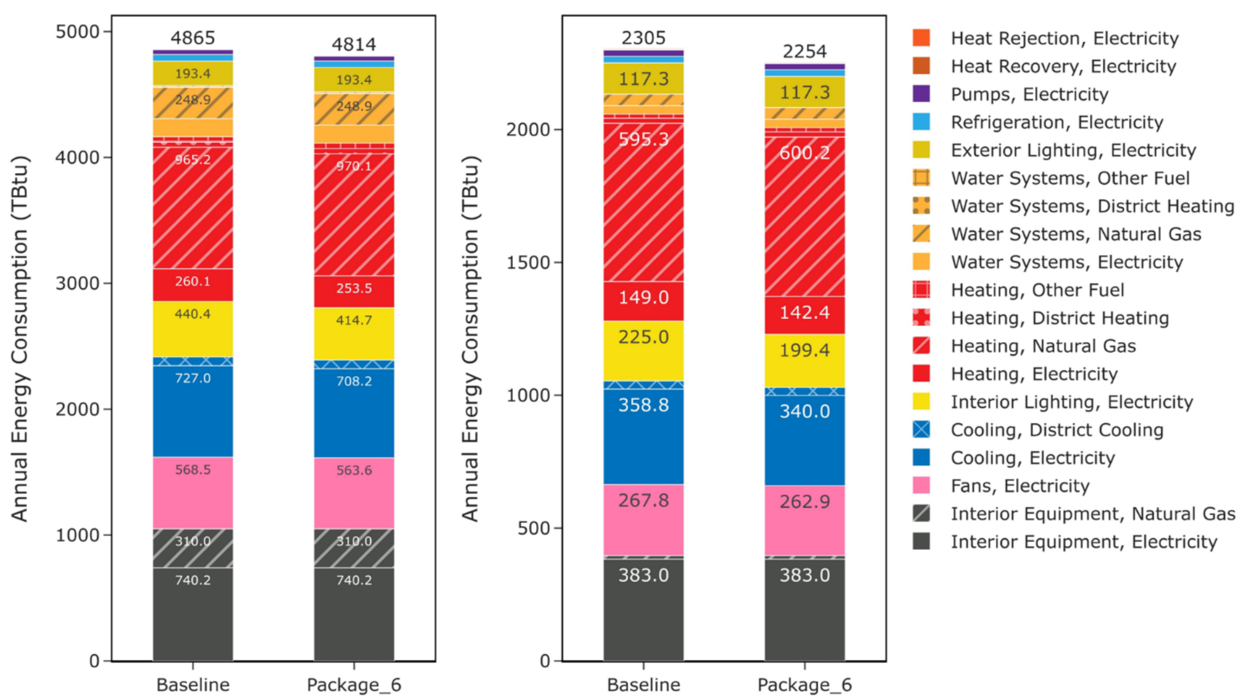

Figure 4. Comparison of annual site energy consumption between the ComStock baseline and the Thermostat and Lighting Control for Load Shedding package scenario, with individual building peak reduction objective, for the whole stock (left) and applicable buildings only (right). Energy consumption is categorized both by fuel type and end use.

The package focuses on load shedding strategies providing demand flexibility every weekday in offices, schools, and warehouses, so the energy savings presented here are less prominent, and are regarded as side benefits from the measures. There are considerable savings for interior lighting, electric heating, and electric cooling energy (11.42%, 4.43%, and 5.24%, respectively for applicable buildings) due to setback controls during the 4-hour peak windows every workday, and the fan energy is reduced accordingly. The increase in natural gas site energy use is primarily due to higher heating loads resulting from reduced heat gains from lighting equipment, without corresponding adjustments to the natural gas heating schedule. Heating electricity savings occur because the reductions from heating setpoint adjustments outweigh the increased heating demand. Conversely, cooling loads decrease for the same reason, leading to additional cooling electricity savings on top of those from cooling setpoint adjustments. More detailed discussion on energy impacts can be found in the documentations of each single measure. Overall, the figure demonstrates that the demand flexibility package upgrade yields incremental energy savings over the baseline scenario.

5.1.3 Stock Utility Bill Impacts

The annual utility bill impacts are presented in this section, representing additional co-benefits when targeting individual building peak demand reductions. Because we apply many electricity utility rate structures that are available for a building located in a certain geographical location, our data includes many annual utility bills per building model. Figure 5 shows the comparison between two scenarios (i.e., baseline and package) and includes three different electricity utility bill statistics (i.e., maximum, mean, and minimum) at the stock level. Overall, it shows around 2% of savings among the different rates, attributed to reduced costs of electricity consumption and/or demand charges. The comparison in Figure 6 highlights the three statistics across all electric utility bill costs for applicable buildings and breaks down the scenarios of both electric heating+cooling and cooling only, which yields increased bill savings by around 4%. In addition, the capability to flex the load is higher with both electric heating and cooling, and thus the energy bill cost savings are slightly higher as compared to electric cooling only.

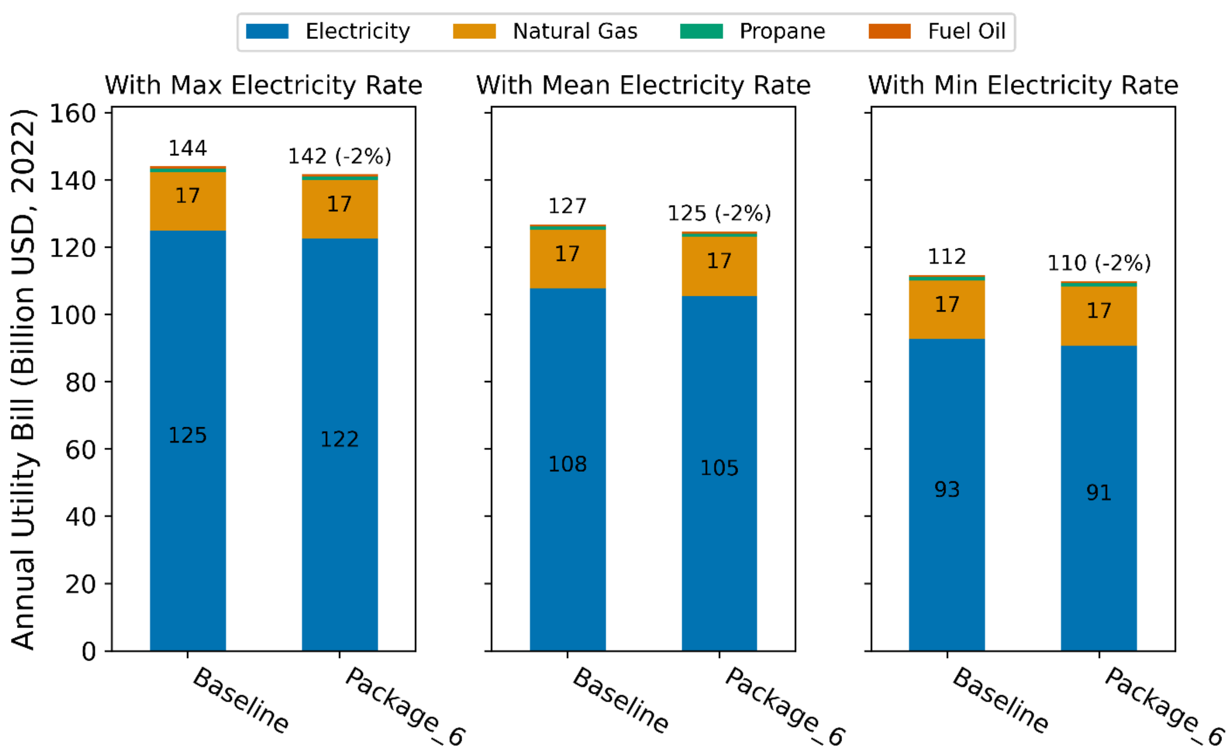

Figure 5. Stock annual utility bill comparison of the ComStock baseline and the Lighting Control for Load Shedding scenario, with individual building peak reduction objective

Three sets of bill costs are presented: maximum electricity rate, mean electricity rate and minimum electricity rate.

