ComStock Measure Documentation:

Thermostat and Lighting Control for Load Shedding + Photovoltaics With 40% Rooftop Coverage

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National Renewable Energy Laboratory

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List of Acronyms

CBECS	Commercial Building Energy Consumption Survey
EIA	U.S. Energy Information Administration
HID	high-intensity discharge
HVAC	heating, ventilating, and air-conditioning
Kg	kilogram
LED	light-emitting diode
MMBtu	million British thermal units
MWh	megawatt-hour
PADD	Petroleum Administration for Defense District
RE	renewable energy
URDB	Utility Rate Database

Executive Summary

Building on a three-year effort to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models, this work produces national datasets that empower analysts working for federal, state, utility, city, and manufacturer 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 and results of the baseline model are discussed in the final technical report of the End-Use Load Profiles project.

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* refer to various "what-if" scenarios that can be applied to buildings.

An *end-use savings shape* is the difference in energy consumption between a baseline building (or collection of buildings) and a building with an energy efficiency or demand flexibility measure applied. It results in a time-series profile broken down by end use and fuel (electricity or on-site gas, propane, or fuel oil use) at each time step as well as annual aggregations.

This report describes an upgrade package of three ComStock measures—thermostat control for load shedding, lighting control for load shedding, and photovoltaics (PV) with 40% rooftop coverage—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).

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 webpage.

Table ES-1. Summary of Key Modeling Specifications

Package Title	Thermostat and Lighting Control for Load Shedding + PV With 40% Rooftop Coverage
Technology description	• This package combines three measure scenarios: thermostat control for load shedding, lighting control for load shedding, and PV with 40% rooftop coverage. It relaxes thermostat set points (heating and cooling) and reduces lighting levels to reduce the building's daily electricity peak demand during demand flexibility events, and it installs PV on the rooftop covering 40% of the roof area for on-site power generation. • Demand flexibility events are dispatched every weekday for four hours. The timing of the dispatch window is centered around each individual building's peak load profile for the day. 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 four-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, for the dispatch window and the ramp back to the original set points over two hours after the window for rebound control. • The lighting level (the corresponding power) is reduced 30% for the dispatch window, and it resumes to the original value after the window. • Control decisions of the two measures are made independently, without considering the integration of the 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 cover 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.
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])
Natural gas	-0.32%	-0.75%	-4.9
Electricity	19.88%	39.64%	630.0

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	18.5%	35.5%	20
Natural gas	0.0%	0.0%	0
Fuel oil	0.0%	0.0%	0
Propane	0.0%	0.0%	0
Total	15.7%	30.7%	20

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

Median Percent Savings (Applicable Buildings Only)	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean Daily Peak of the Month	13.1%	15.4%	17.5%	22.9%	30.6%	30.6%	31.8%	29.8%	25.3%	19.7%	14.6%	12.6%

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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 in Large Offices*, *Lighting Control for Load Shedding* and *Photovoltaics With 40% Rooftop Coverage*.

2 ComStock Baseline Approach

The following sections provide high-level summaries of the ComStock™ baseline approach for thermostat and interior lighting. For more details 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 (supplemental 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 light-emitting diodes (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 (HID) mercury vapor	Incandescent A-shape	Incandescent decorative	Incandescent decorative
Gen 2	T8 linear fluorescent	HID metal halide	Halogen A-shape	Halogen decorative	Halogen decorative
Gen 3	T5 linear fluorescent	HID 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 impacts 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 the impacts from characteristics such as building types and operating hours.

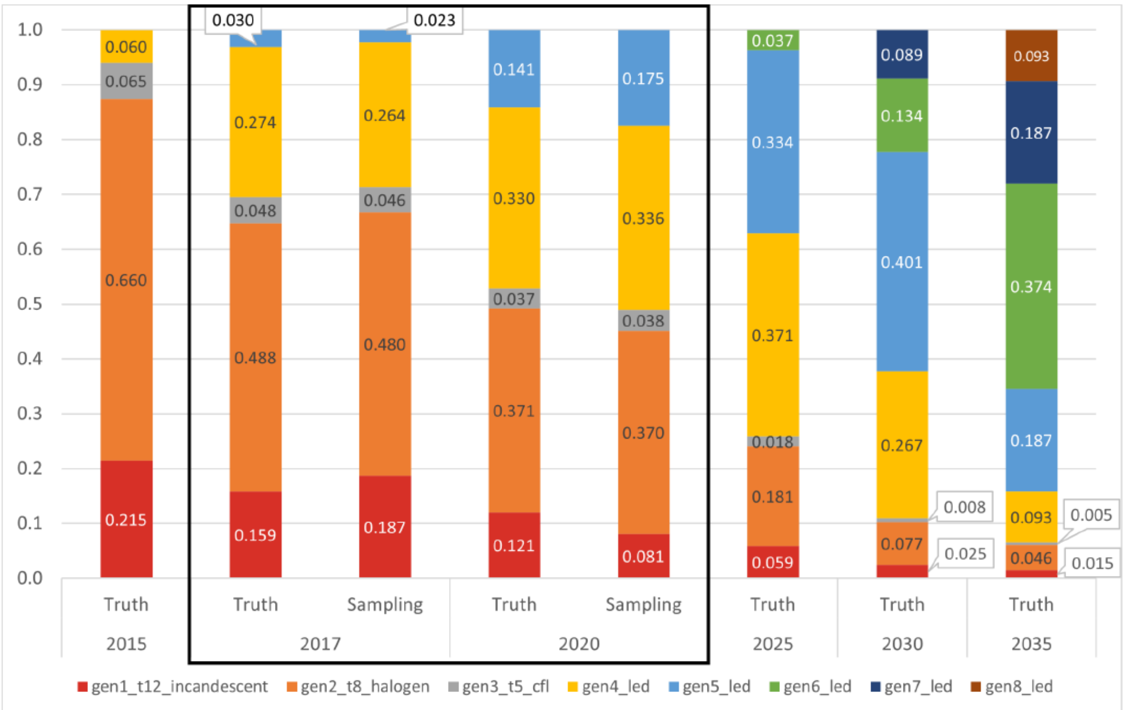

Figure 1. "Truth" lighting generation distribution (0–1) from validated data and comparison of 2017 and 2020 ComStock sampling results

2.3 Rooftop Photovoltaics

The ComStock baseline model does not currently include photovoltaics (PV); however, according to the 2018 Commercial Building Energy Consumption Survey (CBECS), fewer than 2% of commercial buildings have on-site PV [4]. So, although this study does not account for buildings that already have PV, the impact of this prevalence is somewhat minimal.

