ComStock Measure Scenario Documentation: Interior Lighting Controls

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Acknowledgments

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List of Acronyms

DEER	Database for Energy Efficient Resources
EFLH	equivalent full load hours
EIA	U.S. Energy Information Administration
kBtu	kilo British thermal unit
kW	kilowatt
kWh	kilowatt-hour
LED	light-emitting diode
LPD	lighting power density
LSM	lighting subcommittee model
TBtu	trillion British thermal units
URDB	Utility Rate Database

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Executive Summary

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

ComStock is a highly granular, bottom-up model that uses various data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual 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 measures that cover market-ready technologies and study their mass adoption impact on the baseline building stock, utility bill affordability, and grid reliability. "Measures" refers to various "what-if" scenarios that can be applied to buildings. The results for the baseline and measure scenario simulations are published in public datasets that provide insights into building stock characteristics, operational behaviors, utility bill impacts, and annual and subhourly energy usage by fuel type and end use.

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

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

Table ES-1. Summary of Key Modeling Specifications

Package Title	Interior Lighting Controls
Technology Description	This measure applies interior lighting controls (daylighting sensors and occupancy sensors) to the model. Daylighting sensors detect the amount of natural light in a space and reduce artificial lighting in the space to maintain a desired brightness level. Occupancy sensors detect the presence of occupants in a space and turn off the lights if no one is present.
Performance Assumptions	• Daylighting sensors are applied to the model using EnergyPlus built-in daylighting controls objects. Some checks are applied to ensure that the size of the window and the size of the space is appropriate for daylighting controls per the International Code Council regulations for Interior Lighting Controls. • Occupancy sensors are modeled as a percent lighting power density reduction based on the space type. The percent reduction in lighting power density was derived from ASHRAE 90.1-2019 "Performance Rating Method Lighting Power Density Allowances and Occupancy Sensor Reductions Using the Space-by-Space Method."
Applicability	• All buildings in the stock will end up getting daylighting controls or occupancy controls in at least one space in the model. Many spaces will get both types of controls.

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Package Title	Interior Lighting Controls
	• Some individual spaces may not receive lighting controls if they a) already have daylighting or occupancy controls, or b) the space does not meet the criteria for lighting controls. • **100% stock floor area applicable**
Release	2025 Release 2: 2025/comstock_amy2018_release_2/

National annual results for site energy and utility bills are summarized in Table ES-2 and Table ES-3.

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

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

Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (Trillion British Thermal Units)
Natural Gas	-1.5%	-1.5%	-24.0
Electricity	3.6%	3.6%	118.3
Other Fuel*	-1.7%	-1.7%	-0.9
Total	1.9%	1.9%	93.4

*Combination of fuel oil and propane annual site energy results

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

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

End Use/Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (Billion USD, 2022)
Natural Gas	-1.5%	-1.5%	-0.3
Electricity	3.5%	3.5%	3.9
Fuel Oil	-2.5%	-2.5%	<0.0
Propane	-1.2%	-1.2%	<0.0
Total	2.8%	2.8%	3.6

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1 Introduction

Lighting control is a method of conserving lighting energy and costs in buildings by reducing or turning off artificial lighting when it is not necessary. There are many types of lighting control methods, including [1]:

- **Daylighting controls**. Reduce lighting usage during daylight hours by dimming or turning off lights in spaces where enough natural light is present
- **Manual dimmers**. Reduce lighting wattage and output when full brightness is not required; some types of lights are not compatible with dimmers, or do not become more efficient when dimmed
- **Occupancy sensors**. Turn on/off lights by detecting indoor activity in a space; occupancy sensors can work in various ways, including detecting sound, heat, or motion
- **Vacancy sensors**. Similar to occupancy sensors, but require occupants to manually turn on the lights
- **Motion sensors**. Turn off lights by detecting when someone walks into a space, then turning them off a short while later; commonly used for security or utility lighting, but not as useful indoors except in infrequently occupied spaces like closets or other storage areas
- **Timers**. Programming lights to turn off or on at certain times; most useful if there are consistent hours when a space is used or not used, but timers do not respond to changes in day-to-day activities
- **Manual control**. The simplest form of lighting control; an occupant turning lights on and off when they are not required.

This measure will implement Daylighting Controls and Occupancy Sensors, as we determined these lighting controls methods to be the most realistic to be implemented in commercial buildings, as well as the most appropriate for modeling in ComStock. The other lighting controls methods listed can be effective in reducing lighting energy use; however, we found there are too many variables that contribute to how these control strategies are deployed and therefore would be difficult to implement effectively in building energy models.