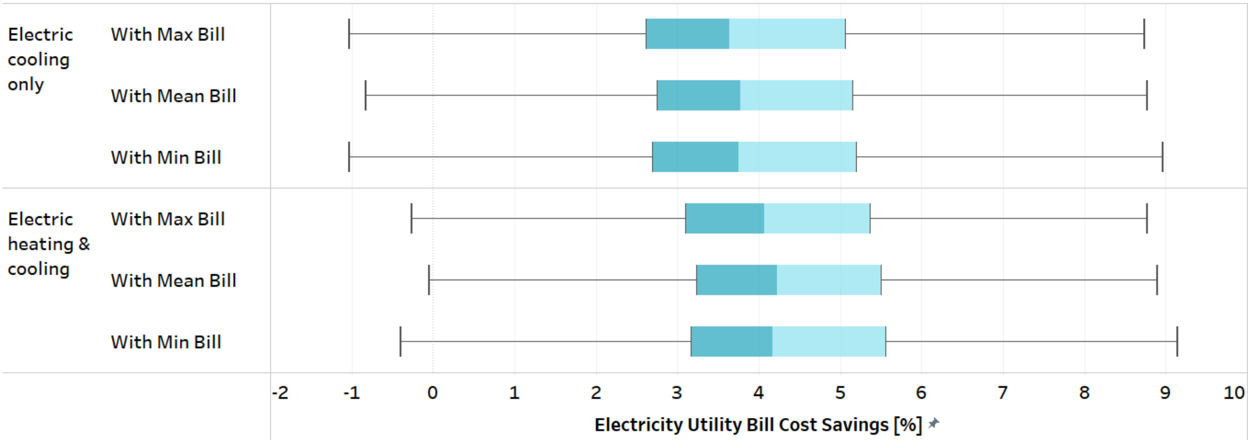

Figure 6. Distribution of annual electricity bill savings compared to the baseline model for maximum, mean, and median bills, with individual building peak reduction objective (for applicable buildings)

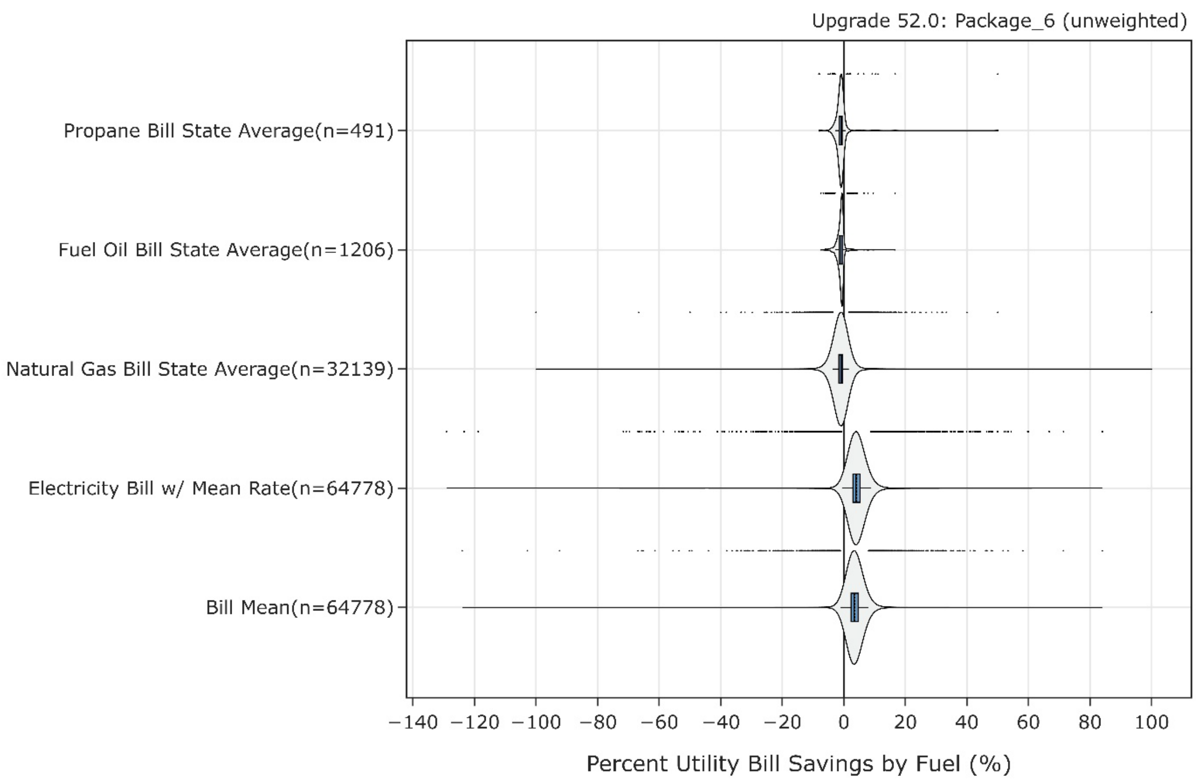

Figure 7. Percent bill savings for ComStock models with the Thermostat and Lighting Control for Load Shedding package by fuel types, with individual building peak reduction objective

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.

5.1.4 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes. Note that site energy savings can be useful for these purposes, but other factors should be considered when drawing conclusions, as they do not necessarily translate proportionally to source energy savings or energy cost.

Figure 8 and Figure 9 show the percent site energy savings distributions by end use and fuel types, respectively. Percent savings provide relative impact of the measure at the individual building level. The breakdowns show consistent conclusions drawn in the energy and bill impact sections (5.1.2 and 5.1.3)—the measure benefits mainly from lighting, cooling and heating electricity savings, as well as corresponding fan energy savings while sacrificing savings from heating energy with various non-electricity fuel types.

