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ComStock Measure Documentation: Lighting Control for Load Shedding

Jie Xiong and Janghyun Kim

National Renewable Energy Laboratory

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List of Acronyms

Btu	British thermal units
CBECS	Commercial Buildings Energy Consumption Survey
DR	demand response
EIA	U.S. Energy Information Administration
EUI	energy use intensity
GEB	grid-interactive efficient building
HVAC	heating, ventilating, and air conditioning
RE	renewable energy
URDB	Utility Rate Database
TOU	time of use

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 the modeling methodology for a single end-use savings shape measure—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 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.

Table ES-1. Summary of Key Modeling Specifications

Technology Description	• The lighting control for load shedding measure applies lighting dimming control to reduce the lighting load during the building's electricity peak window every weekday. • The measure takes daily peak load schedule inputs generated by the method "Dispatch Schedule Generation" described in the "Supplemental Documentation: Dispatch Schedule Generation for Demand Flexibility Measures" to determine the start and end times of the predicted peak window, and then adjusts the lighting level by a percentage reduction from the original schedules during the peak window to reduce the peak demand.
Performance Assumptions	• By default, the peak window length is set to be 4 hours. • The measure is flexible and allows users to adjust the lighting dimming percentage value. • The default adjustments in this study are set to -30%. This means the lighting power is reduced by 30% compared to the baseline model during the dispatch periods. • The lighting levels are set back to original schedule values after the peak window.

Applicability		• This measure is applicable to (large, medium and small) offices, warehouses, and primary and secondary schools. • This measure is applicable to approximately 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 (TBtu)
Natural Gas	-0.40%	-0.89%	-6
Electricity	0.88%	1.78%	27.3

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.

End Use / Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (Million USD, 2022)
Electricity	1.0%	1.8%	1
Natural Gas	0.0%	0.0%	0
Fuel Oil	0.0%	0.0%	0
Propane	0.0%	0.0%	0
Total	0.80%	1.5%	1

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
Max Daily Peak of the Month	3.0%	3.4%	3.1%	3.2%	3.8%	3.5%	3.4%	3.6%	3.7%	3.5%	3.4%	3.0%
Median Daily Peak of the Month	3.8%	3.9%	3.5%	3.5%	4.0%	3.8%	4.0%	4.0%	3.9%	3.8%	4.1%	3.9%

Table of Contents

Executive Summary v
1 Technology Summary 1
1.1 Grid-Interactive Efficient Buildings With Demand Flexibility 1
1.2 Lighting Control Strategies for Demand Flexibility 1
2 ComStock Baseline Approach 4
3 Modeling Approach 7
3.1 Applicability 7
3.2 Technology Details 9
3.2.1 Objective Selection and Input Schedule 9
3.2.2 Lighting Schedule Generation 9
3.3 Utility Bills 9
3.4 Limitations and Concerns 10
4 Output Variables 13
5 Results 17
5.1 Single Building Measure Tests 17
5.1.1 Daily Peak Load Reduction 18
5.2 Stock Demand Flexibility Performance for Peak Reduction 18
5.2.1 Monthly Quartile Statistics Distribution of Daily Peak Reduction 19
5.3 Stock Energy Impacts 20
5.4 Stock Utility Bill Impacts 22
5.5 Site Energy Savings Distributions 24
References 26
Appendix A. 29

List of Figures

Figure 1. "Truth" lighting generation distribution (0-1) from validated data and comparison of 2017 and 2020 ComStock sampling results ... 5
Figure 2. Example weekday lighting schedules (fractional factor to fully ON) ... 6
Figure 3. Floor area prevalence of building types and applicability for each building type ... 8
Figure 4. Building count prevalence of building types and applicability for each building type ... 8
Figure 5. Comparison of load profiles and lighting schedules (baseline and lighting load shed) for peak load reduction objective for test small office model ... 18
Figure 6. Distributions of the percentage of max daily peak load reduction by month compared to the baseline model ... 19
Figure 7. Distributions of the percentage of median daily peak load reduction by month compared to the baseline model ... 20
Figure 8. Comparison of annual site energy consumption between the ComStock baseline and the lighting control for load shedding measure scenario, for the whole stock (left) and applicable buildings only (right) ... 21
Figure 9. Stock annual utility bill comparison of the ComStock baseline and the lighting control for load shedding scenario ... 22
Figure 10. Distribution of annual electricity bill savings compared to the baseline model for maximum, mean, and median bills (for applicable buildings) ... 23
Figure 11. Percent bill savings for ComStock models with the lighting control for load shedding upgrade by fuel types ... 24
Figure 12. Percent site energy savings distribution for ComStock models with applied measure scenario by end use ... 25
Figure 13. Percent site EUI savings distribution for ComStock models with applied measure scenario by end use ... 25
Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division ... 29
Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type ... 29
Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type ... 30
Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division ... 30

List of Tables

Table ES-1. Summary of Key Modeling Specifications ... v
Table ES-2. Summary of Key Results for Annual Site Energy Savings ... vi
Table ES-3. Summary of Key Results for Annual Utility Bill Savings ... vi
Table ES-4. Summary of Key Results for Monthly Peak Savings. ... vi
Table 1. Lighting Generations and Associated Technologies for Each Category ... 4
Table 2. Average Building-Level LPD (W/ft^2) by Lighting Generation and Building Type ... 4
Table 3. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type ... 9
Table 4. Output Variables Calculated From the Measure Application ... 13
Table 5. Default Options for Measure Parameters ... 17
Table 6. Summary of Site Energy Savings From Upgrade Measure Application vs. the ComStock Baseline ... 21

1 Technology Summary

The lighting control for load shedding measure applies lighting dimming control to reduce the lighting load during the peak window every weekday. The measure takes daily peak load schedule inputs generated by the method "Dispatch Schedule Generation" described in the "Supplemental Documentation: Dispatch Schedule Generation for Demand Flexibility Measures" to determine the start and end times of the predicted daily peak window, and then adjusts the lighting level by a percentage reduction from the original schedules during the peak window to reduce the peak demand.

1.1 Grid-Interactive Efficient Buildings With Demand Flexibility

Electricity consumers across the residential, commercial, and industrial sectors are increasingly interested in opportunities to reduce their electricity bills and environmental footprint. Simultaneously, utilities, system operators, and state decision makers are aiming to reduce costs, more effectively utilize existing grid assets, and maintain power system reliability. At the intersection of the customer and utility perspectives, buildings and their associated loads offer opportunities to align the interests of consumers, system operators, and policy decision makers. Interactivity between buildings and the broader electricity system expands these opportunities and is enabled by advancements in building control technologies, data availability, advanced metering, new tariff designs, and improved analytics for energy management. Collectively, these smart technologies for energy management are often referred to as grid-interactive efficient buildings (GEBs). GEBs utilize high-efficiency components to reduce electricity demand and increase the flexibility of specific building loads, responding to real-time signals or advanced calls for demand response (DR), or targeting bill savings associated demand regulations such as time-of-use (TOU) rates and rates with demand charges. By shedding and shifting building load, these GEBs can reduce electricity bills or the cost of operating the grid, all while maintaining the comfort of building occupants.

Many studies have been devoted to building control for grid services during the past few years ([1], [2], [3], [4], [5], [6], [7], [8], [9], [10]). There are five technical interventions or measures used in a building's demand profile modification in the literature ([11], [12], [13], [14], [15], [16], [17]). The first, energy efficiency, refers to techniques that help reduce the net demand during both on-peak and off-peak periods. The second, peak shaving or load shedding, refers to reducing the on-peak demand, i.e., when the demand in the power grid is high. The third method is load shifting, which means altering the demand profile to meet certain performance criteria, usually involving a reduction in on-peak demand and an offset by a load increase at a different time. The fourth method is renewable energy, which utilizes distributed energy resources to coincidently reduce on-peak demand. The last is modulation, which provides rapid adjustments to regulate frequency and voltage and assure power quality. The existing methods that fall within these five categories can help reduce demand charges directly or indirectly.

1.2 Lighting Control Strategies for Demand Flexibility

Lighting systems are reported [18] to consume 10.4% of all energy (EIA 2018, CBECS Table E.1), and 17.4% of electricity in commercial buildings in 2018 (EIA 2018, CBECS Table E.3) , making them the second largest contributors to commercial electricity use (slightly less than ventilation systems). Lighting systems thus have great potential for load management. Lighting loads in commercial buildings are dependent on the space type, schedule, and lighting technology type (e.g., ballast type), but the lighting load profiles usually share similar or consistent daily patterns across commercial buildings (according to daily operating patterns, such as weekday or weekend operation, office hours, or noon break), which yields great demand flexibility potential. The GEB technical report series [19] evaluates that advanced sensors and controls of lighting system have high potential for grid interaction capability.