ComStock assumes all roofs to be flat. Flat roofs are not required for commercial PV, but the roof style can impact the panel mounting type and possibly the panel angle. This work does not consider these potential constraints and assumes that ideal panel angles can be used on every roof. Additionally, ComStock does not currently include shading from neighboring buildings and trees. Although many commercial buildings do not have notable shading limitations, this analysis might overestimate the potential of PV for those that do. This could be particularly impactful for some buildings with relatively lower height than their neighbors or surrounding wooded areas.

3 Modeling Approach

The following sections summarize the applicability and modeling approaches for the *Thermostat Control for Load Shedding in Large Offices*, *Lighting Control for Load Shedding* and *Photovoltaics With 40% Rooftop Coverage* upgrades included in this upgrade package. For more detailed descriptions of each individual measure, reference the individual upgrade documentations.

3.1 Applicability

3.1.1 Demand Flexibility Measures Applicability

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

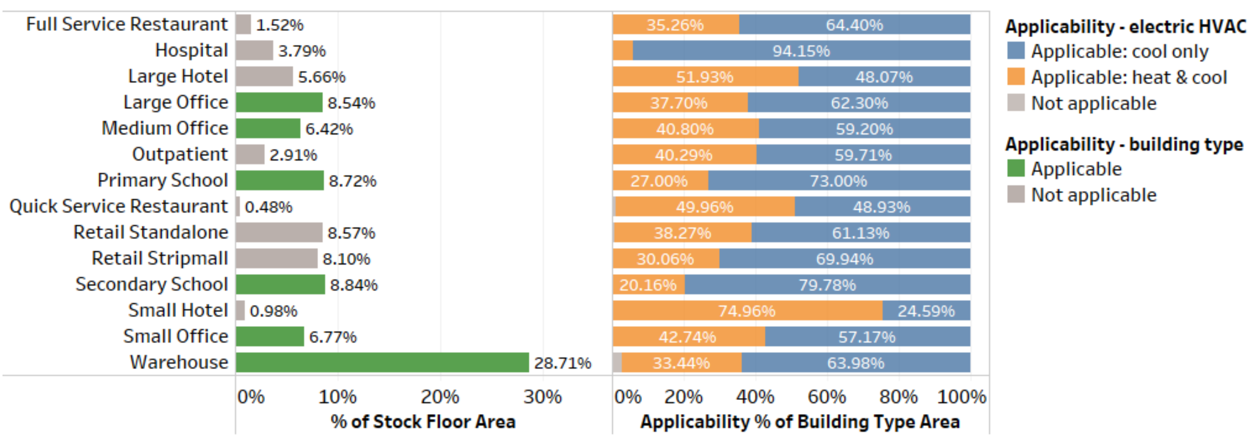

Figure 2. Prevalence of building types and applicability for each building type (for both scenarios) and HVAC fuel type (for the thermostat control scenario)

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 the associated HVAC systems. The measure will identify and adjust the temperature set point schedules of the thermostats controlling the electric heating systems or the electric cooling systems.

3.1.2 Photovoltaics Applicability

The rooftop PV measure scenario is applicable to all models in the ComStock baseline. No building models are excluded. In practice, some commercial buildings might be less suitable to rooftop PV, which this applicability criteria does not account for (e.g., the roof does not have 40% of the area available for PV). And the ComStock baseline does not currently include the estimated <2% of commercial buildings that already have PV; therefore, this study likely slightly overestimates the potential for mass commercial rooftop PV adoption in the stock.

3.2 Technology Specifics

3.2.1 Rooftop Photovoltaics

This measure leverages the PVWatts® EnergyPlus® objects. PVWatts is a National Renewable Energy Laboratory tool that estimates the energy production of grid-connected PV systems [5]. The workflow applies PVWatts objects with total power levels corresponding to 40% of the model's roof area. The panels are fixed with no tracking.

3.2.2 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*, with selection of individual building peak load reduction as objective, a daily load dispatch schedule corresponding to the daily peak building loads will be generated and used as the input of both upgrades to determine the periods when the lighting level and thermostat set points should be adjusted. The building load and peak timing are assessed after accounting for PV generation, represented by the net building load (i.e., total load minus on-site generation). As a result, the dispatch schedule may differ from the one determined without PV applied, as the PV generation can reshape the (net) load profile and potentially shift the timing of peak demand. Specifications of parameters for generating the peak schedule are defined in detail in the supplemental documentation.

3.2.3 Thermostat Control

The Thermostat Control for Load Shedding in Large Offices 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.

3.2.4 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.

3.2.5 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

Default DF Parameter	Thermostat Control for Load Shedding	Lighting Control for Load Shedding	PV Parameter	PV With 40% Rooftop Coverage
Objective	Individual building peak load reduction		**Inverter efficiency**	96%
Load prediction method	Perfect prediction (full baseline simulation)		**DC/AC ratio**	1.10
Peak window determination method	Centered with peak		**System losses**	14%
Length of peak window	4 hours		**Panel rated eff.**	21%
Control actions during peak window	±2°C	N/A	**Panel area**	40% of roof
Lighting adjustment method	N/A	30% reduced	**Title & azimuth**	Varies
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	$0.070/kBtu	$0.012/kBtu	$0.048/kBtu
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	$0.035/kBtu	$3.530/kBtu

Natural gas bills are estimated using the 2022 EIA averages by state. The 2022 EIA natural gas prices (commercial price) and the EIA heat content of natural gas delivered to consumers are used to create an energy price in dollars per thousand Btu [6].