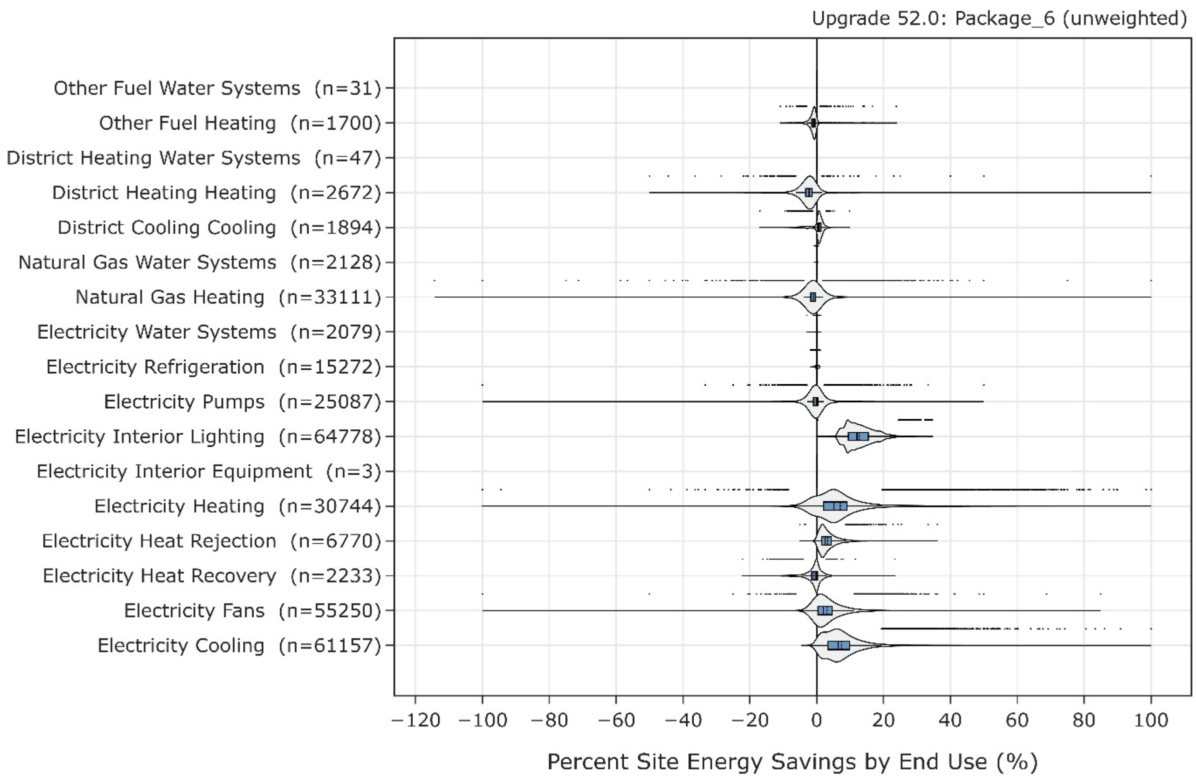

Figure 8. Percent site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type, with individual building peak reduction objective

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.

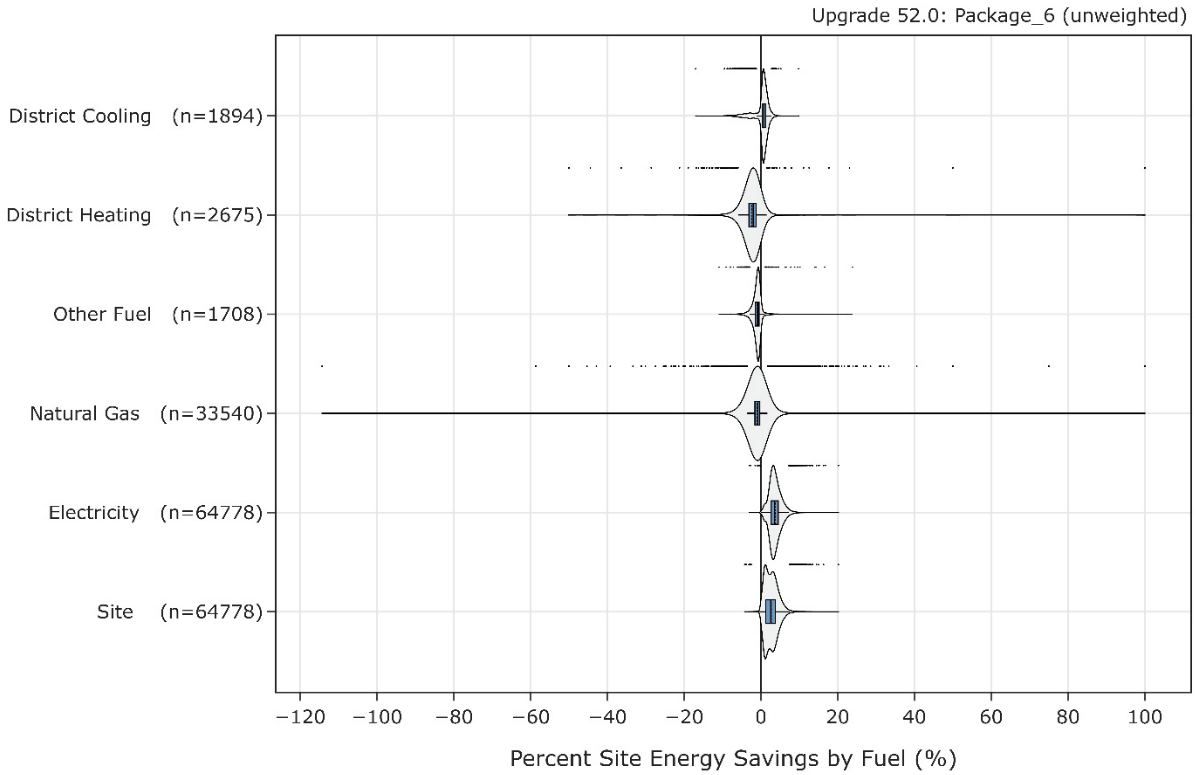

Figure 9. Percent site energy savings distribution for ComStock models with the applied measure scenario by fuel type, with individual building peak reduction objective

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.

5.2 Results from the Grid-Level Peak Load Reduction Objective

5.2.1 Demand Flexibility Performance

Figure 10 shows the distribution of savings percentages of mean daily peak load during the grid peak windows, by month for the upgrade scenario with grid peak reduction objective compared to the baseline model. The distribution shows overall substantial positive peak reduction throughout the year, with seasonal pattern showing higher savings in summer months. The combined impact of the two scenarios shows higher savings potential during summer due to the extra decreased cooling load from dimmed lights.