The energy and cost savings potential of lighting controls may vary greatly from building to building. For example, buildings with spaces that are unoccupied for large periods of time can have higher savings potential with occupancy sensors, whereas buildings with large amounts of natural light can benefit more from daylighting sensors. ASHRAE 90.1 and Title 24 standards require lighting controls in some spaces in new construction buildings. This measure will consider that certain spaces may already have code-required lighting controls and will not apply to these spaces. This will be discussed in further detail in Section 3.

In the ComStock baseline, interior lighting accounts for 9% of total stock site energy [2]. Therefore, the energy savings potential for this measure is somewhat limited. However, reducing lighting energy, particularly during unoccupied times or during peak electricity periods, can benefit the grid and save lighting energy and utility costs in commercial buildings. In addition, lighting controls can impact heating, ventilating, and air conditioning energy use, as turning off lighting during summer reduces internal heat gains, and therefore, cooling requirements. However, the reverse is also true—turning off lights in the winter reduces internal gains and increases heating requirements.

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2 ComStock Baseline Approach

Interior lighting in ComStock follows a technology baseline approach, meaning that energy consumed by lighting is set by an assumed distribution of a particular lighting technology (e.g., T8 or linear light-emitting diodes [LEDs]), rather than following a lighting power density (LPD) allowance defined in a specific energy code version. The technology baseline approach recognizes that buildings typically do not use their full lighting power allowance. It also explicitly labels lighting technology and subsystems in the energy model for granular energy efficiency measure analysis. Two components specify interior lighting: the lighting power density and the interior lighting schedule. The lighting power density is determined by the distribution of lighting technologies in the stock, the lighting technology properties, and the space type properties. The lighting schedule is determined by a default lighting schedule by space type, occupancy hour adjustments, and magnitude variability. The ComStock lighting baseline approach is documented thoroughly in the ComStock Reference Documentation [3] and the LED Lighting measure documentation [4].

2.1 Lighting Technology

ComStock interior lighting in the baseline is determined using a lighting 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. Lighting generations are assigned to each building model during sampling based on the year of the last interior lighting replacement and the energy code in force during that year.

Table 1. Lighting Generations and Associated Technologies for Each Category. Table from [4].

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

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2.2 Lighting Power

The technology baseline approach follows a similar process to how the ASHRAE 90.1 lighting subcommittee determines the LPD allowance for a given space type in ASHRAE 90.1. In the lighting subcommittee model (LSM), four categories of lighting are considered when estimating the lighting needed to meet the target horizontal illuminance for a space:

- General Lighting
- Task Lighting
- Supplemental Lighting
- Wall Wash Lighting.

Values for all of these terms are specified in the LSM. The LSM is exact, using a specific lighting product, room geometry, distribution of lighting systems, and other properties to determine the LPD allowance for a given space type (in units of power per square foot). ComStock uses the LSM approach as a baseline for determining LPDs, but makes several modifications to the calculations, which are documented in detail in the ComStock Reference Documentation [3]. Table 2 provides the average installed building-level LPDs in ComStock by building type and lighting generation.

Table 2. Average Building-Level Lighting Power Densities (watt/square foot) by Lighting Generation and Building Type. Table from [4].

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

2.3 Lighting Schedules

Modeling all buildings using the same average lighting schedule is not realistic, especially when the focus is narrowed to a certain building type, region, and end use. For example, varying characteristics such as different operating hours (i.e., when a building starts and ends its business operation), different peak timing (i.e., when a building has the highest demand during the day),

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and different levels of baseload (i.e., how much electricity is used during unoccupied hours) should be captured to reflect the realistic performance of buildings in the stock. To reflect this variation in building operation in the models for interior lighting usage in commercial buildings, we used the standardized end-use data from the End Use Load Profiles effort to derive a distribution of building schedule characteristics. A distribution of operating hours and a base-to-peak ratio metric was derived from measured data and then used as an input to the ComStock workflow. Schedules for weekends and weekdays are modeled differently, as is realistic in most commercial building types. In addition, space types within a model can have different lighting schedules and LPDs; however, the base-to-peak ratio is assigned at the building level.