Compared to HVAC systems, currently installed lighting systems are less automated; approximately 6% of commercial buildings have building automation systems for lighting [18] (EIA 2018, CBECS Table C.13) in the U.S.—so it is more difficult to achieve load flexibility strategies through existing automated lighting controls. However, advances in lighting technologies have led to cost-effective intelligent lighting control applications via lighting-application specific controllers (LAS controllers) coupled with Internet of Things (IoT) and wireless technologies, and controllable lighting products such as dimmable ballasts or LEDs. The U.S. General Services Administration (GSA) reports that advanced lighting controls reduced LED lighting energy use by 43% [20], and retrofitting fluorescents to LEDs yields 40% investment return [21]. Therefore, low-cost retrofitting for controlling existing lighting systems in commercial buildings is possible. By 2035, DOE projects that one-third of lighting in the commercial sector will be connected to the grid, driven by energy codes, utility rebates, energy savings, and non-energy benefits driven by data and analytic capabilities [19].

Lighting systems have two advantages for demand flexibility capability. First, adjustment of lighting energy use can be nearly instantaneously realized with lighting controls, which makes lighting systems one of the most reliable, elastic, and responsive end uses for dynamic load management. Lighting systems are one of the two major targets (the other is thermostats) for demand response programs, through either direct load control/override by utilities or incentive-regulated user response. Second, the amount of light dimming required to productively reduce electric loads does not need to compromise occupant comfort. Various studies ([22], [23], [24], [25]) have suggested that reducing lighting levels from the recommended values within a certain range (13%–25%) is acceptable without occupants noticing it or causing significant visual discomfort, for short duration (hours).

Although energy efficiency measures regarding overall minimization of lighting energy use could be designed based on such fact, it is not the target of discussion in this measure documentation. Other factors affecting visual comfort and productivity such as light levels, glare, etc., or affected by surrounding environment such as windows and fenestration systems, are assumed to be taken into account in the ComStock Baseline Approach, which generates the original lighting schedules described in next section, and demand flexibility potential lies upon these factors without significant interference.

Typical lighting control methods include on/off control, (discretized) multi-level control, and (continuous) dimming control. Modern lighting products such as fluorescent fixtures with dimmable ballasts and LEDs are designed to enable continuous dimming, which is very common in the market nowadays, while on/off or multi-level controls can approximate (stepped) dimming by properly grouping/clustering design of the controlled luminaires in a space, such as the proportional load shedding method presented in [26]. Studies related to lighting controls applied for demand flexibility are very limited due to the low penetration of automated lighting in the commercial sector. Case studies in California [27] quantified the demand savings of a single dimmable fixture to be 22.7W–30W from different reduction ranges (70% to 30% up to 100% to 50%), and the demand savings intensity of grouped control lighting to be 0.45W/ft^2 by switching off a quarter of fixtures (equivalent to dimming from 100% to 75%). It also estimated 1GW peak reduction potential for all commercial buildings in California by assuming a 20% lighting peak demand reduction goal is achieved. According to a report by the Lighting Controls Association [28], many large buildings (over 10,000 ft^2) built after 2016 in California are capable of at least 15% load reduction in case of a demand response event, partly through automated lighting control systems, to be compliant to the state's Title 24 Building Energy Efficiency Standards (2016 version, Part 6—Energy Code). The Lighting Research Center at Rensselaer Polytechnic Institute and the New York State Energy Research and Development Authority (NYSERDA) conducted several demand response studies [29] in New York to apply ballast products with load-shedding capability on both new and retrofitted buildings and demonstrated 25%–30% lighting load shed capability.

2 ComStock Baseline Approach

This measure modifies the existing model interior lighting schedules during the daily peak demand windows (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 Reference Documentation [30] for default schedules, and Section 3.3.4 “Interior Lighting Schedule Magnitude Variability” in the End-Use Load Profiles project report [31] 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 surface). 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
1	T12 Linear Fluorescent	High Intensity Discharge (HID) Mercury Vapor	Incandescent A-Shape	Incandescent Decorative	Incandescent Decorative
2	T8 Linear Fluorescent	HID Metal Halide	Halogen A-Shape	Halogen Decorative	Halogen Decorative
3	T5 Linear Fluorescent	HID Metal Halide	Compact Fluorescent Screw	Compact Fluorescent Pin	Compact Fluorescent Pin
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 (LPD) allowance for a given space type. Table 2 provides the average installed building-level LPDs in ComStock by building type and lighting generation.

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

	Lighting Generation				
Building Type	**1**	**2**	**3**	**4**	**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

	Lighting Generation				
Building Type	1	2	3	4	5
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 technologies were assigned to each building model during the sampling process, based on validated distribution data (Figure 1), and introduced with variability representing realistic installation trends of different generations and impact of building sizes. Default interior lighting schedules come from the OpenStudio-Standards DOE prototype building models [32]. The schedules are then adjusted with varying base-to-peak ratios (BPRs) to incorporate impact from characteristics such as building types and operating hours.

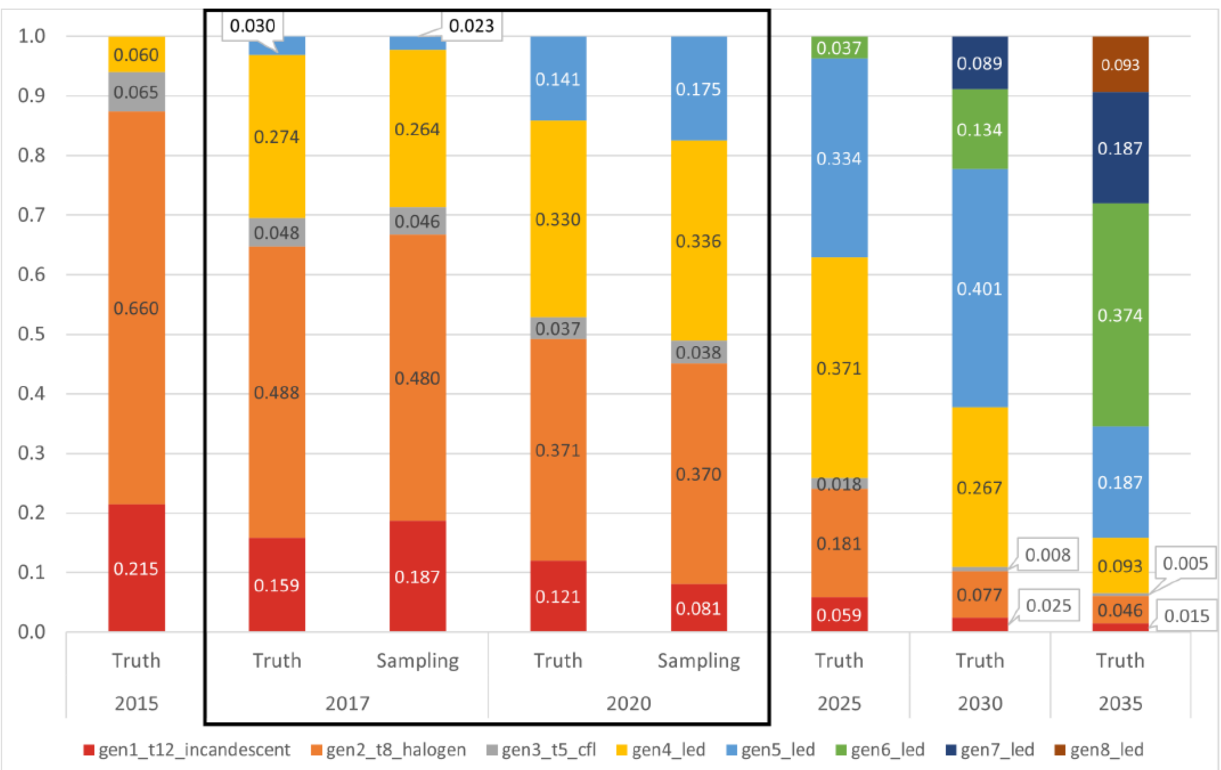

Figure 1. "Truth" lighting generation distribution (0-1) from validated data and comparison of 2017 and 2020 ComStock sampling results

The following figure shows two sets of example weekday lighting default schedules versus the corresponding BPR-adjusted schedules for large and small office buildings in the ComStock baseline models.