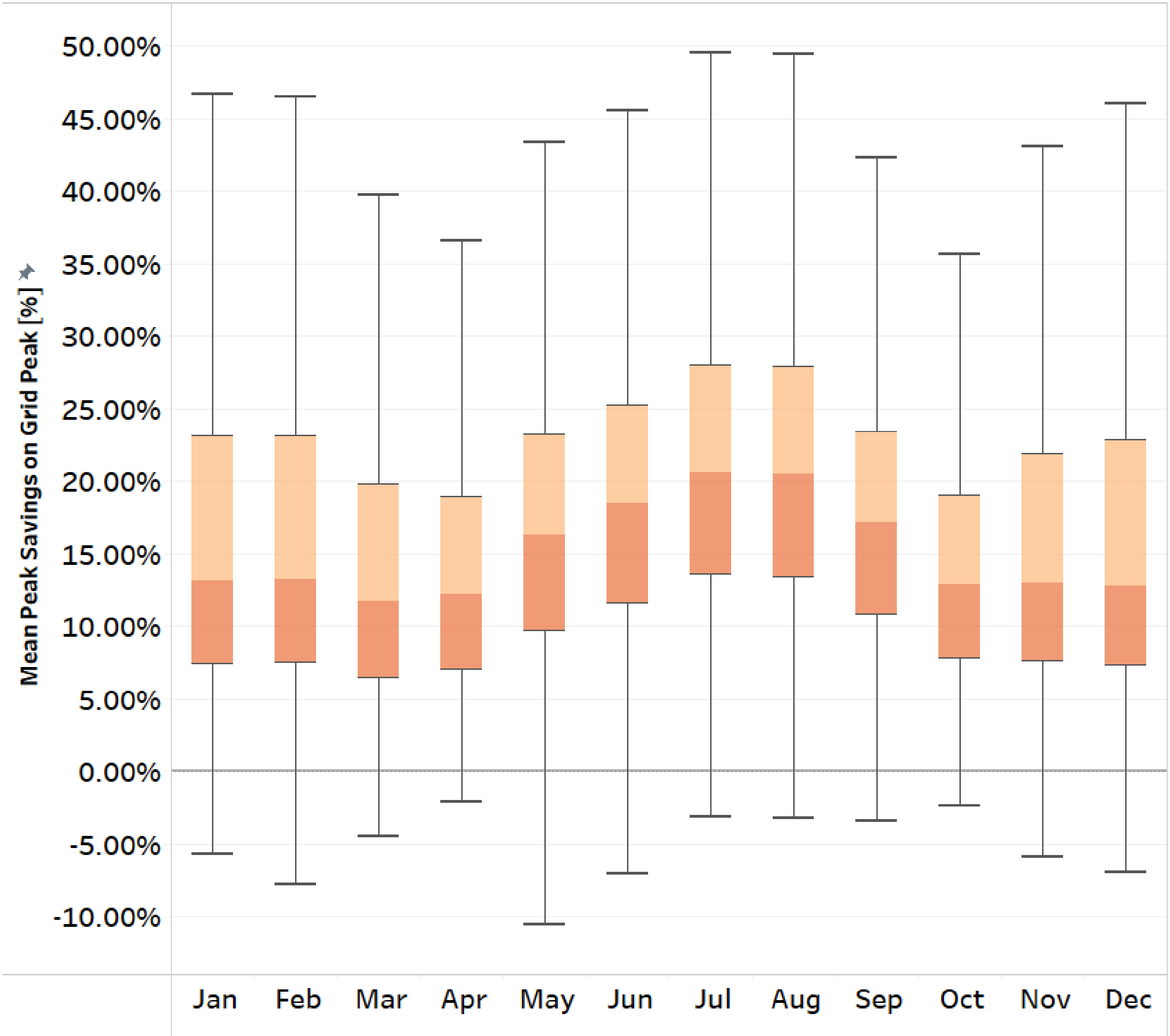

Figure 10. Distribution of the percentage of mean daily peak load reduction during grid peak windows by month compared to the baseline model, with grid peak reduction objective

5.2.2 Stock Energy Impacts

The grid peak objective demonstrates 0.73% total site energy savings (35.6 TBtu) for the U.S. commercial building stock modeled in ComStock, with 1.55% savings for applicable buildings only. The savings contributions by end use and fuel type are summarized in Table 7 and illustrated in Figure 11.

Table 7. Summary of Site Energy Savings From Upgrade Measure Application, With Grid Peak Reduction Objective 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 Energy	0.73%	1.55%	35.6
Total Electricity	1.23%	3.40%	39.0
Total Natural Gas	-0.22%	-0.52%	-3.4
Natural Gas Heating	-0.35%	-0.57%	-3.4
Electric Heating	0.96%	1.69%	2.5
Electric Cooling	2.06%	4.21%	15.0
Electric Fans	0.58%	1.24%	3.3
Interior Lighting	4.09%	8.04%	18.0

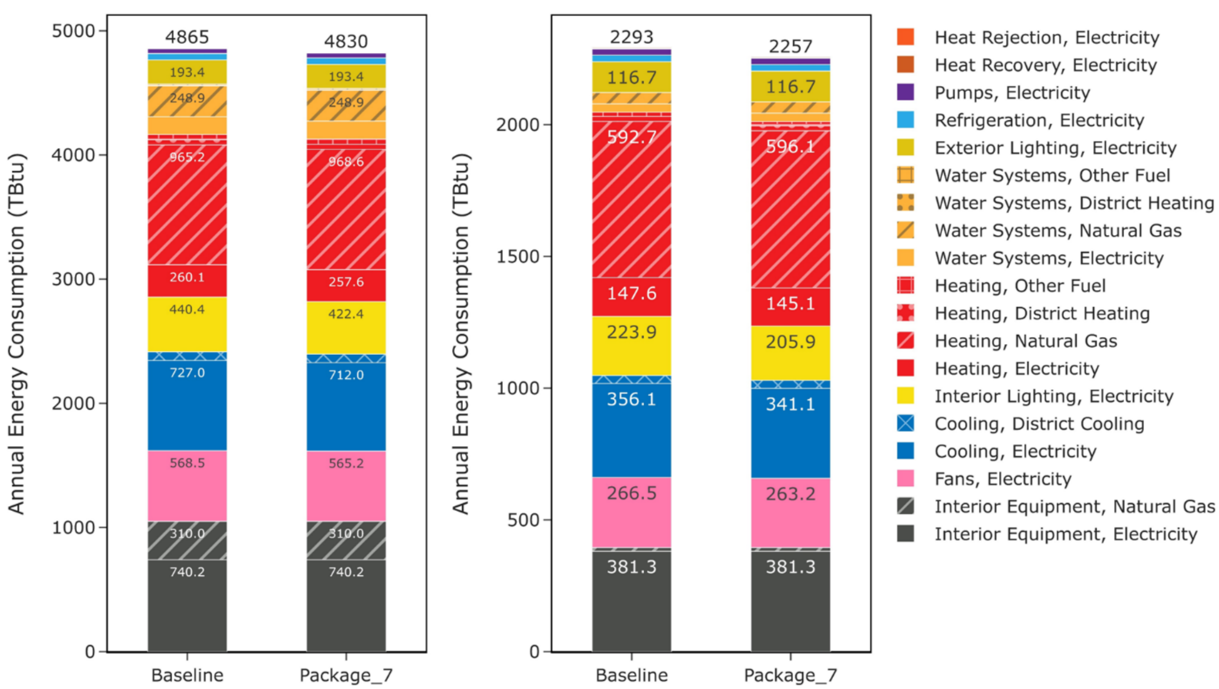

Figure 11. Comparison of annual site energy consumption between the ComStock baseline and the upgrade package scenario, with grid peak reduction objective, for the whole stock (left) and applicable buildings only (right). Energy consumption is categorized both by fuel type and end use.

There are considerable savings for interior lighting, electric heating, and electric cooling energy (8.04%, 1.69%, and 4.21%, respectively for applicable buildings) due to setback controls during the 4-hour peak windows every workday, and the fan energy is reduced accordingly. However, the savings potentials with grid peak objective are lower than the ones with individual peak objective for all the end uses.

5.2.3 Stock Utility Bill Impacts

Overall, it shows around 1% savings among the different rates, mainly attributed to reduced electricity consumption. The comparison in Figure 13 shows around 2% of the savings for the three statistics across all electric utility bill costs for applicable buildings.