Propane and fuel oil bills are estimated using the 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 [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 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 the ComStock electric utility rates is the Utility Rate Database (URDB), which includes rate structures for approximately 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, 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 nonbuilding-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 [9]. Although 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 dimming 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 the results. First,

this measure relies on the user-provided inputs of the 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 the 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 the 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 lighting dimming percentage and length of peak window, and the impact can vary depending on the building properties and the weather conditions. We applied simple parametric analysis on the input parameters to justify the selection of the default values, but detailed fine-tuning and other practical considerations are needed to determine the best parameter set(s).

- The current scope of the 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 a minimal impact on occupants due to the low occupancy, whereas the occupancy distributions in schools are much more complicated and dynamic, and the ranges of acceptable visual environments vary depending on the functions of the spaces and the 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 areas). We have chosen the applicability of the building types with assumed dimming in all contained space types and the 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 as the objective function. There are many other objective functions that have different, possibly conflicting goals, such as grid-level peak reductions, grid-level operating cost reductions, and building-level utility bill reductions. We are targeting daily peak load reduction from the prospect of individual buildings instead of the grid demand needs. This might lead to load management conflicts between single buildings and the grid. We plan to add the objective of 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 the daily dispatch window for demand response control, as we are investigating the maximum potential of applying demand flexibility measures in the stock level; however, the actual implementation of the demand flexibility strategy could be much less frequent than daily, such as 10–15 events per season in typical demand response programs, which would impact the results.

- This study assumes that all roofs have 40% unshaded area available for a PV array, which may not be the case for all buildings. For example, a 2016 NREL report suggests smaller values in some cases (e.g., buildings under 5000 ft2 average only 26% area)[10]. This may overestimate the potential of PV in some cases. Alternatively, some buildings show negative net metered electricity usage with PV covering 40% of the roof area. This can suggest an oversized PV system in some cases, depending on the goals of the project.
- The ComStock baseline does not include any PV. CBECS 2018 estimates that ~2% of commercial buildings use PV, so this study may slightly overestimate the impact of mass adoption of PV.
- The PV assumptions in this work primarily follow the defaults used in the PVWatts tool. Although these are meant to be reasonable, real PV systems designs may vary, which can impact performance.
- The PV Watts module used in this analysis does consider roof shading from the PV panels. Shading could affect the solar heat gain on the roof. The overall impact of this potential roof shading is likely minimal, especially in the context of larger multistory commercial buildings. However, it could have some impact on heating and cooling loads.
- This study uses a DC-to-AC size ratio of 1.1, which is the default assumption in PVWatts. This is a conservative estimate, with other sources suggesting higher values of 1.2–1.3. A higher value can increase the prevalence of clipping, where PV output beyond what the inverter can handle is lost. However, a higher ratio can be more economical for some projects.
- Net metering impacts on utility bills are not included in this study; the PV panels simply reduce the electricity demand on the building meter at the time of generation, with no resale back to the utility. This may underestimate the savings presented in this report and in the ComStock public dataset. However, PV energy that is generated but not used by the building is reported in the public dataset, enabling users to account for excess generation as needed.

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
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
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

Variable Name	Description
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

Variable Name	Description
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
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
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
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
out.electricity.pv.energy_consumption	Annual PV electricity energy consumption in kWh, negative values indicate generation
out.electricity.net.energy_consumption	Annual net electricity energy consumption in kWh with negative values indicating excess onsite electricity generation sent back to the grid

5 Results

This section presents the results 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, the 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 Demand Flexibility Performance for Peak Reduction

Figure 3 show the distributions of savings percentages of maximum and median daily peak load, respectively, by month for the default scenario compared to the baseline model. The distributions of the statistics share overall positive monthly peak reduction, and show clear pattern of higher savings in summer. The savings are mainly contributed by the PV generation, which reduces the building loads in general and thus reduces daily peak demand. The pattern of higher savings in summer results from (1) increased PV generation due to greater solar availability and higher system efficiency, and (2) stronger alignment between PV generation and building load profiles during this season.