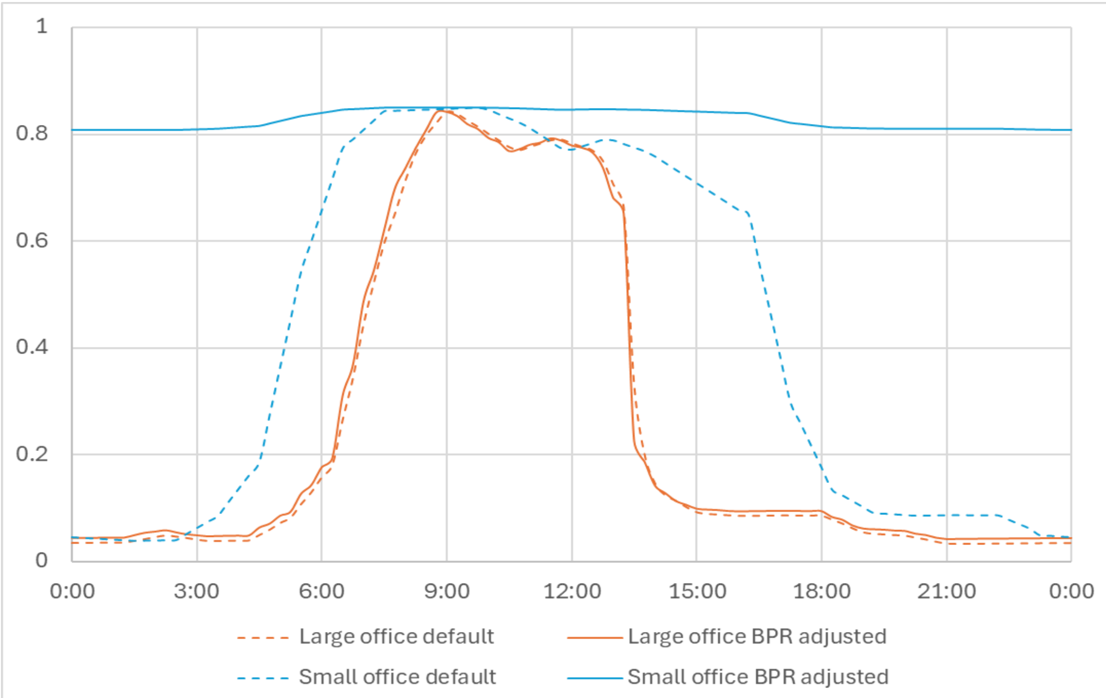

Figure 2. Example weekday lighting schedules (fractional factor to fully ON)

3 Modeling Approach

3.1 Applicability

Despite the existing low population of installed control systems for lighting in commercial buildings, this measure is likely applicable to most commercial building types, as it targets lighting (schedule) control regardless of the details of lighting system operations. Based on the technical and practical references and feasibility evaluation of current ComStock models discussed below, we determine in this study the applicability of this measure to office buildings (small, medium and large), warehouse, and schools (primary and secondary).

There are only a few resources that discuss the building and system type limitations of demand flexibility applications on commercial buildings. The ASHRAE GEB guide [18] states that hospital and laboratory buildings with specific temperature, humidity, and pressurization requirements are not suitable for demand flexibility HVAC control, and similarly those buildings have specific lighting requirements for safety concerns such as the surgery space. It also points out that office buildings, high-rise multifamily buildings, and warehouses are ideal targets for demand flexibility applications because of their wider acceptable indoor environmental conditions. For retail/grocery stores and restaurants, customer's satisfaction to lighting conditions becomes the priority as it has positive correlation with economic benefit, which yields fewer opportunities for demand flexibility that might compromise occupant comfort in peak periods. For example, darker conditions may affect customers' consuming willingness. Great potential of lighting demand flexibility lies in hotels and schools when integrated with occupancy control (potential load flexibility varies with states of occupancy), but there are many aspects of practical considerations affecting the feasibility such as space type-specific requirements (gym, conference room, etc.) and weather-related operation issues (humidity/mold control), which require more rigorous research and design on actual application for these building types. Hotels have more distinctive lighting environment requirements between occupied and unoccupied rooms, and thus designing load management strategies for hotels relies heavily on occupancy control, which is out of the scope for this measure development study.

Moreover, different spaces in the same building would have different lighting condition requirements and might require different control strategies. For example, gym or laboratory spaces in schools have stricter light level requirements compared to classrooms or restrooms, leaving less room for lighting control. However, in this measure, it is reasonable to assume the control implementation is applicable to all the spaces in applicable buildings, regardless of space types, to ensure the generalizability of the measure in the stock level. This assumption is based on the approximation that the underestimated potential impact of the measure on some spaces (e.g., unoccupied rooms) would be offset by the overestimated impact on some other spaces with stricter lighting requirements (which correspond to insignificant proportion of building area and loads) in a building with proper design of controls in practical applications.

This measure assumes the applicable buildings are or should upgrade to be equipped with controllable lighting systems, as a pre-requisite for lighting control, capable of meeting any specific dimming target via dimmable fixtures or proper design of control (e.g., turning off selective fixtures to achieve net dimming target).

Figure 3 shows the area percentage of large, medium and small office buildings, primary and secondary schools, and warehouses among all the commercial building types in ComStock. Overall, 68.00% of the total stock floor areas are applicable for this measure. Figure 4 shows the building count percentage of the corresponding applicability, representing 2,800,013 or 59.29% applicable buildings, out of 4,722,342 buildings in the national stock level, with weighting factors applied. More specifically, 925,888 small offices, 98,309 medium offices, 33,119 large offices, 242,631 primary schools, 296,142 secondary schools and 1,203,924 warehouses are applicable.

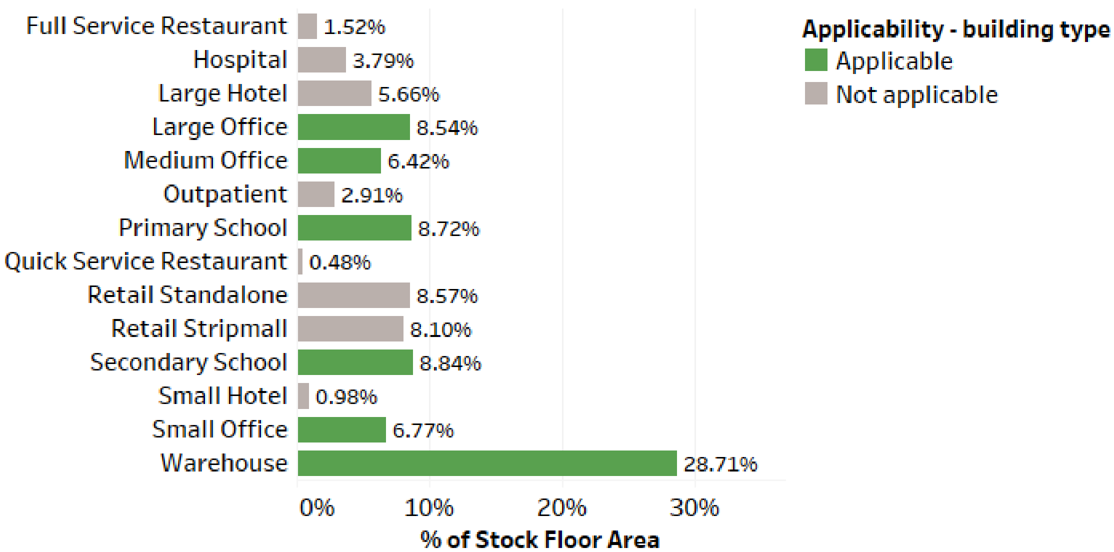

Figure 3. Floor area prevalence of building types and applicability for each building type

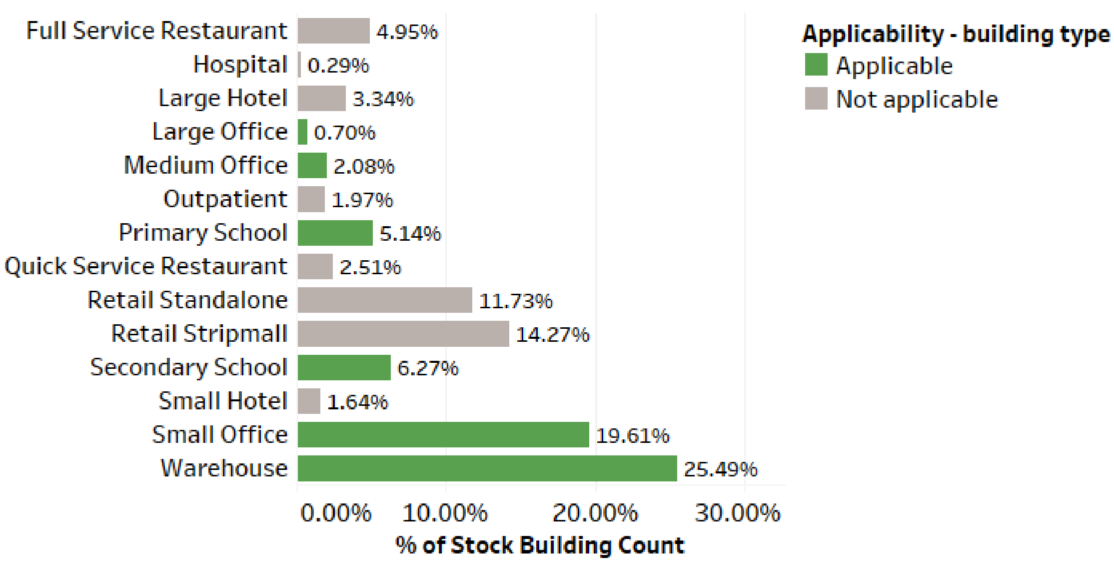

Figure 4. Building count prevalence of building types and applicability for each building type

3.2 Technology Details

3.2.1 Objective Selection and Input Schedule

The peak load reduction objective targets electrical load and applies a load shedding strategy to reduce the daily peak (electric) load of the building. With the selected objective, by applying the method "Dispatch Schedule Generation" described in the "Supplemental Documentation: Dispatch Schedule Generation for Demand Flexibility Measures", a daily load dispatch schedule will be generated and used as the input of this measure. Specifications of parameters for generating the peak schedule are defined in detail in the supplemental documentation. Specifically for the peak load reduction objective, the daily dispatch windows are determined corresponding to the time frame where the predicted daily peak demand is centered.