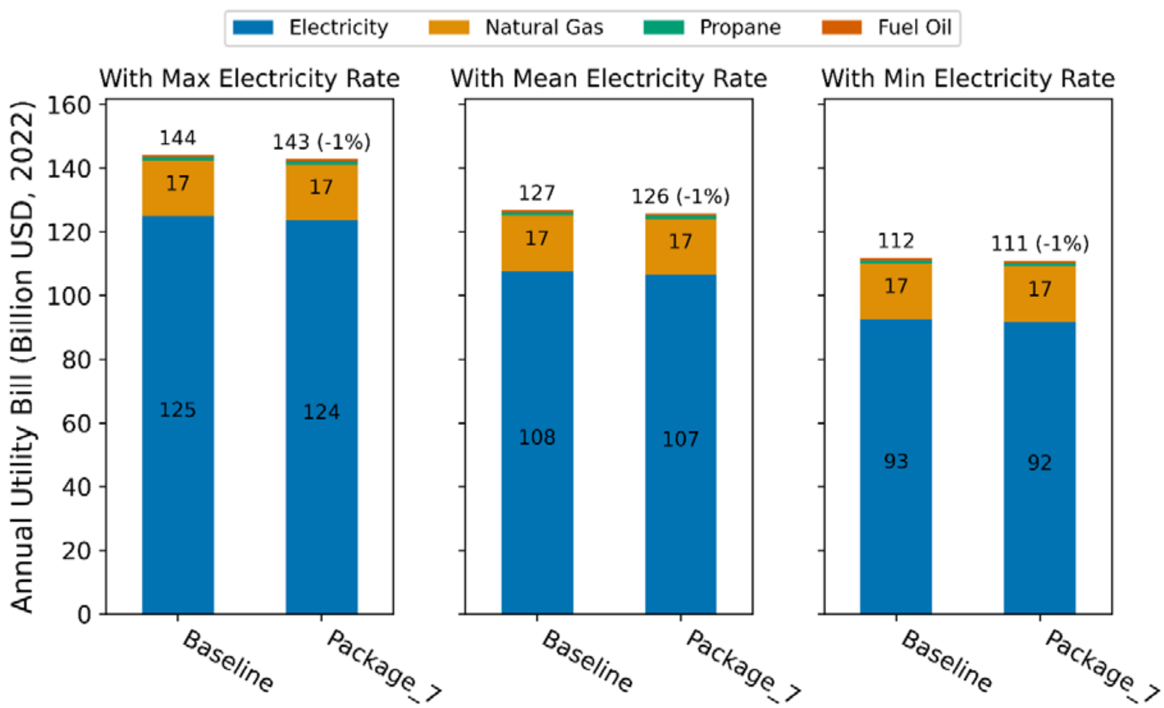

Figure 12. Stock annual utility bill comparison of the ComStock baseline and the Lighting Control for Load Shedding scenario, with grid peak reduction objective

Three sets of bill costs are presented: maximum electricity rate, mean electricity rate and minimum electricity rate.

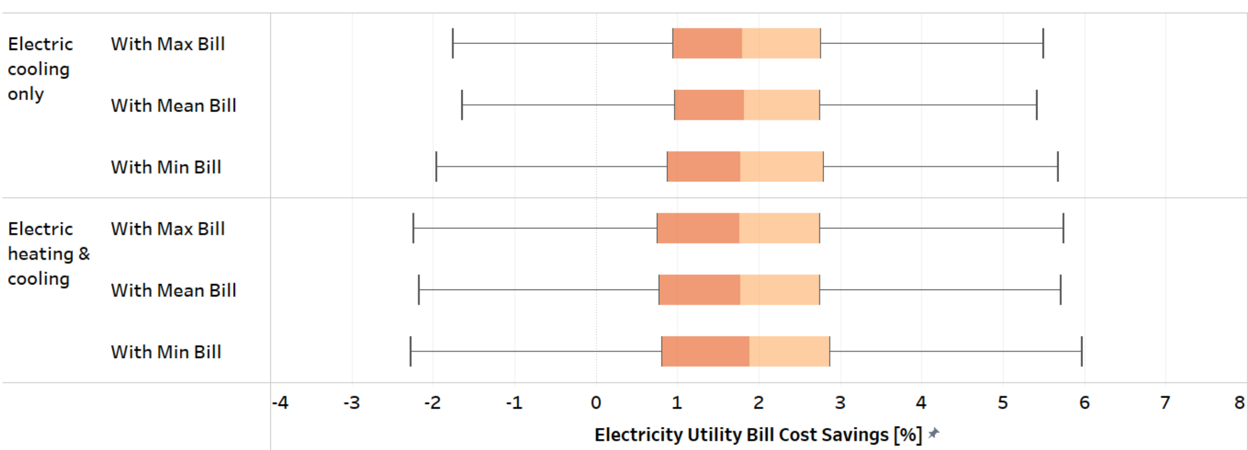

Figure 13. Distribution of annual electricity bill savings compared to the baseline model for maximum, mean, and median bills, with grid peak reduction objective (for applicable buildings)

5.3 Comparative Analysis on Different Objectives

5.3.1 Demand Flexibility Performance

Figure 14 shows the comparison of distributions of the savings percentages of mean daily peak load with respect to different target time frames (for the whole day or during grid peak windows), and with different scenarios (individual peak reduction objective or grid peak reduction objective).