2.4 Interior Lighting Controls

ComStock has limited prevalence of interior lighting controls in the baseline, which are based on daylighting sensor requirements set in the ANSI/ASHRAE/IES Standard 90.1 [5] (for simplicity, referred to as "ASHRAE 90.1" throughout this document)[1] and Title 24 standards [6] [7]. Daylighting sensors are present in baseline models that are constructed with an energy code of ASHRAE 90.1-2010 or newer. In California, where the Title 24 series of codes is used and models are based off Database for Energy Efficient Resources (DEER) templates, daylighting sensors are added in models constructed with energy code DEER 2014 or newer. In total, the buildings with these newer energy codes only make up 2.1% of the stock floor area; therefore, daylighting sensors have relatively limited prevalence in the ComStock baseline.

In addition, daylighting sensors are not present in every space in those models. There are several criteria that must be met for daylighting sensors to be added to a space, which are derived by the International Code Council 9.4.1.1 - Interior Lighting Controls [8] [9]. These criteria include thresholds for the size of the space, size of the window, minimum lighting power, effective aperture, and other requirements. All this logic is built into the openstudio-standards library [10], such that the daylighting sensors modeled in ComStock models follow the requirements of existing codes and standards. Daylighting sensors in both the baseline and the Interior Lighting Controls upgrade measure leverage the built-in openstudio-standards methods for consistency and accuracy.

Occupancy controls are not explicitly modeled in the ComStock baseline. In many spaces and building types, the lighting schedule is reduced during nights and weekends when the building is unoccupied. In some ways, this nighttime schedule reduction reflects the concept of occupancy controls but is more likely a reflection of manual or timed lighting controls in which the lights are turned off during nonbusiness hours. True occupancy controls would mean that lights could turn off periodically throughout the day in unoccupied spaces using sensors. This level of detail is very difficult to capture in energy models (which cannot accurately model the movement of people throughout a building). Therefore, the methodology chosen for model occupancy controls is a simplified approach and will be described in the next section.

[1] ANSI: American National Standards Institute; IES: Illuminating Engineering Society

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3 Modeling Approach

3.1 Applicability

This measure combines two lighting controls techniques: daylighting controls and occupancy sensors. Each type of lighting control will have its own applicability criteria, but when combined, this measure is applicable to 100% of the stock. We deem a building model to be applicable to this measure if at least one space in the model receives either daylighting controls, occupancy sensors, or both. In a vast majority of buildings, there are many spaces that will end up receiving one or both lighting controls.

3.1.1 Daylighting Controls

The applicability for daylighting controls is determined using a modified approach to the International Code Council 9.4.1.1 criteria defined in the previous section [9]. For daylighting controls to be *required by code* in a space, it must meet a handful of criteria including minimum thresholds for space size, window size, lighting power, and effective aperture. In this upgrade measure, we loosened these criteria because this measure is meant to reflect a building optionally installing daylighting controls for energy/cost savings purposes, as opposed to just meeting the code minimum requirements. Therefore, to apply daylighting sensors in this upgrade measure, the space only needs to meet the space size and window size thresholds. This was chosen to avoid unrealistic scenarios wherein a daylighting sensor is installed in a tiny space or a space with no windows. However, the minimum lighting power and effective aperture criteria were not used in the upgrade scenario. Daylighting sensors were added to at least one space in 91% of models.

3.1.2 Occupancy Sensors

Applicability for occupancy sensors is determined based on ASHRAE 90.1-2019 Table G3.7 – Performance Rating Method Lighting Power Density Allowances and Occupancy Sensor Reductions Using the Space-by-Space Method [11]. This table defines a percent LPD reduction for common space types to represent the effects of occupancy sensors. Hence, occupancy controls are applied to a model on a space-by-space basis. The specifics of this methodology will be discussed in more detail in subsequent sections. In total, occupancy controls were applied to at least one space in 100% of models.

3.2 Measure Scenario Modeling Methodology

3.2.1 Daylighting Controls

Daylighting controls in ComStock are modeled using built-in methods from the openstudio-standards library [10], mainly the model_add_daylighting_controls method. This method automates the process of adding daylighting controls to spaces in a model based on several criteria related to geometry, lighting power, etc. There are three types of daylighting control zones modeled, each of which come with specific criteria to be required in a space [9] [12]:

- **Primary sidelighting control.** Zones adjacent to exterior vertical fenestration; must meet window and space size criteria, as well a minimum lighting power threshold

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- **Secondary sidelighting control.** Zones deeper into a space beyond the primary sidelit zone; must meet window and space size criteria, as well a minimum lighting power threshold
- **Toplighting control.** Zones where skylights are present; must meet the space size criteria and minimum lighting power threshold.