3.2.2 Lighting Schedule Generation

This measure clones all the schedules that are used for lighting. The cloned schedules are then adjusted by the specified percentage change during the peak window aligned with the input peak schedule. The adjusted schedules will be assigned to the corresponding lighting equipment to replace the original schedules in the model. The measure is flexible and allows users to adjust the dimming percentage, but for this study, the adjustment is set to be an absolute -30% change corresponding to the fully ON operating scenario of the lights by default according to the ASHRAE GEB Guide [33]. For example, if at a given time the original lighting level is 80%, the adjusted level will be 50% instead of 56%. A minimum lighting threshold of 5% is set for this "absolute change" option in case the original lighting level is less than the default adjustment value (<30%), when a complete turn-off is not favorable or acceptable for safety considerations (e.g. corridor light). The option "relative change" is also available for user to select, where the dimming percentage adjustment will correspond to the original lighting level – in the same example above, the adjusted lighting level will then be 56% with this option.

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 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 [30]. Summary statistics from this implementation are shown in Table 3. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 3. 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 2022 EIA averages by state. 2022 U.S. EIA Natural Gas Prices - Commercial Price and U.S. EIA Heat Content of Natural Gas Delivered to Consumers are used to create an energy price in dollars per kBtu [34].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type and U.S. EIA residential Weekly Heating Oil and Propane Prices (October - March) and EIA assumed heat content for these fuels are used to create an energy price in dollars per kBtu [35]. 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 [36]. The URDB rates include detailed cost features such as time-of-use pricing, demand charges, ratches, etc. ComStock only uses URDB rates that were entered starting in 2013, and a cost adjustment factor is applied such that the rates reflect 2022 U.S. dollars.

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

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

For buildings with no URDB electric utility assigned, or for buildings where none of the stored rates are applicable, the annual bill is estimated using the 2022 EIA Form-861 average prices based on the state each model is located in [37]. 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

Below are the limitations and concerns for this measure that have been identified to date.

- 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 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 performance of the measure with dispatch windows perfectly matching to daily peak load represents the "best scenario" of actual implementation of the measure in the real world, where daily peak load might be unpredictable. The differences in performance of different options and the limitations and concerns of the dispatch window generation method described in the "Supplemental Documentation: Dispatch Schedule Generation for Demand Flexibility Measures" also apply to the implementation of this measure. For example, the objective function 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 for determination of the best parameter set(s) for specific building(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 due to low occupancy, while the occupancy distributions in schools are much more complicated and dynamic. 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 the applicability of building types assuming dimming in all contained space types in a building, and upgraded lighting technology to make DF control possible and generalizable. Such selection lost some extend of potential evaluation for a certain number of building types (e.g., hotels) that are not generalizable for now 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 a single building and the grid. We plan to add the objective of bill cost reduction in the future to align the demand control of building with the grid demand management strategy through the medium of utility rates.

- We do not limit the number of days (events) and fix the duration of daily dispatch window for demand response control, as we are investigating the maximum potential of applying DF measures in the stock level, but actual implementation of DF strategy may be far less frequent than daily, such as 10-15 events per season in typical demand response programs, which would impact results. This daily load shedding strategy aims to aggregate individual buildings' daily operations to evaluate the potential demand flexibility in the stock level, given the assumption that operations providing daily load shed are feasible and the affected comfort range is acceptable, even if the economic benefit (bill savings) would be comparatively small.

4 Output Variables

Table 4 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 lighting control for load shedding measure 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 4. 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
median_daily_peak_apr_kw	Median of daily electric peak loads (in kW) in April

Variable Name	Description
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

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
average_of_top_ten_highest_peaks_use_winter_kw	Average peak load of top 10 highest daily electric peak loads during winter season

Variable Name	Description
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

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 or electrification strategy, depending on the use case.

5.1 Single Building Measure Tests

Several single building measure tests are performed to demonstrate the implementation of the developed measure, as shown in the following sections. Specifically, a small office building model is applied as the sample model to evaluate performance, and the test results are shown in five consecutive summer weekdays (7/16-7/20) to illustrate details of the load profiles for comparison.

The default input parameters are summarized in Table 5.

Table 5. Default Options for Measure Parameters

Parameter	Default Lighting Control for Peak Load Reduction
Objective	Peak load reduction
Length of peak window	4 hours
Lighting adjustment method	Absolute percentage change (compared to fully ON)
Lighting level adjustment (on peak)	30% reduced
Load prediction method	Perfect prediction (full baseline simulation)
Peak window determination method	Centered with daily peak

5.1.1 Daily Peak Load Reduction

Figure 5 shows the load profiles and (representative) lighting schedules of the test model from simulations corresponding to baseline (orange dash line) and default upgrade (blue solid line) scenarios for comparison. Comparison between the baseline profile and the load shed window (appearing as valleys) illustrates the timing of the peak window for each day. The variation of peak window timings – morning, noon, and afternoon peaks all present in this representative week – indicates that the measure is capable of tracking the change of daily peak time and adjusting the lighting schedule accordingly, resulting in reduced peak load every day.

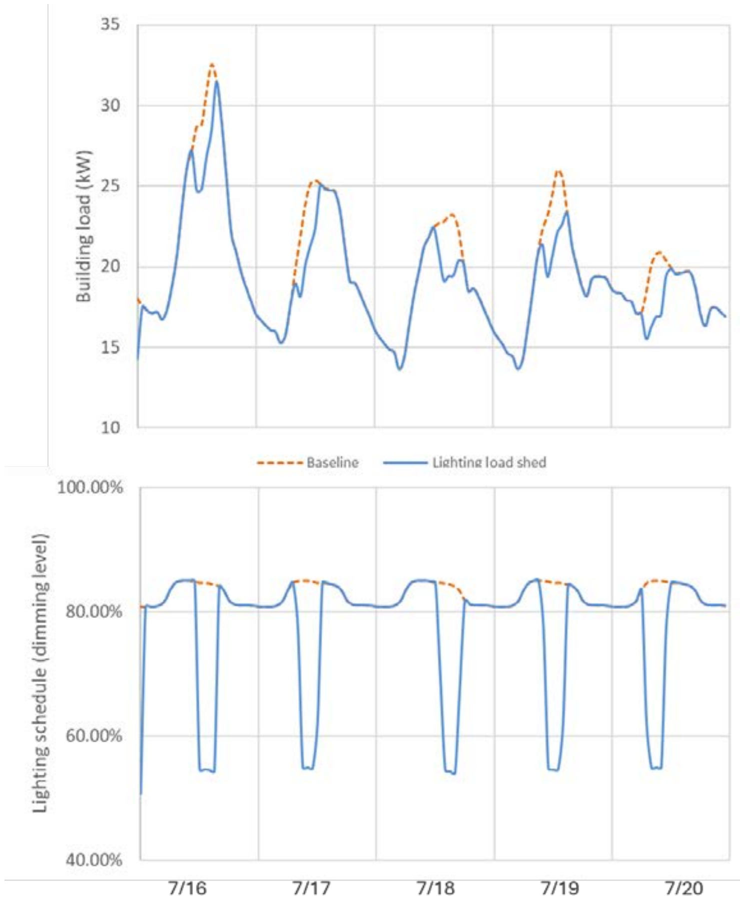

Figure 5. Comparison of load profiles and lighting schedules (baseline and lighting load shed) for peak load reduction objective for test small office model

5.2 Stock Demand Flexibility Performance for Peak Reduction

In this section, we are presenting and discussing stock-level impacts in various prospectives. This section illustrates some aggregated statistics of metrics that are determined to be essential to evaluate the performance of the demand flexibility measure, but they may not depict all of the nuances with demand flexibility.

As the measure aims to reduce daily building peak load, we extract the daily peak load data from the simulation results, which determines the center of the 4-hour demand flexibility window. All applicable models to this measure record 365 daily peaks across the simulation year. For each month (e.g., January), there is a certain number of daily peaks (e.g., 31 daily peak values) available to investigate. To balance the granularity of daily peak data and the visualization level of performance analysis, five quartile statistics (minimum, 25th percentile, median, 75th percentile, and maximum) of daily peak values in each month are calculated for all applicable models to represent the monthly performance of the applied upgrade. These statistics are further illustrated in a boxplot distribution for stock-level summary. Among these statistics, the median and maximum are the two most representative values to evaluate the stock-level performance of the measure.

5.2.1 Monthly Quartile Statistics Distribution of Daily Peak Reduction

Figure 6 and Figure 7 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.