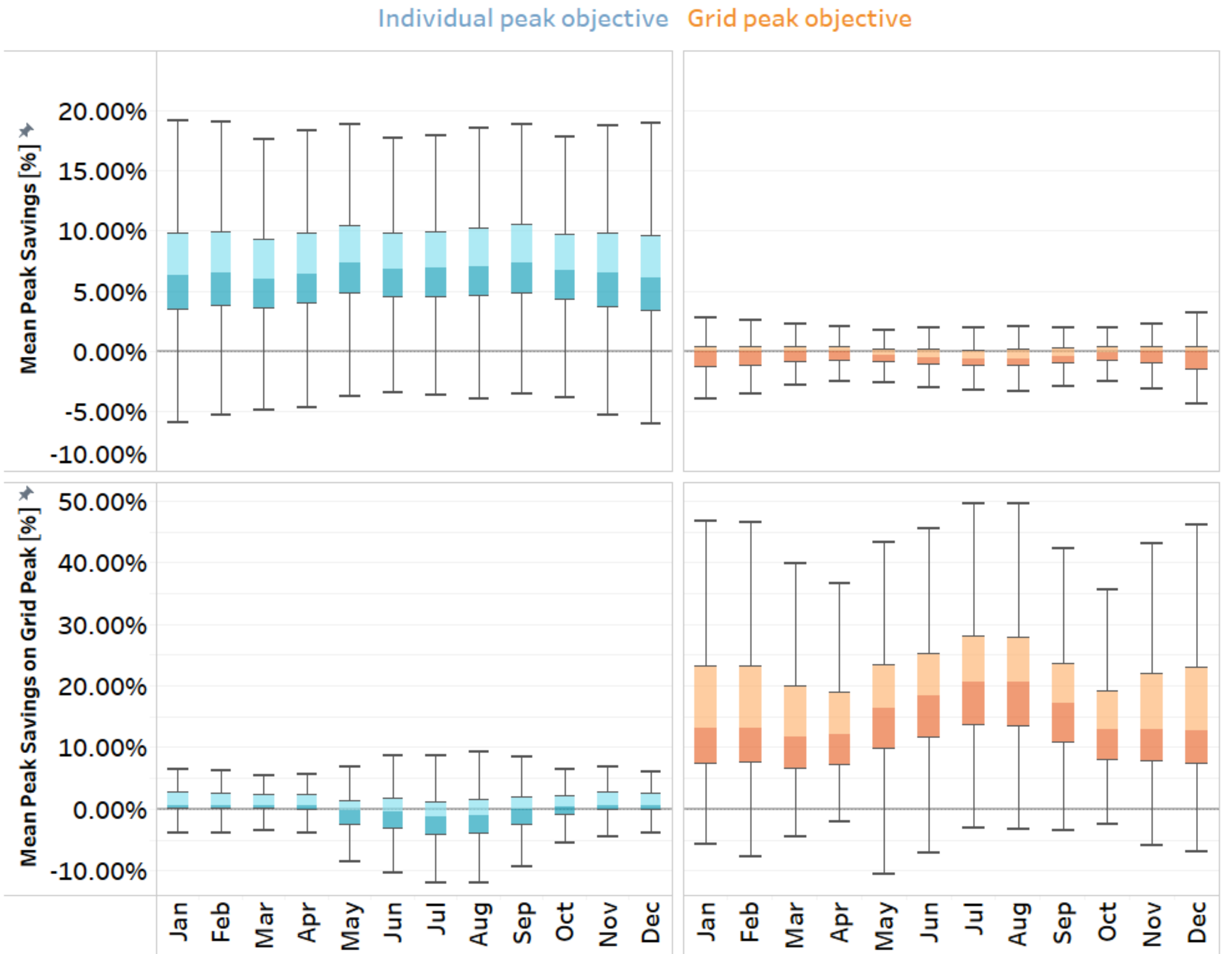

Figure 14. Distribution of the percentage of mean daily peak load reduction by month compared to the baseline model, during the whole day (top) and grid peak window (bottom), with individual building peak reduction objective (left, blue) and grid peak reduction objective (right, orange)

Despite the savings illustrated in Figure 3 and Figure 10, demand flexibility control targeting each building's own peak demand shows minimal to negligible impacts on peak savings during grid critical periods, and even negative savings during cooling months (lower left). Similarly, demand flexibility control targeting grid-level profile results in no-change to slightly adverse savings in terms of overall peak savings (top right). These discrepancies indicate the general misalignment between grid peaks and individual building peaks—the time gaps between these two peaks always exceed the dispatch window, so controls targeting the building-level peak loads have substantially reduced influence on the grid peak periods, and vice versa. In other words, the non-coincidence of grid and building peaks leads directly to the differences observed in the results.

5.3.2 Stock Energy Impacts

Figure 15 shows the energy consumption comparison between the upgrade packages with different objectives. The comparison shows that the demand flexibility strategy with an individual building peak objective saves more energy than controls with a grid peak objective, and the differences are mainly contributed by HVAC (thermostat) control.

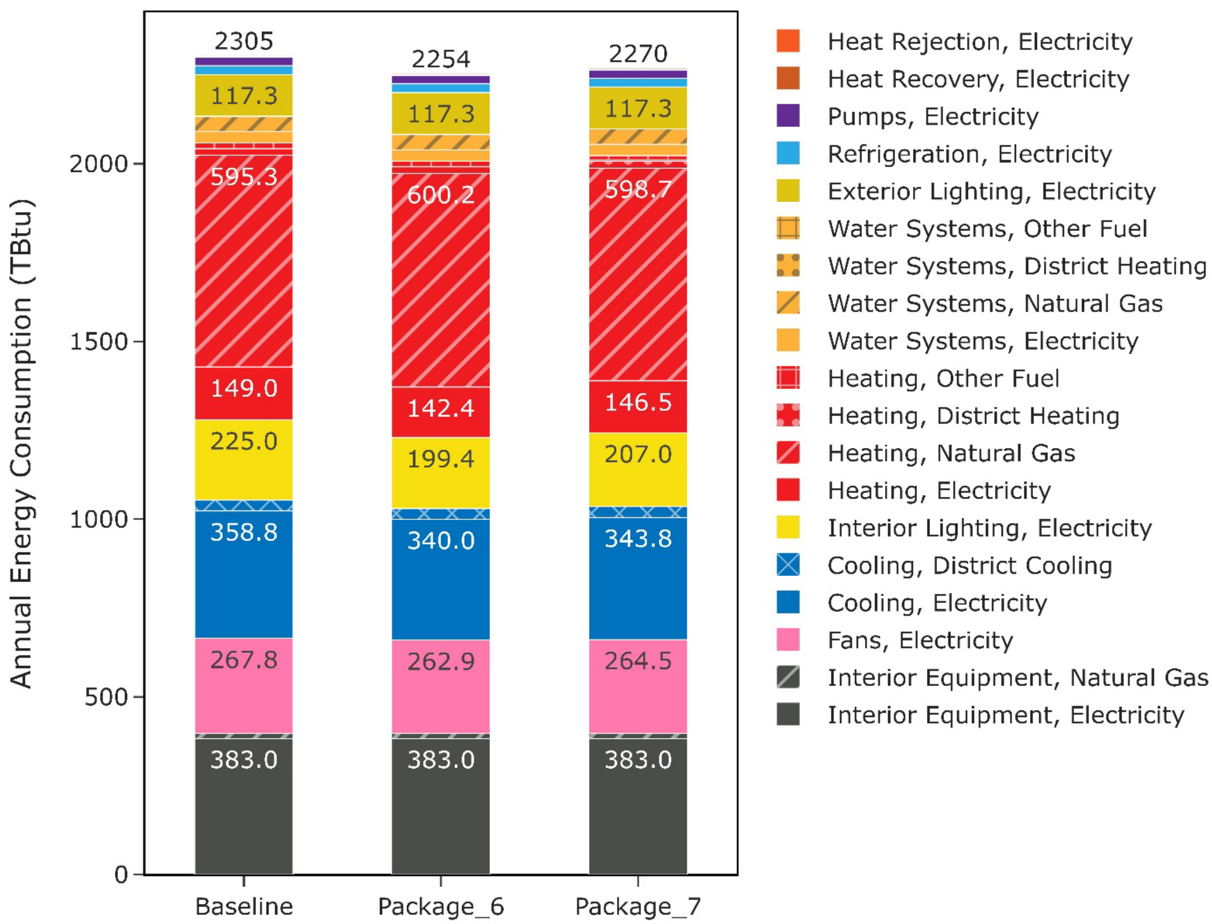

Figure 15. Comparison of annual site energy consumption between the ComStock baseline and demand flexibility upgrade packages with different objectives (package 6 – individual building peak reduction objective, package 7 – grid peak reduction objective), for applicable buildings only

Energy consumption is categorized both by fuel type and end use.

5.3.3 Stock Utility Bill Impacts

Figure 16 shows the utility bill cost savings comparison between the upgrade packages with different objectives. Again, the demand flexibility strategy with an individual building peak objective shows higher bill cost savings potential than controls with a grid peak objective, although it also reveals a higher potential of negative savings risk. Further breaking down the mean bill into different categories of utility rate structures in Figure 17 shows that the larger savings come from both peak reduction for demand charges and energy reduction for energy charges.