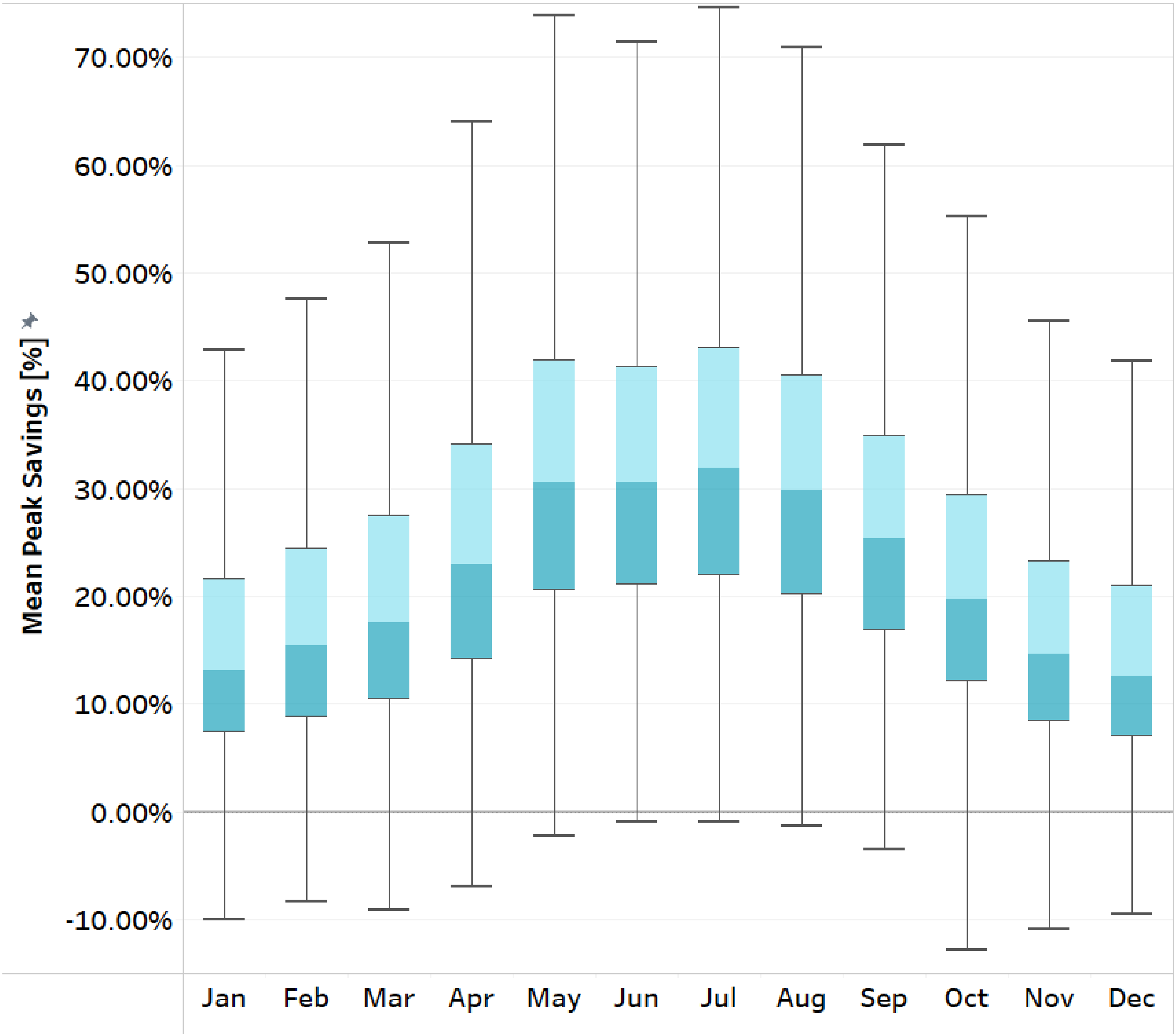

Figure 3. Distribution of the percentages of mean daily peak load reduction by month compared to the baseline model

5.2 Stock Energy Impacts

This section presents the annual energy impacts. The thermostat and lighting control for load-shedding + PV package demonstrates 12.84% total site energy savings (625.1 trillion Btu [TBtu]) for the U.S. commercial building stock modeled in ComStock, with an average of 27.15% 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 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	12.84%	27.15%	625.1
Total electricity	19.88%	39.64%	630.0
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
Electricity gen used	18.11%	36.11%	573.9
Electricity gen excess	23.51%	46.88%	745.0

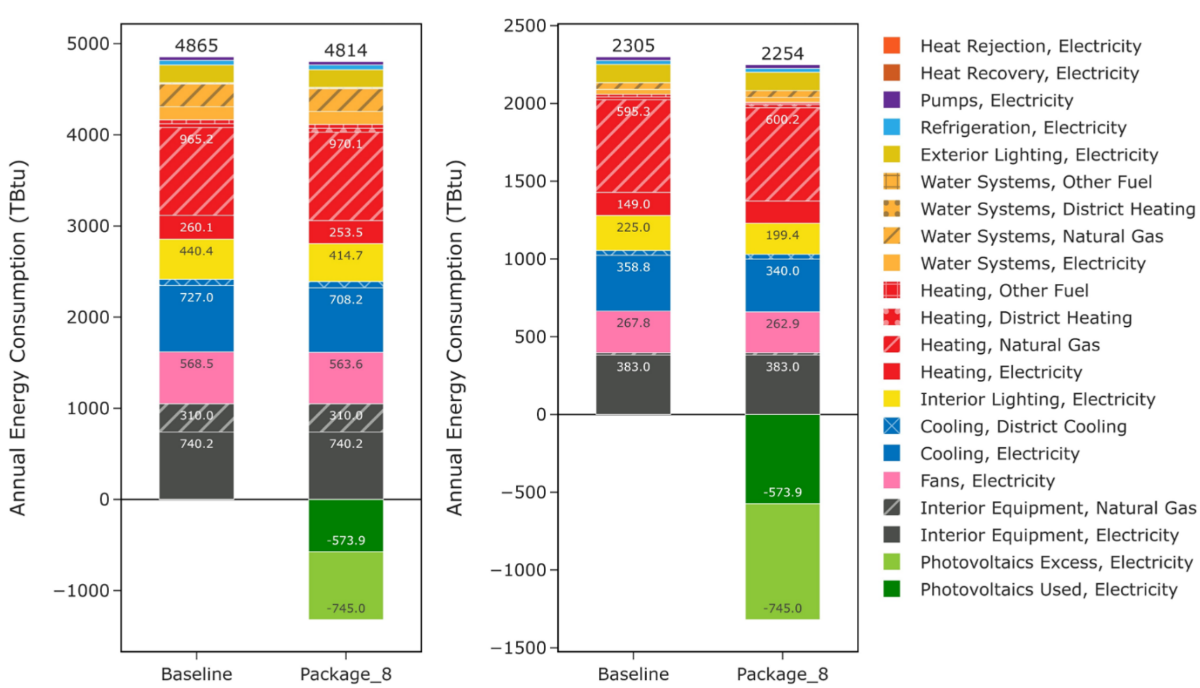

Figure 4. Comparison of annual site energy consumption between the ComStock baseline and the thermostat and lighting control for load-shedding with PV package scenario for the whole stock (left) and applicable buildings only (right). Energy consumption is categorized both by fuel type and end use.

Although there are considerable savings for interior lighting, electric heating, and electric cooling energy (11.42%, 4.43%, and 5.24%, respectively for applicable buildings), primary (electricity) energy savings are contributed by electricity generation through PV system

(36.11%). The overall end-use consumption profile remains structurally similar compared to the scenario without PV upgrade. More detailed discussion on energy impacts can be found in the documentation of demand flexibility measure package.