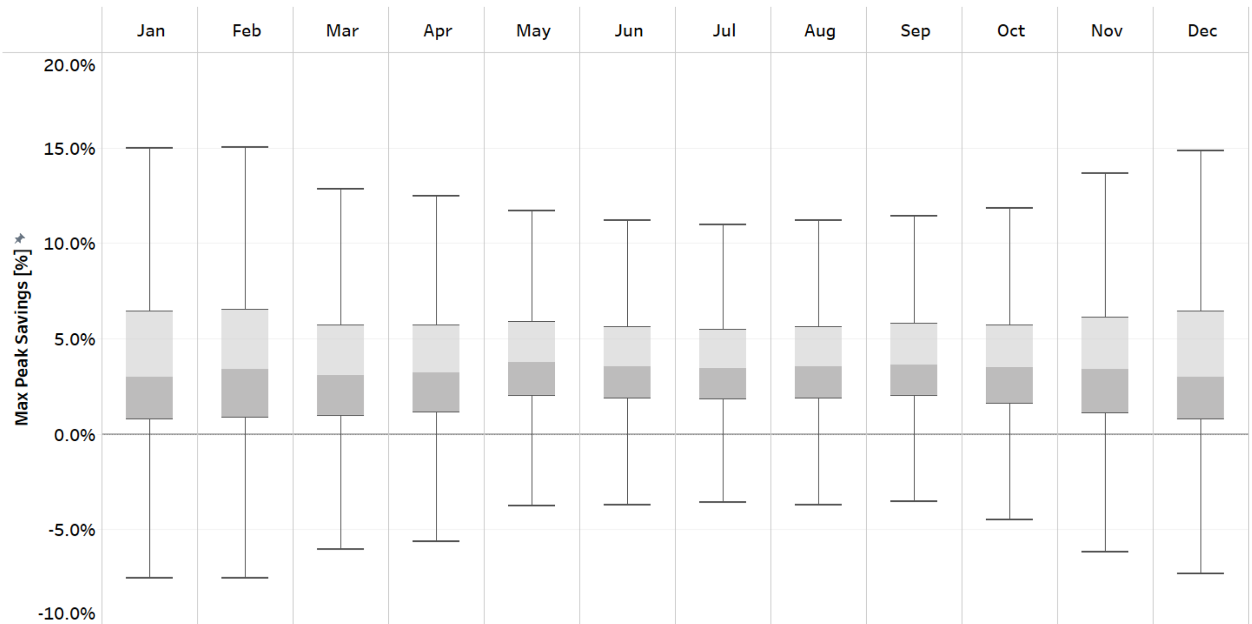

Figure 6. Distributions of the percentage of max daily peak load reduction by month compared to the baseline model

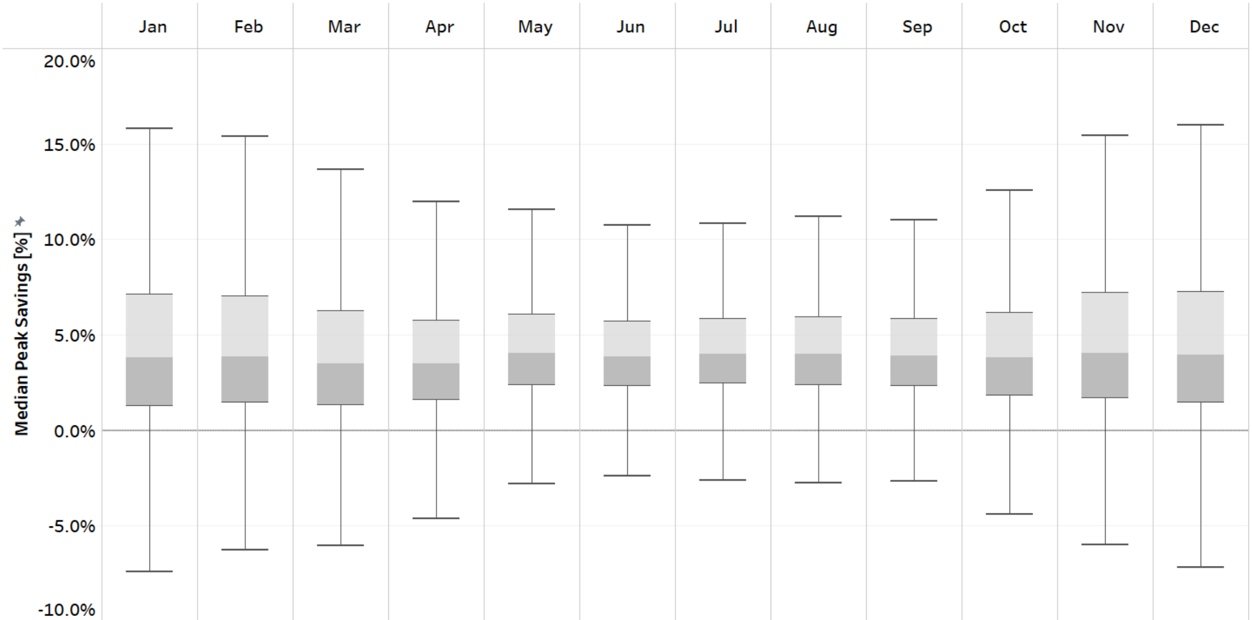

Figure 7. Distributions of the percentage of median daily peak load reduction by month compared to the baseline model

Both distributions of the statistics share overall positive monthly peak reduction patterns. The negative peak reductions are due to the increased (HVAC) heating load and/or fan load resulted from decreased heat emission from lighting equipment during peak hours exceeding the benefits from decreased lighting electricity usage. The heating load is more significant in non-cooling seasons and thus both statistics show larger variances in winter and shoulder seasons. This effect would be seemly impactful in buildings with non-electric heating systems (i.e. natural gas heating), where the baseline total electricity load is so low that a slight increase in fan operation could result in a relatively high (percent) change, which leads to negative peak savings. However, the actual impacts of those negative savings would be negligible as they (mostly) correspond to the minimal electric load days in a year.

5.3 Stock Energy Impacts

The annual energy impacts in stock level are presented in this section, but these are not necessarily the target objective of demand flexibility, and the daily dispatch strategy proposed in this measure may have distinctive impacts compared to other general demand flexibility/response programs. The lighting control for the load shedding measure with peak load reduction objective demonstrates 0.52% total site energy savings (22.5 trillion British thermal units [TBtu]) for the U.S. commercial building stock modeled in ComStock, and 1.10% savings for the applicable buildings. The savings contributions by end use and fuel type are summarized in Table 6 and are illustrated in Figure 8.

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	0.43%	0.90%	21.0
Total Electricity	0.88%	1.78%	27.3
Total Natural Gas	-0.40%	-0.89%	-6.0
Natural Gas Heating	-0.59%	-0.96%	-6.0
Electric Heating	-0.66%	-1.22%	-1.2
Electric Cooling	0.42%	0.84%	3.0
Electric Fans	0.14%	0.30%	0.8
Interior Lighting	5.92%	11.71%	24.7

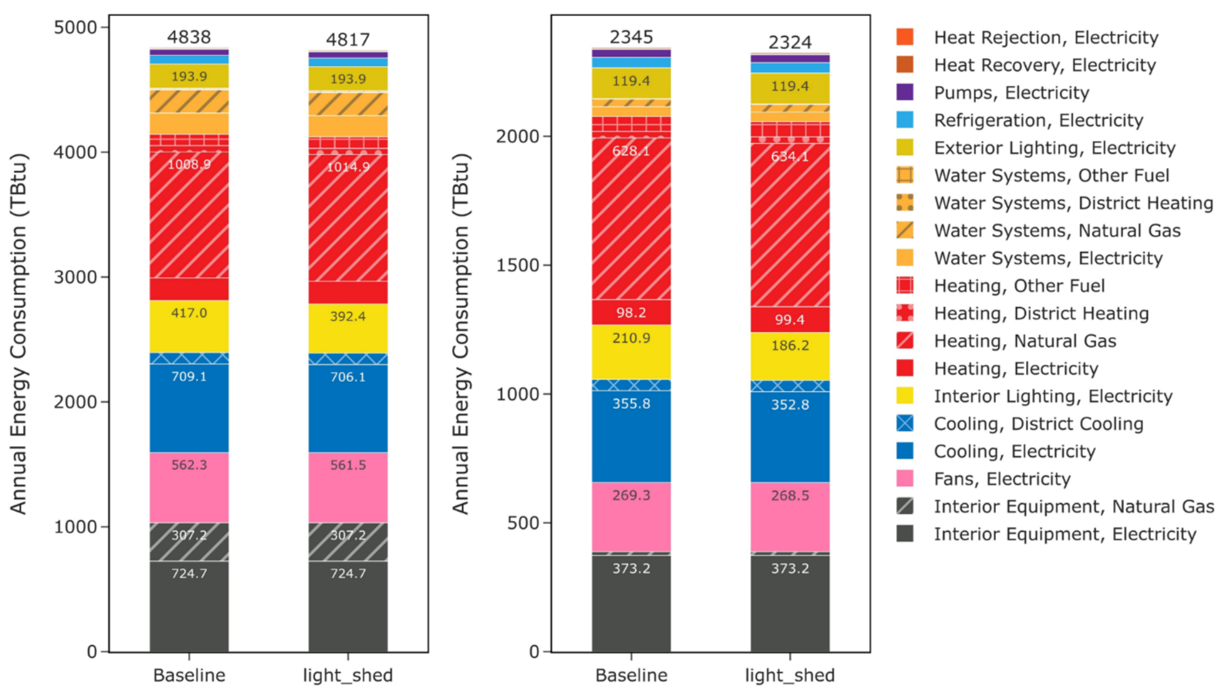

Figure 8. Comparison of annual site energy consumption between the ComStock baseline and the lighting control for load shedding measure scenario, for the whole stock (left) and applicable buildings only (right)

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

The measure focuses on load shed for electric lighting systems in offices, schools and warehouses, so the energy savings are less prominent at the stock level, which includes various non-applicable building types and fuel types. The site energy increase for natural gas and electric heating are mainly attributed to the increased heating load caused by lowered heat gain from lighting equipment, which is expected whenever internal loads are reduced. On the other hand, the cooling load is reduced for the same reason and results in cooling electricity savings. The objective of the measure is to provide demand flexibility by shaving load peaks on a daily basis instead of improving energy efficiency , so the energy savings are treated as side benefits from the measure. However, the developed load shed measure is not exclusive to other energy efficiency measures; it could be integrated with them to provide demand flexibility while saving energy.