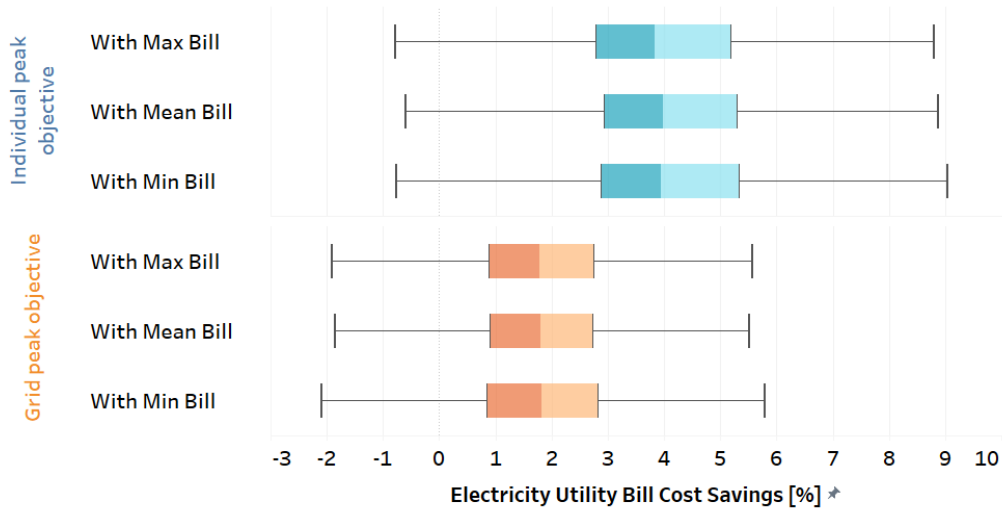

Figure 16. Comparison of annual electricity utility bill cost savings between the ComStock baseline and demand flexibility upgrade packages with different objectives, for applicable buildings

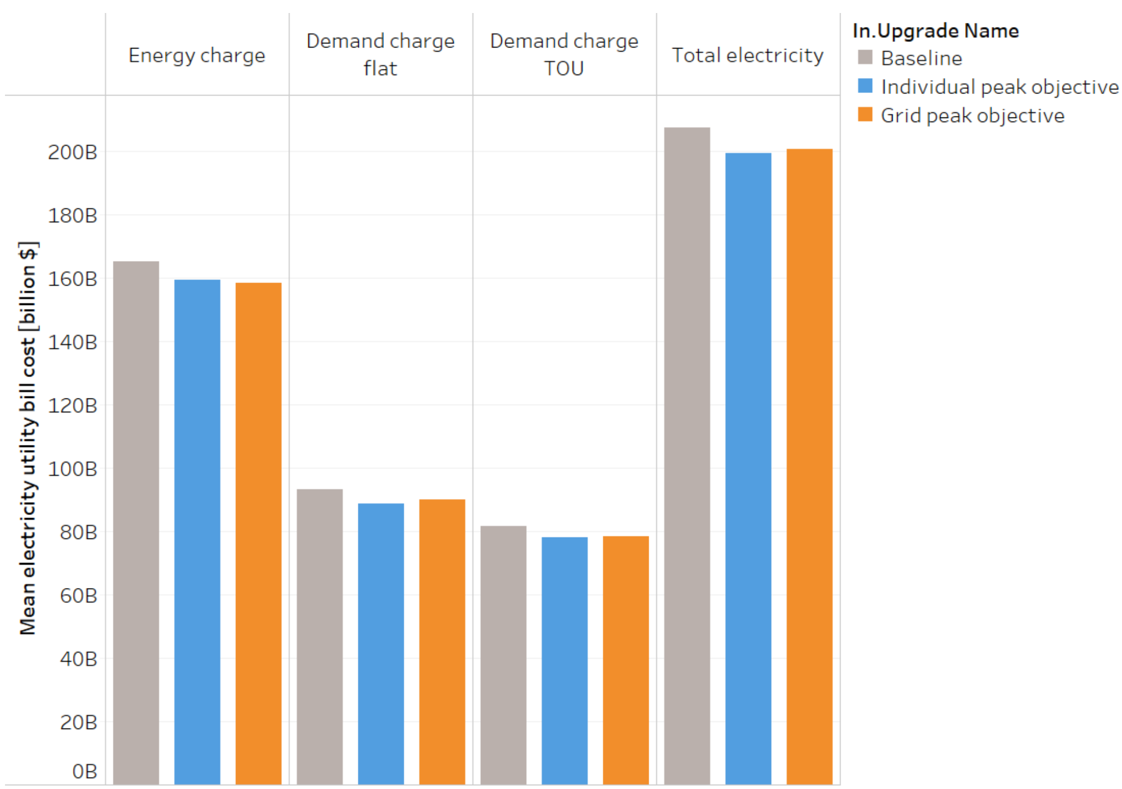

Figure 17. Comparison of mean electricity utility bill cost breakdowns based on cost categories between the ComStock baseline and demand flexibility upgrade packages with different objectives, for applicable buildings