5.3 Stock Utility Bill Impacts

This section presents the annual utility bill impacts. Because we apply many electricity utility rate structures that are available for a building located in a certain geographic 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 approximately 15% savings among the different rates, mainly attributed to the reduced electricity consumption. 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 and cooling and cooling only, which yields increased bill savings of approximately 30%–40%, with comparably higher savings when only electric cooling system is applicable for demand flexibility control.

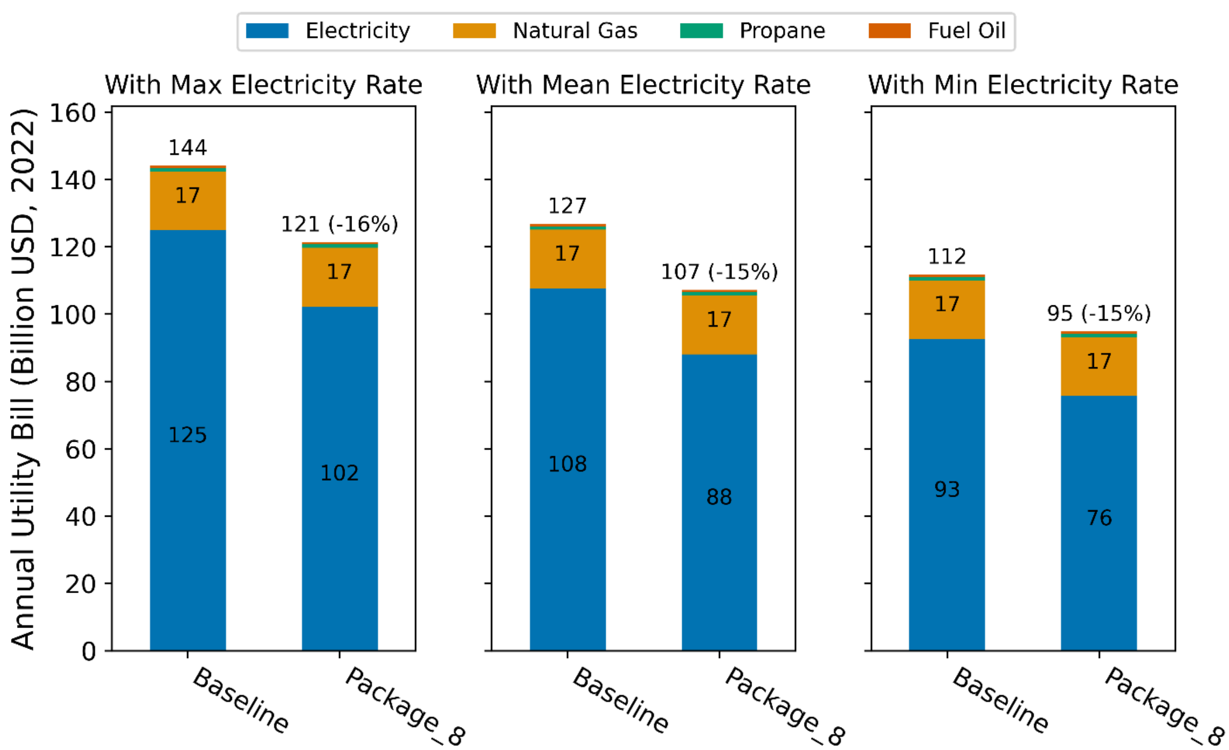

Figure 5. Stock annual utility bill comparison of the ComStock baseline and the thermostat and lighting control for load-shedding with PV package scenario.

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

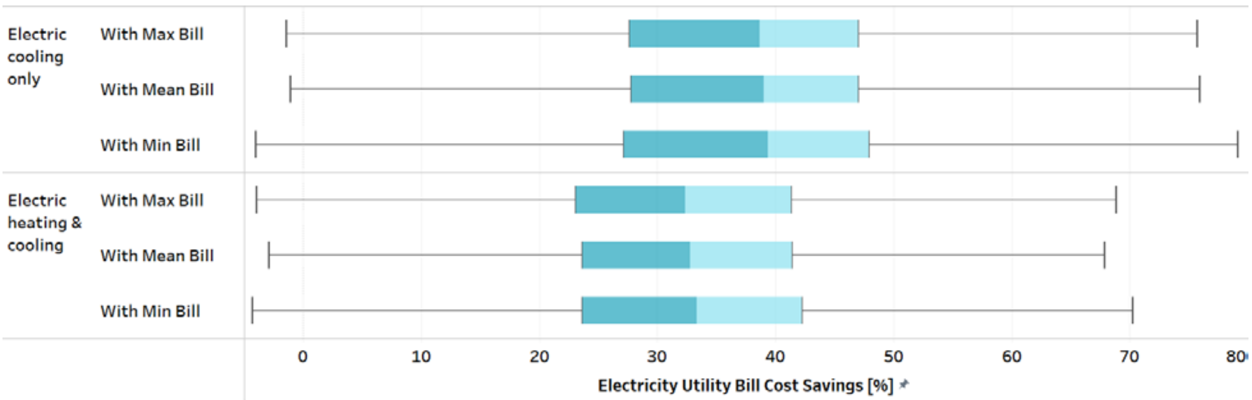

Figure 6. Distribution of annual electricity bill savings compared to the baseline model for maximum, mean, and median bills (for applicable buildings)