5.4 Stock Utility Bill Impacts

This section includes comparison of annual utility bills that buildings are subject to using different energy sources (i.e., electricity, natural gas, propane, fuel oil, etc.), but bill costs are not necessarily the sole objective of demand flexibility. 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 9 shows the bill comparison of baseline and measure impact at the stock level, with respect to the maximum, mean, and median bills among all considered utility rate structures. Overall, it shows consistently around 1% savings among the different rates references, mainly resulting from reduced electricity consumption.

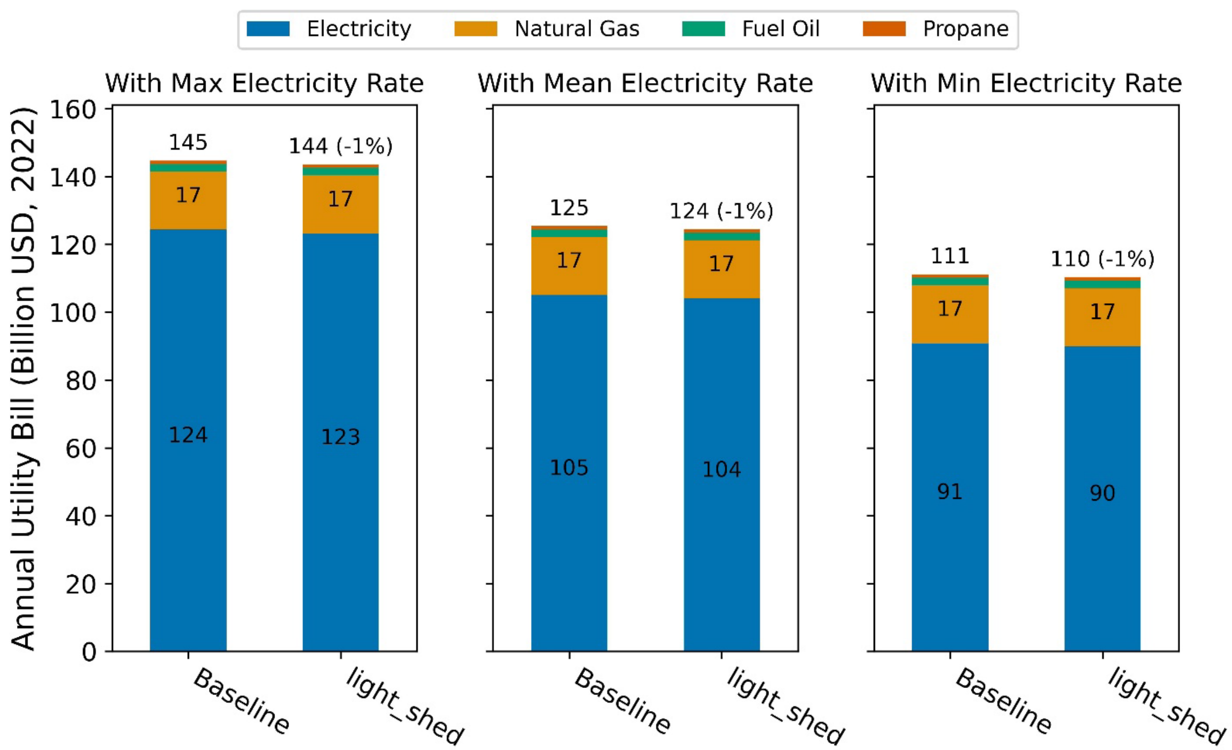

Figure 9. Stock annual utility bill comparison of the ComStock baseline and the lighting control for load shedding scenario

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

Figure 10 presents the distribution of annual bill savings across all applicable buildings and shows slightly better overall savings performance around 2%. Note that the stock level bill savings above are diluted, as 32% of the stock (for building area prospective) is not applicable to the measure.

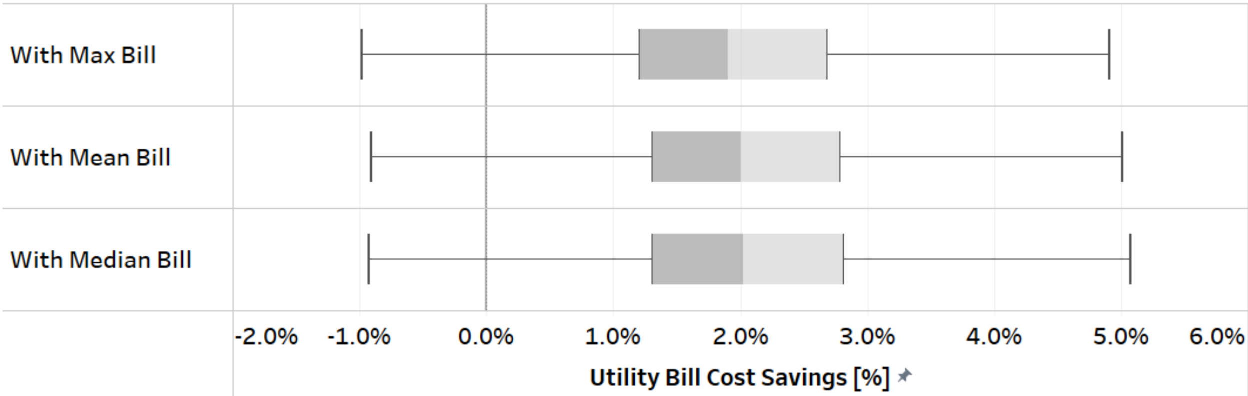

Figure 10. Distribution of annual electricity bill savings compared to the baseline model for maximum, mean, and median bills (for applicable buildings)

Savings corresponding to the max bill are slightly smaller than the mean or median ones, indicating that the rate structure resulting in max bill may benefit less in peak reduction or has no portion related to demand. The bill savings are primarily from:

1) Net energy use reduction (major)

2) TOU rates that have matched time of peak prices with the peak windows on a monthly average (there could be negative savings for TOU rates that have peak prices outside of the daily peak window identified by this measure)

3) Applicable monthly or seasonal demand charge reduction.

These savings underestimate the benefits from a measure targeting daily peak load reduction, as most rate structures consider peak demand charge on a monthly or seasonal basis, while demand response programs or rate structures, including DR incentives that favor daily demand flexibility control, are currently not able to be directly integrated into ComStock analysis.

Figure 11 shows the breakdown of savings by fuel types for applicable buildings. Again, the electricity bill savings result directly from the net savings of reduced lighting electricity consumption and increased heating electricity usage, while the increase in site energy for non-electric fuels is mainly contributed by increased heating demand for non-electric HVAC heating equipment, which present in around 20%-40% applicable floor area depending on building types in the stock level.