Note: TOU = time of use

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Appendix

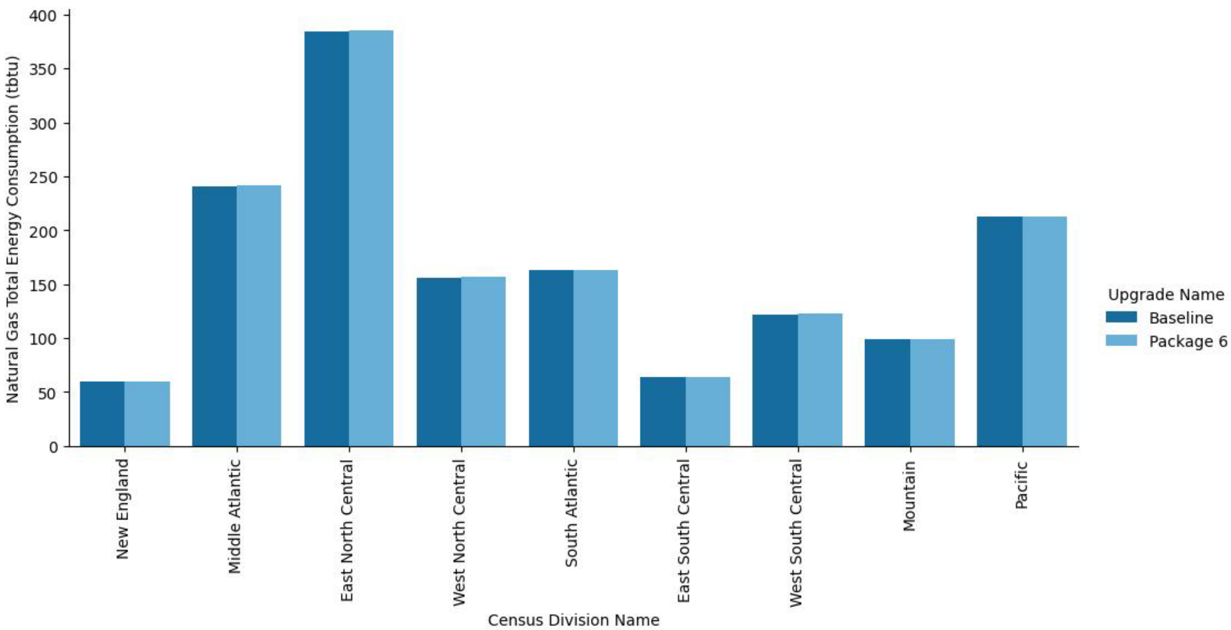

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

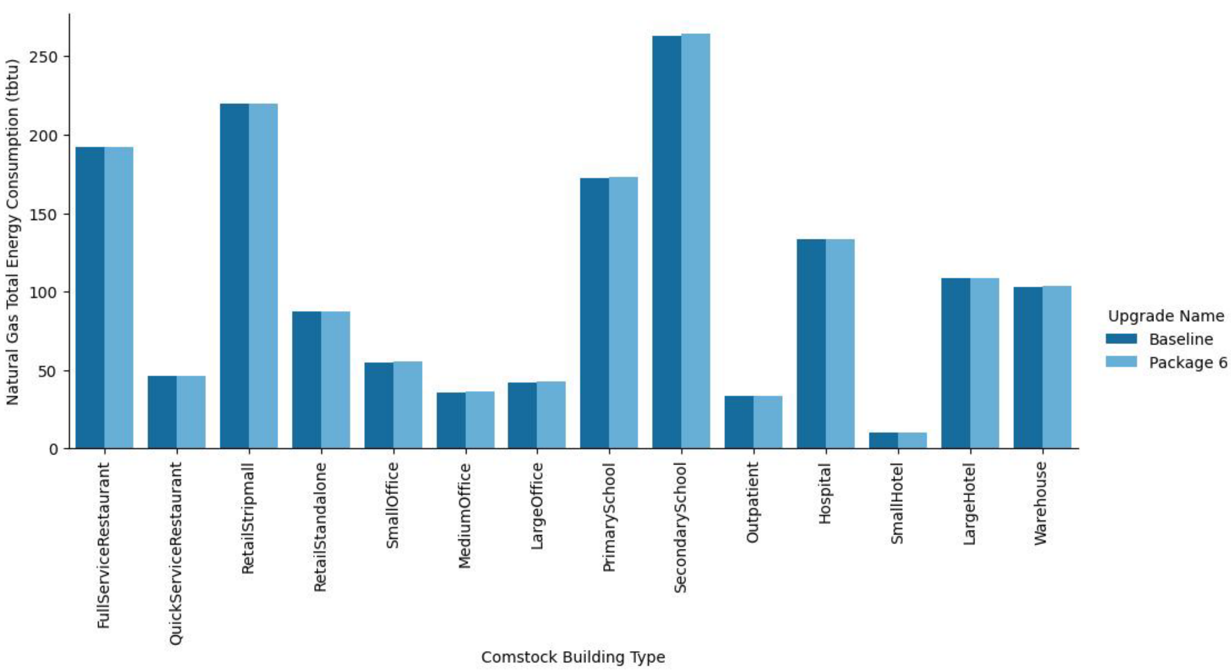

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

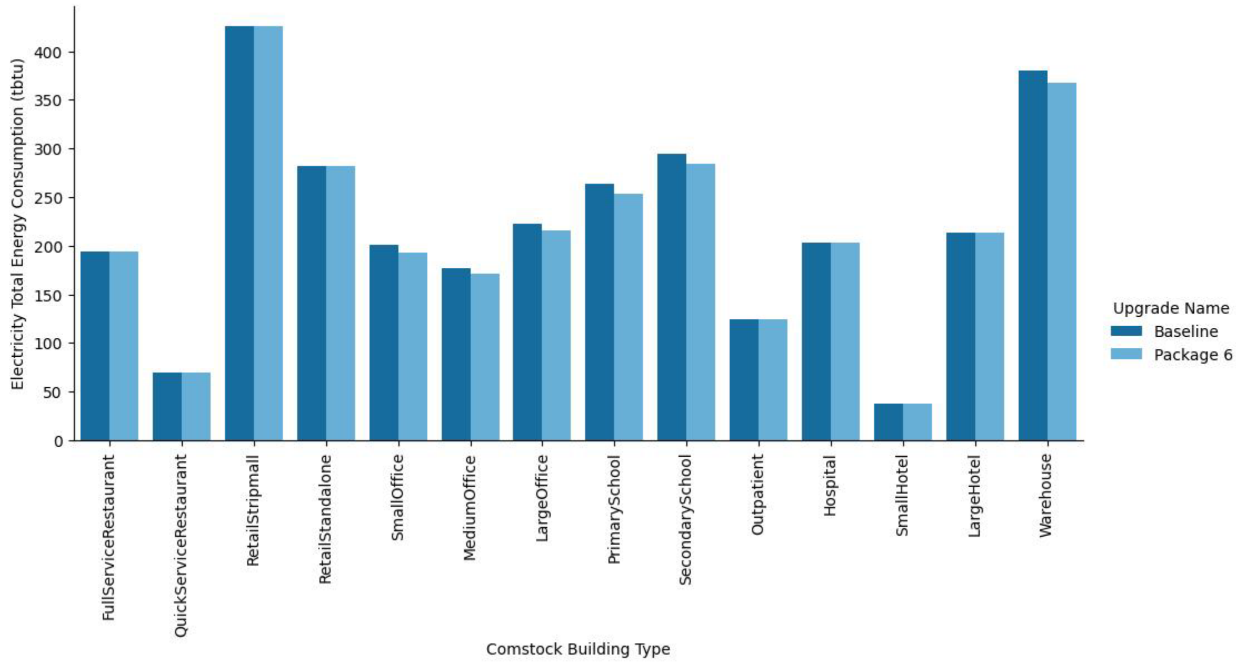

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

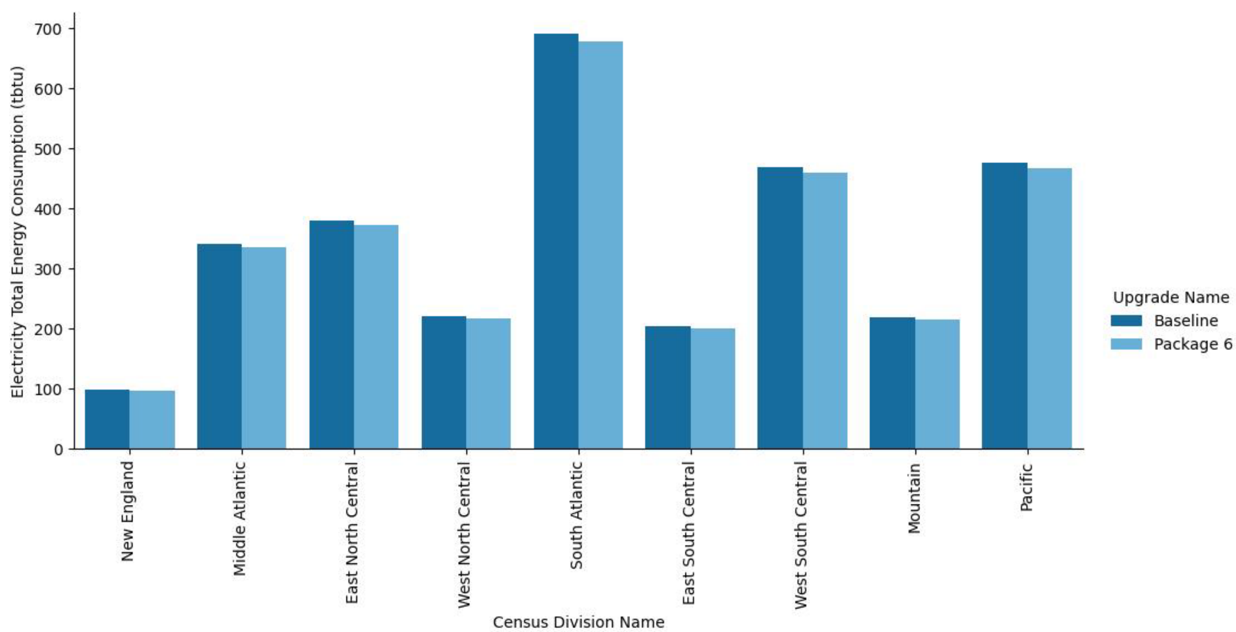

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division