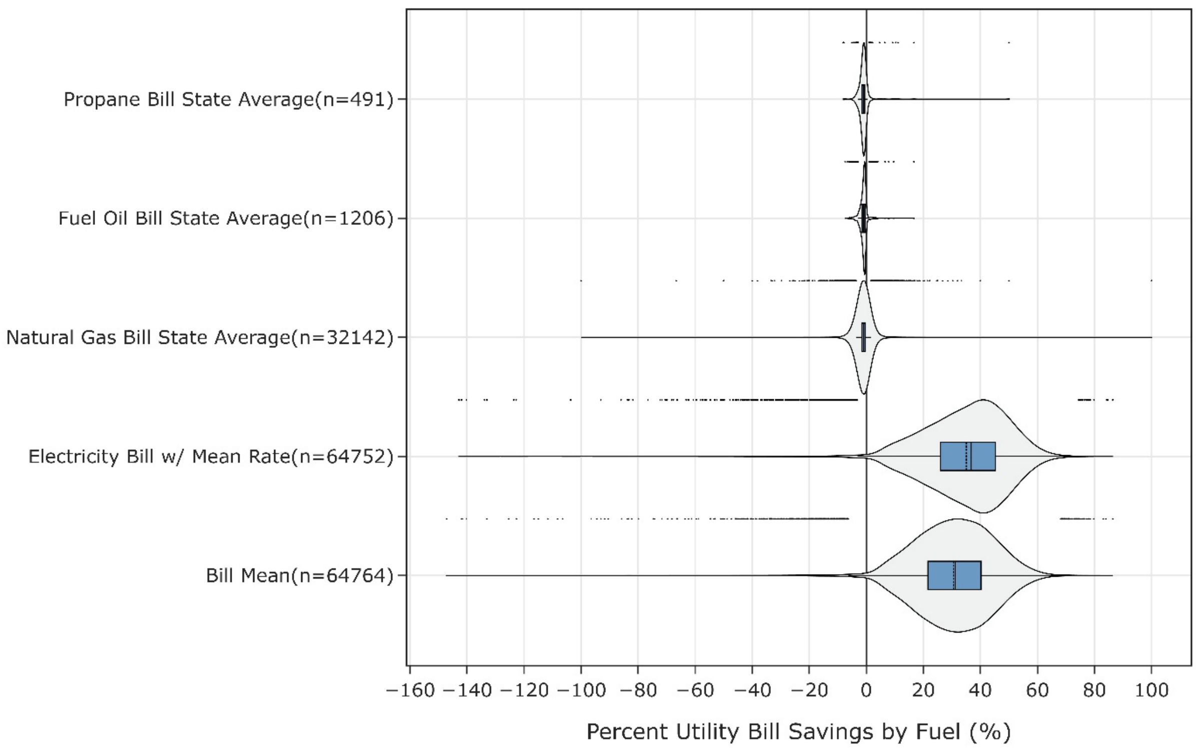

Figure 7. Percent bill savings for ComStock models with t the thermostat and lighting control for load-shedding with PV package scenario by fuel types.

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.

5.4 Site Energy Savings Distributions

This section discusses the site energy consumption for quality assurance/quality control. Note that the 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 (5.2 and 5.3)— 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 nonelectricity fuel types.

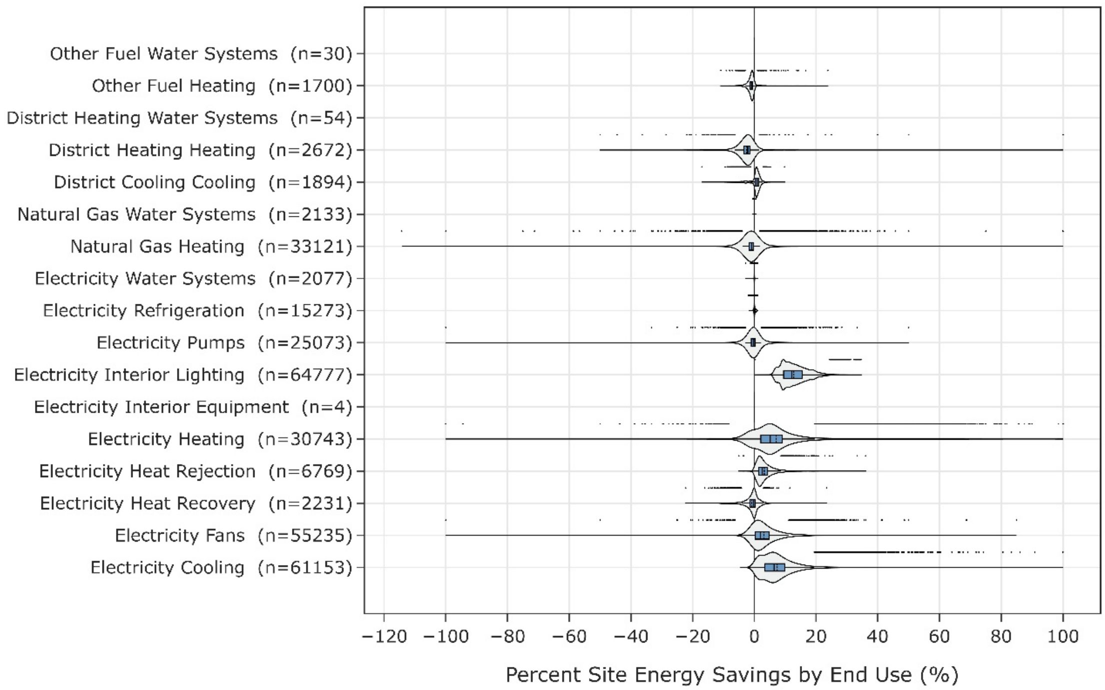

Figure 8. Percent site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type.

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.