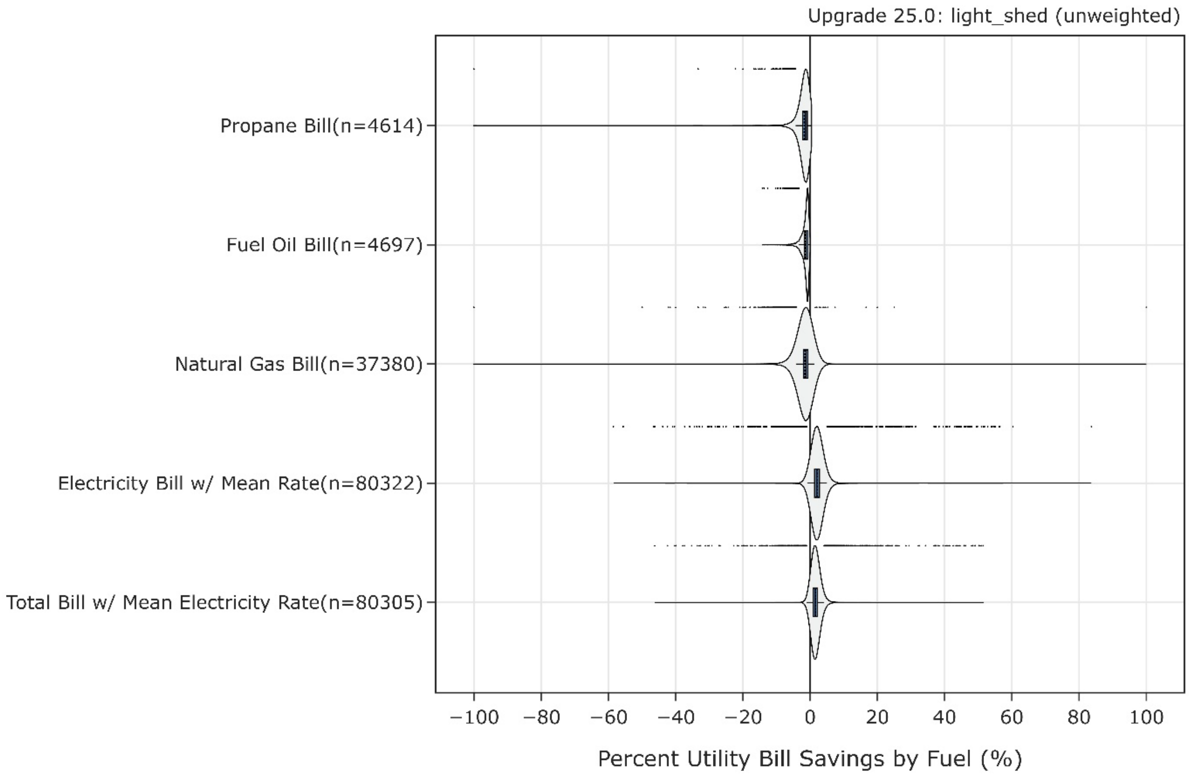

Figure 11. Percent bill savings for ComStock models with the lighting control for load shedding upgrade by fuel types

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.

5.5 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 12 and Figure 13 show the percent site energy and energy use intensity (EUI) savings distributions by end use and fuel types, respectively. Percent savings provide relative impact of the measure at the individual building level, while site EUI savings provide absolute (or aggregated) scale of impact. The breakdowns show consistent conclusions drawn in the energy and bill impact sections (5.3 and 5.5) – the measure benefits mainly from lighting and cooling electricity savings while sacrificing savings from heating energy with various fuel types.

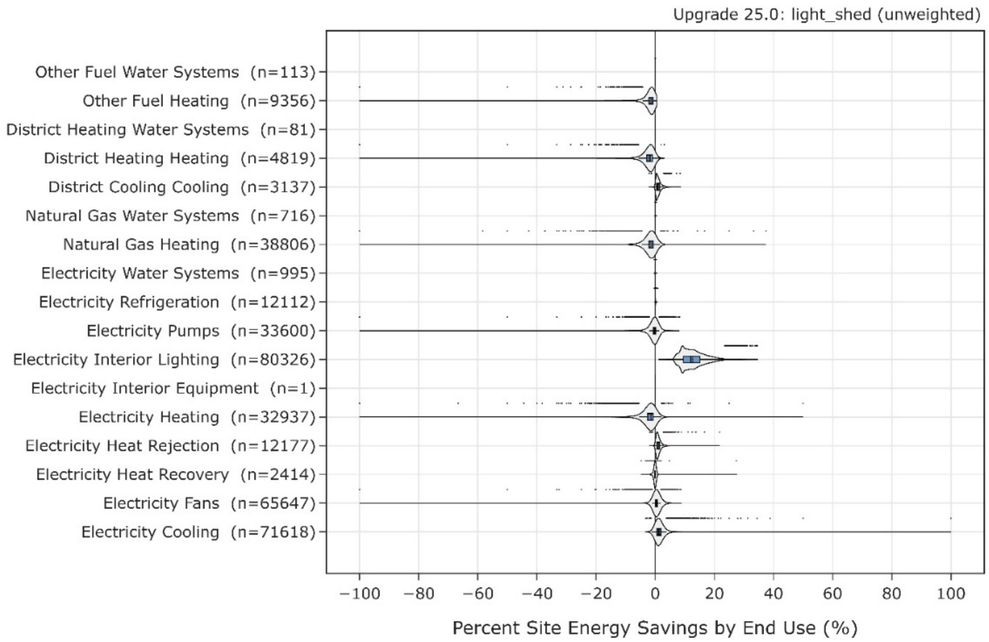

Figure 12. Percent site energy savings distribution for ComStock models with applied measure scenario by end use

The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of ComStock models that were applicable for energy savings for the fuel type category.

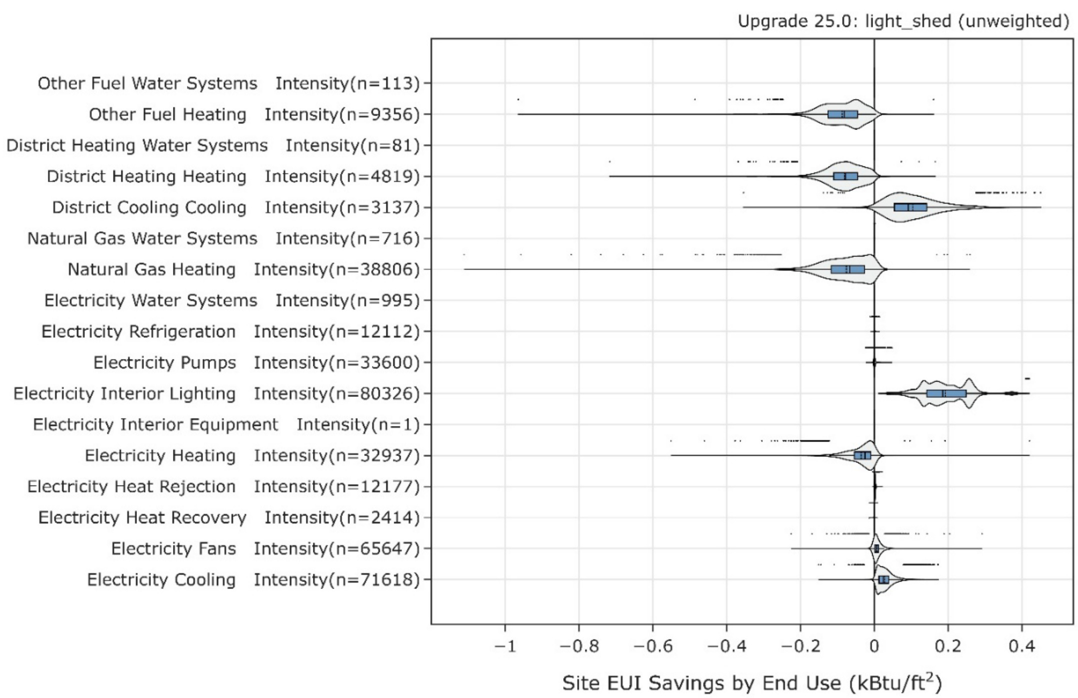

Figure 13. Percent site EUI savings distribution for ComStock models with applied measure scenario by end use

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 A.

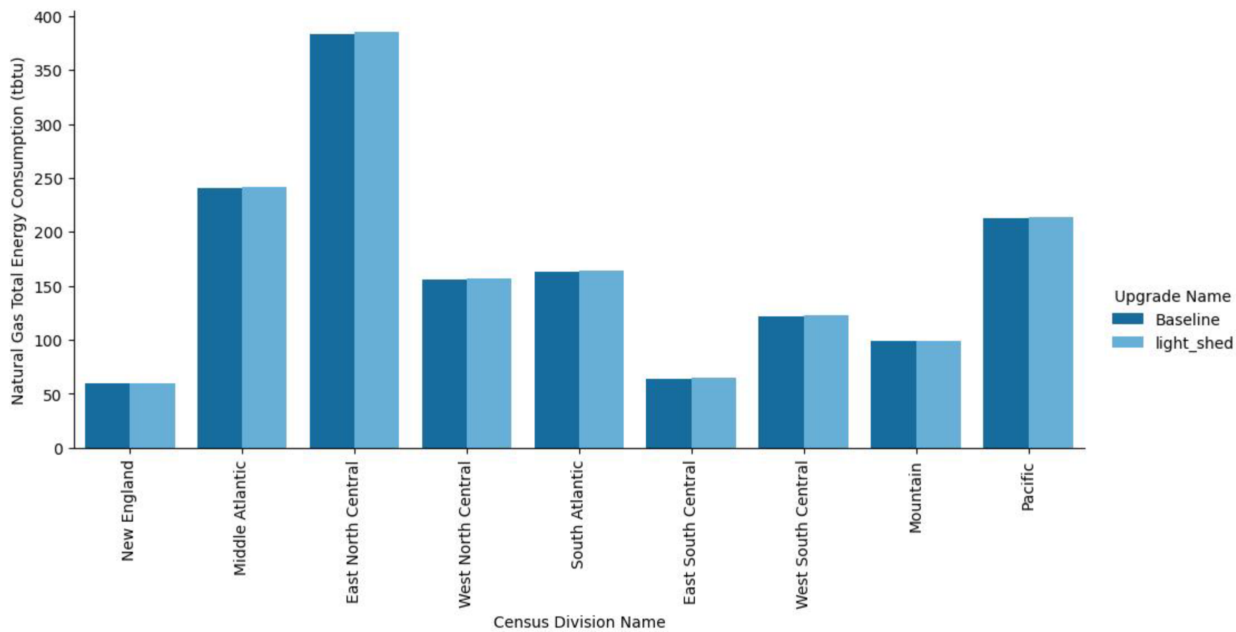

Figure A-1. Site annual natural gas consumption of the ComStock baseline and the measure scenario by census division