Primary sidelighting control is the most common type of daylighting control and is most commonly required by codes and standards. When this method is applied in ComStock, the measure loops through each space, evaluating the sidelighting and toplighting zone criteria, and determining which daylighting controls are required for a given space. Note that skylights are not modeled in ComStock, therefore toplighting control will never be required in this measure scenario. The criteria in this measure were loosened such that more zones receive daylighting controls than just those specifically required by code. Therefore, to apply daylighting sensors in this upgrade measure, the space only needs to meet the space size and window size thresholds. This was chosen to avoid unrealistic scenarios where a daylighting sensor is installed in a tiny space or a space with no windows. The other criteria, such as minimum lighting power and effective aperture, were not used in the upgrade scenario. This allows daylighting sensors to be applied in more zones for the purpose of evaluating maximum energy savings for this control strategy.

Once the daylight control requirements are determined for each space, the openstudio-standards method sets an illuminance setpoint (typically 375 lux) and other lighting control parameters for the space. Then, it adds two daylighting sensors to the zone, which detect light properties in the space during each time step and inform the lighting object and schedule if daylight is sufficiently lighting the space. The locations of the sensors are calculated within the method, typically one closer to the window and one deeper into the space. The sensors assume a three-tier stepped dimming approach. In addition, it assumes several other parameters, such as a maximum glare index, to assess and optimize visual comfort in the space. For more details about the built-in daylighting methods, see the openstudio-standards repository.

3.2.1.1 Excluded Spaces

As mentioned previously, a space must meet floor area and window area requirements for daylighting sensors to be added. The main requirement that comes into play for determining if daylighting controls will be added is that the window area in a space must be 20 square feet or larger. In spaces with insufficient window area, daylighting sensors would not be very impactful.

When applying daylighting controls to the model, the measure will also omit any spaces that already have daylighting controls present. In the baseline of ComStock, daylighting controls are added to some spaces in buildings with a template of ASHRAE 90.1-2010 or newer, and DEER 2014 or newer. However, these buildings make up roughly 2% of floor area of ComStock, so daylighting controls are added to a vast majority of the stock in spaces that meet the geometry criteria.

3.2.2 Occupancy Sensors

Occupancy sensors are more difficult to represent realistically in energy modeling. Occupancy is modeled in ComStock as an occupant density per space type. Occupancy schedules represent the

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fraction of the full occupancy that is present during each hour of the day. Occupancy schedules in the baseline are already coordinated with lighting schedules, such that when occupancy is low, the lighting schedule is likely already reduced at that time. In a way, this represents the concept of occupancy sensors but is more so just a reflection of manual or timed lighting controls in which the lights are turned off during nonbusiness hours. True occupancy controls would mean that lights could turn off periodically throughout the day in unoccupied spaces using sensors by monitoring sound, heat, or motion. This level of detail is very difficult to capture in energy models (which cannot accurately model the movement of people throughout a building).

ASHRAE 90.1-2019 (Table G3.1 – Modeling Requirements for Calculating Proposed and Baseline Building Performance) defines modeling requirements for automatic lighting controls, including occupancy sensors [11]. This methodology involves "reducing the lighting schedule each hour by the occupancy sensor reduction factors in Table G3.7." Table G3.7 – Performance Rating Method Lighting Power Density Allowances and Occupancy Sensor Reductions Using the Space-by-Space Method defines a percent reduction in LPD for many different space types [11]. The space types in Table G3.7 were mapped to ComStock space types to determine the percent LPD reduction to be applied in the model. Table 3 lists each space type modeled in ComStock building types (including DEER models, which are used in California buildings), as well as the percent LPD reduction due to occupancy sensors derived from ASHRAE 90.1-2019.

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Table 3. LPD Reduction by Space Type as Defined in ASHRAE 90.1-2019 Table G3.7 [11]