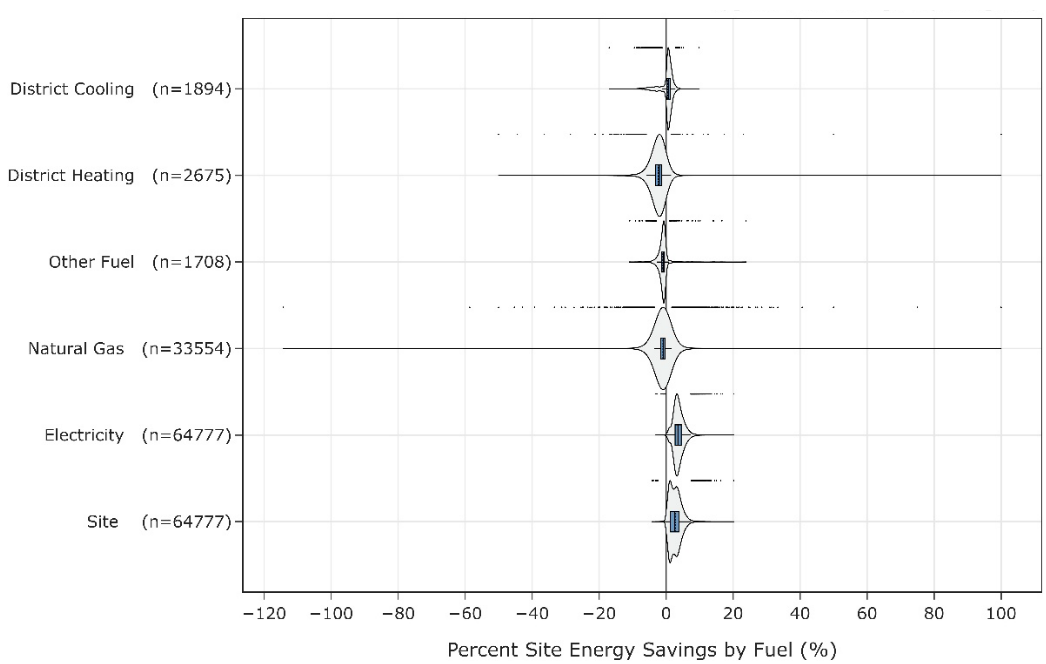

Figure 9. Percent site energy savings distribution for ComStock models with the applied measure scenario by fuel type.

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.