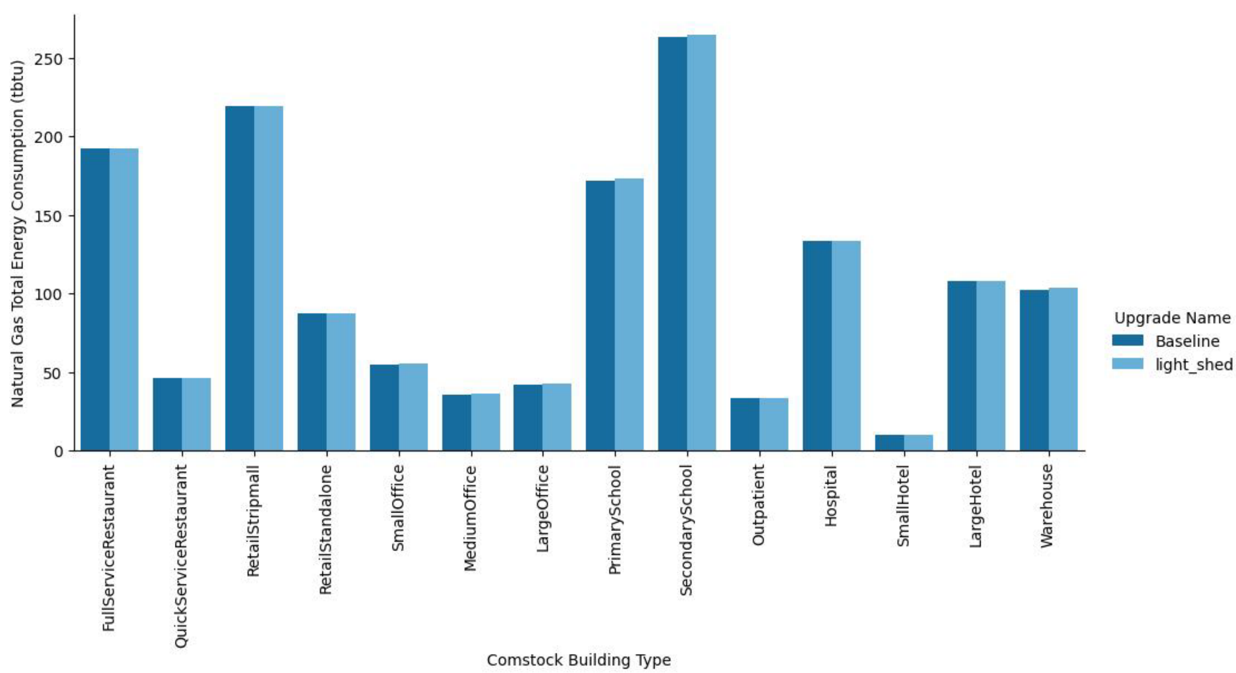

Figure A-2. Site annual natural gas consumption of the ComStock baseline and the measure scenario by building type

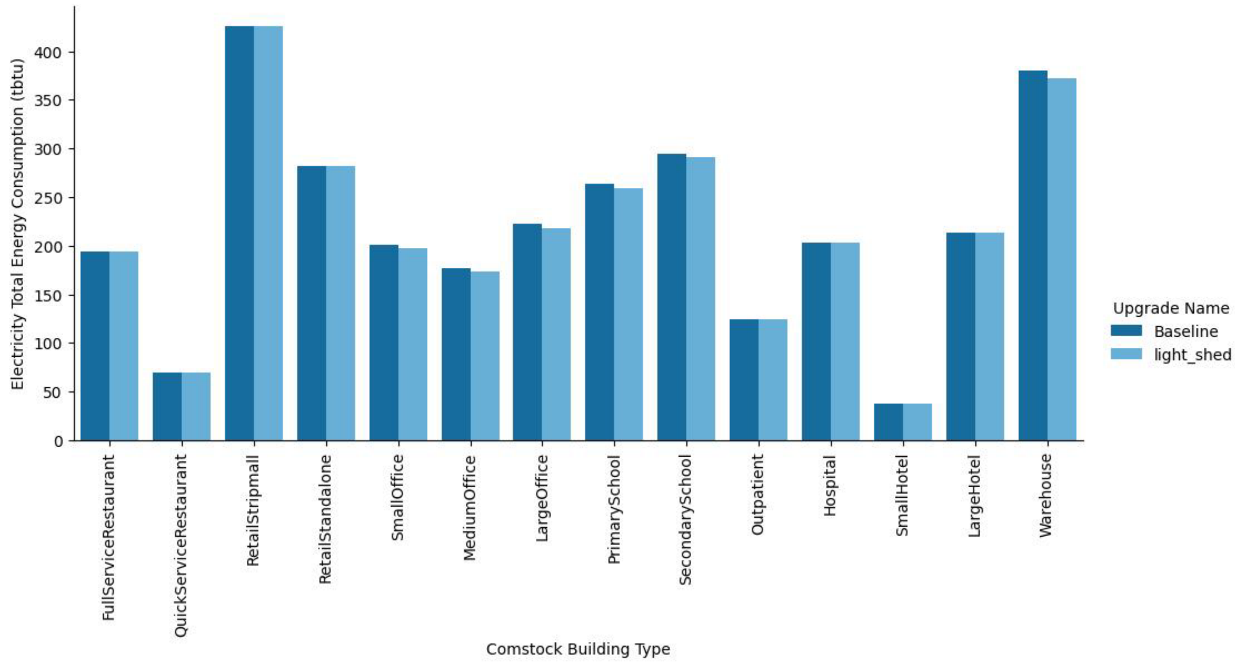

Figure A-3. Site annual electricity consumption of the ComStock baseline and the measure scenario by building type

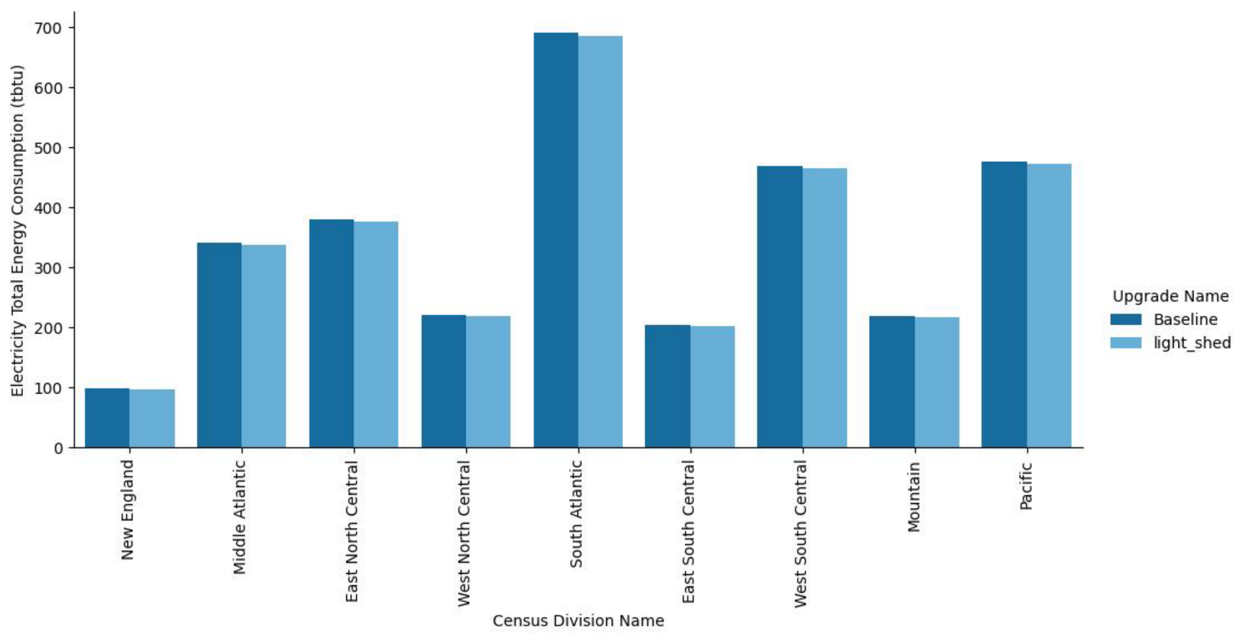

Figure A-4. Site annual electricity consumption of the ComStock baseline and the measure scenario by census division