Building Type	Space Type	% LPD Reduction
	Auditorium	10
	Cafeteria	35
	Classroom	30
	ComputerRoom	25
	Corridor	25
	Gym	35
	Kitchen	30
	Library	15
	Lobby	25
	Mechanical	30
	Office	15
SecondarySchool	Restroom	45
	Cafeteria	35
	Classroom	30
	ComputerRoom	25
	Corridor	25
	Gym	35
	Kitchen	30
	Library	15
	Lobby	25
	Mechanical	30
	Office	15
PrimarySchool	Restroom	45
SmallOffice	WholeBuilding - Sm Office	15
	WholeBuilding - Md Office	15
MediumOffice	OfficeLarge Data Center	0
	WholeBuilding - Lg Office	15
LargeOffice	OfficeLarge Data Center	0
	OfficeLarge Main Data Center	0
	Corridor	25
	Elec/MechRoom	30
	ElevatorCore	0
	Exercise	35
	GuestLounge	0
	GuestRoom123Occ	0
	GuestRoom123Vac	45
	Laundry	10
	Mechanical	30
	Meeting	0
	Office	15
	PublicRestroom	45
	StaffLounge	0
	Stair	75
SmallHotel	Storage	45
	Banquet	35
	Basement	0
	Cafe	35
	Corridor	25
	GuestRoom	45
	Kitchen	30
	Laundry	10
	Lobby	25
	Mechanical	30
	Retail	0
LargeHotel	Storage	45
	Bulk	45
	Fine	45
Warehouse	Office	15
	Back_Space	10
	Entry	0
	Point_of_Sale	0
RetailStandalone	Retail	10

	Strip mall - type 1	10
	Strip mall - type 2	10
	Strip mall - type 3	10
	Dining	35
RetailStripmall	Kitchen	30
	Dining	35
QuickServiceRestaurant	Kitchen	30
	Dining	35
FullServiceRestaurant	Kitchen	30
	Basement	0
	Corridor	25
	Dining	35
	ER_Exam	10
	ER_NurseStn	10
	ER_Trauma	10
	ER_Triage	10
	ICU_NurseStn	10
	ICU_Open	10
	ICU_PatRm	10
	Kitchen	30
	Lab	10
	Lobby	25
	NurseStn	10
	Office	15
	OR	10
	PatCorridor	25
	PatRoom	10
	PhysTherapy	10
Hospital	Radiology	10
	Anesthesia	10
	BioHazard	10
	Cafe	35
	CleanWork	10
	Conference	0
	DressingRoom	10
	Elec/MechRoom	30
	ElevatorPumpRoom	0
	Exam	10
	Hall	25
	IT_Room	25
	Janitor	45
	Lobby	25
	LockerRoom	25
	Lounge	0
	MedGas	10
	MRI	10
	MRI_Control	10
	NurseStation	10
	Office	15
	OR	10
	PACU	10
	PhysicalTherapy	10
	PreOp	10
	ProcedureRoom	10
	Reception	25
	Soil Work	10
	Stair	75
	Toilet	45
	Undeveloped	0
Outpatient	Xray	10

	Classroom	30
	CorridorStairway	25
	Dining	35
	Gymnasium	35
DEER Education Primary School	Kitchen	30
	Classroom	30
	CompRoomClassRm	25
	CorridorStairway	25
	Dining	35
	Gymnasium	35
	Kitchen	30
DEER Education Secondary School	OfficeGeneral	15
	DEER HospitalSurgOutptLab	10
	Dining	35
	Kitchen	30
	OfficeGeneral	15
DEER Hospital	PatientRoom	10
	Dining	35
	BarCasino	35
	HotelLobby	25
	OfficeGeneral	15
	GuestRmCorrid	25
	Laundry	10
	GuestRmOcc	0
	GuestRmUnOcc	45
DEER Hotel	Kitchen	30
	OfficeGeneral	15
	GuestRmCorrid	25
	Laundry	10
	GuestRmOcc	0
DEER Motel	GuestRmUnOcc	45
	LobbyWaiting	25
	OfficeSmall	30
	OfficeOpen	15
DEER Office Large	MechElecRoom	30
	Hall	25
DEER Office Small	OfficeSmall	30
	Dining	35
	Kitchen	30
	LobbyWaiting	25
DEER Restaurant Fast Food	Restroom	45
	Restroom	45
	Dining	35
	LobbyWaiting	25
DEER Restaurant Sit Down	Kitchen	30
DEER Retail Three Story	RetailSales	0
	OfficeGeneral	15
	Work	10
	StockRoom	45
	RetailSales	0
DEER Retail Large	Kitchen	30
	RetailSales	0
DEER Retail Small	StockRoom	45
DEER Storage Conditioned	WarehouseCond	45
DEER Storage Unconditioned	WarehouseUnCond	45

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As a reminder, ComStock models several different types of lighting, including General Lighting, General Lighting (High Bay), Task Lighting, Supplemental Lighting, and Wall Wash Lighting. We made the decision to apply the occupancy sensor LPD reductions only to General Lighting (including High Bay) objects in the model. This is because occupancy sensors are unlikely to be connected to task lights, wall wash lighting, or other forms of specialized supplemental lighting. The measure loops through each space and applies the percent LPD reduction to all General Lighting objects. As a result, the LPD will be reduced by the specified percentage during each hour of the day, in alignment with the ASHRAE 90.1 methodology for modeling occupancy sensors.