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Appendix

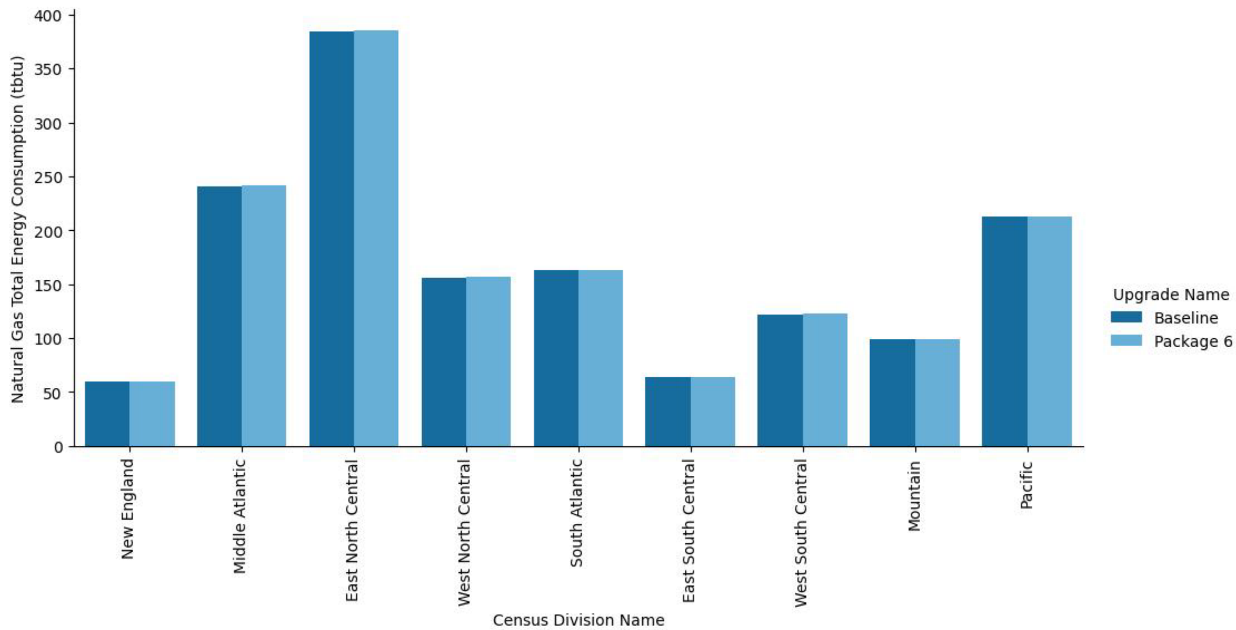

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

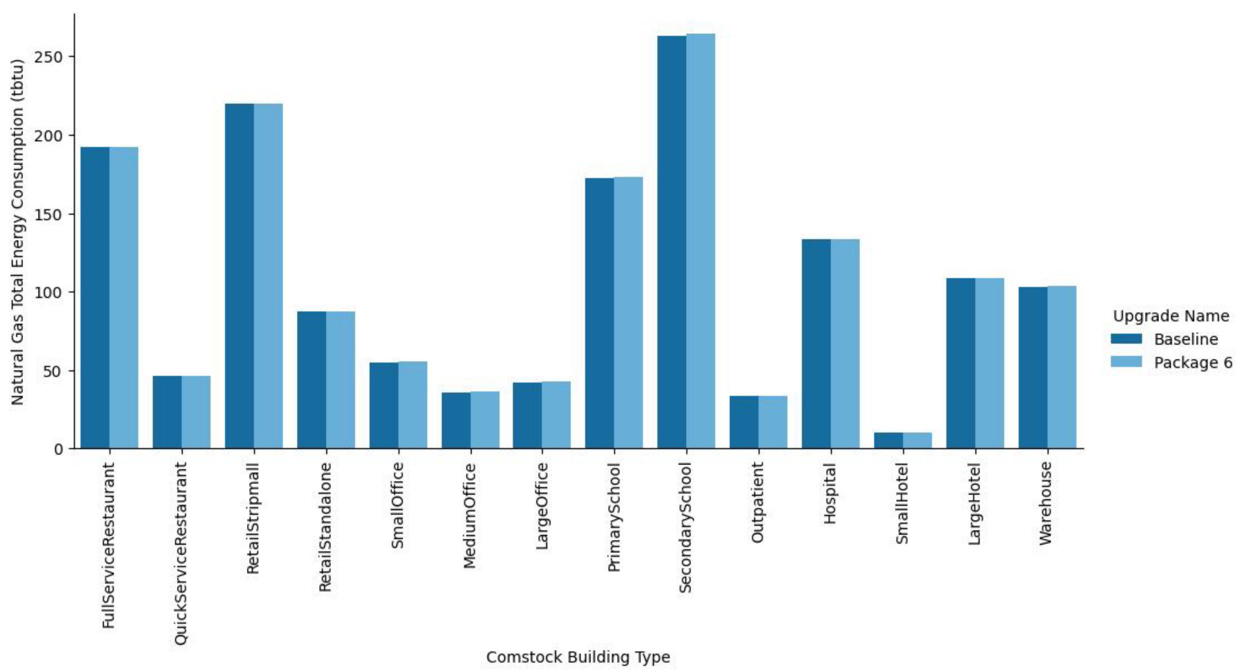

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

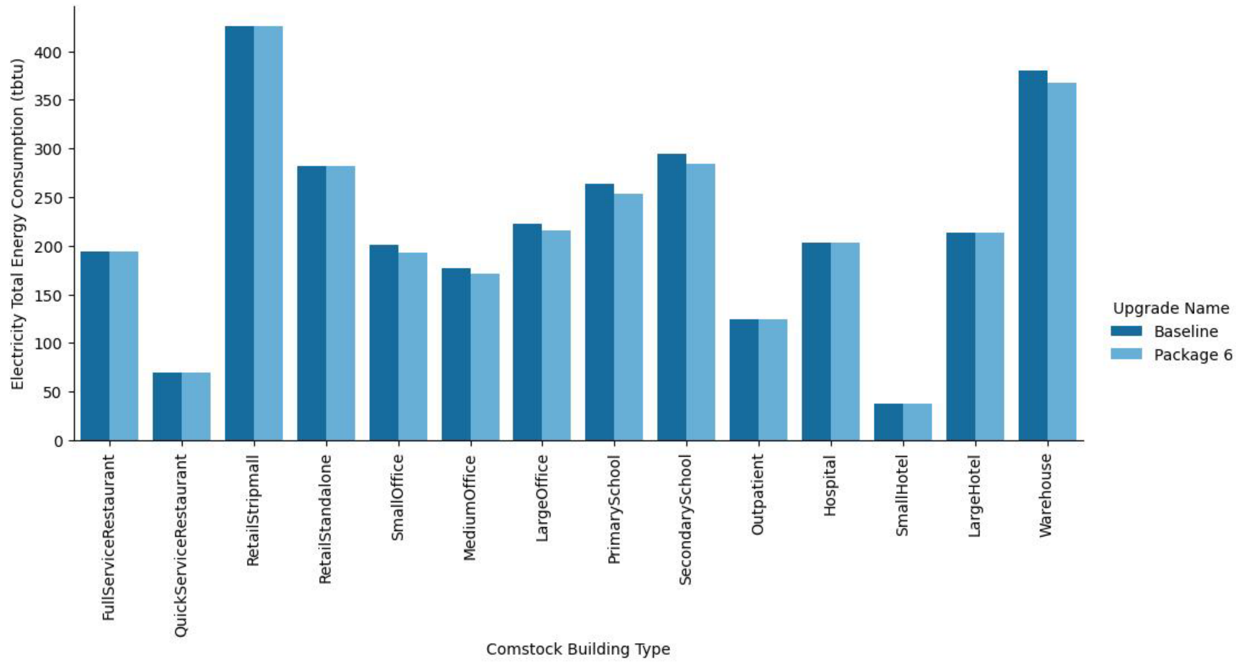

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

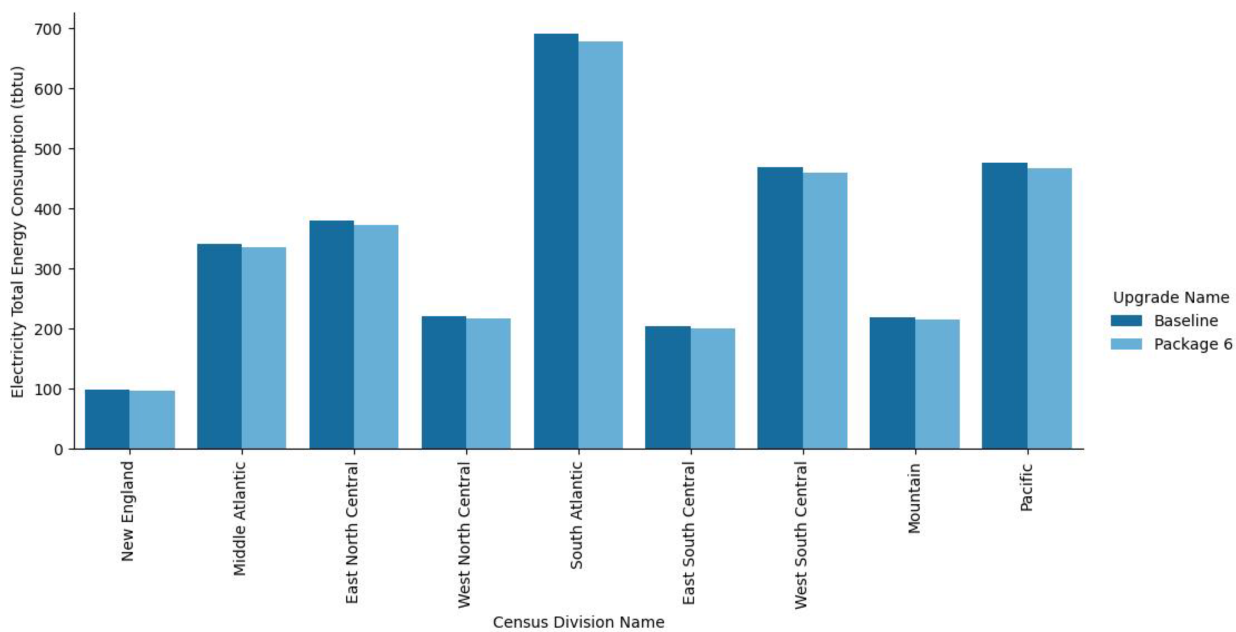

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division