3.2.2.1 Excluded Spaces

Newer versions of ASHRAE 90.1 and Title 24 require certain spaces to have *automatic full-off* lighting controls (i.e., occupancy sensors) [5] [6] [7]. To ensure that we are not inadvertently double counting the impacts of occupancy sensors, we will omit spaces that are already required by code to have occupancy sensors. To do this, the measure will look up the energy code followed by the building at the time of construction. Then, we will use a lookup table that lists which space types are already required to have occupancy sensors and skip those spaces when applying the LPD reductions.

The list of spaces required to have occupancy sensors is shown in Table 4. This table includes both 90.1 and DEER templates, so DEER building types/space types (California models) are mapped to occupancy sensor requirements from Title 24. Note that occupancy sensors started becoming required in the 90.1-2004 and DEER 2011 templates, so older templates are not shown. As can be seen, as we move to newer code versions, more spaces start requiring occupancy sensors. However, buildings built with these newer code versions do not have a large prevalence in the ComStock dataset (roughly 2% of floor area). Therefore, most buildings will still get occupancy sensors in most spaces.

Table 4. Occupancy Control Requirements by Building Type/Space Type and ASHRAE 90.1 and DEER Template [5] [6] [7]

Building Type	Space Type	Required by 90.1-2004	Required by 90.1-2007	Required by 90.1-2010	Required by 90.1-2013	Required by DEER 2011	Required by DEER 2014	Required by DEER 2015	Required by DEER 2017
SecondarySchool	Auditorium			Yes	Yes				
SecondarySchool	Classroom			Yes	Yes				
SecondarySchool	ComputerRoom			Yes	Yes				
SecondarySchool	Restroom			Yes	Yes				
PrimarySchool	Classroom			Yes	Yes				
PrimarySchool	ComputerRoom			Yes	Yes				
PrimarySchool	Restroom			Yes	Yes				
SmallHotel	GuestLounge				Yes				
SmallHotel	Meeting	Yes	Yes	Yes	Yes				
SmallHotel	PublicRestroom			Yes	Yes				
SmallHotel	StaffLounge	Yes	Yes	Yes	Yes				
SmallHotel	Storage			Yes	Yes				
LargeHotel	Banquet				Yes				
LargeHotel	Storage			Yes	Yes				
RetailStandalone	Back_Space			Yes	Yes				
Outpatient	Conference	Yes	Yes	Yes	Yes				
Outpatient	DressingRoom			Yes	Yes				
Outpatient	Janitor			Yes	Yes				
Outpatient	LockerRoom			Yes	Yes				
Outpatient	Lounge				Yes				
DEER Education Primary School	Classroom					Yes	Yes	Yes	Yes

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Building Type	Space Type	Required by 90.1-2004	Required by 90.1-2007	Required by 90.1-2010	Required by 90.1-2013	Required by DEER 2011	Required by DEER 2014	Required by DEER 2015	Required by DEER 2017
DEER Education Secondary School	Classroom					Yes	Yes	Yes	Yes
DEER Education Secondary School	CompRoomClassRm					Yes	Yes	Yes	Yes
DEER Office Large	OfficeSmall					Yes	Yes	Yes	Yes
DEER Office Small	OfficeSmall					Yes	Yes	Yes	Yes
DEER Restaurant Fast Food	Restroom						Yes	Yes	Yes
DEER Restaurant Sit Down	Restroom						Yes	Yes	Yes

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 [3]. Summary statistics from this implementation are shown in Table 5. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 5. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural Gas	$0.007/kilo British thermal unit (kBtu) ($0.70/therm)	$0.012/kBtu ($1.20/therm)	$0.048/kBtu ($4.80/therm)
Propane	$0.022/kBtu ($2.20/therm)	$0.032/kBtu ($3.20/therm)	$0.052/kBtu ($5.20/therm)
Fuel Oil	$0.027/kBtu ($2.70/therm)	$0.033/kBtu ($3.30/therm)	$0.036/kBtu ($3.60/therm)
Electricity	$0.003/kBtu ($0.01/kilowatt-hour [kWh])	$0.035/kBtu ($0.12/kWh)	$3.530/kBtu ($12.04/kWh)

Natural gas bills are estimated using 2022 EIA averages by state. 2022 EIA Natural Gas Prices - Commercial Price and EIA Heat Content of Natural Gas Delivered to Consumers are used to create an energy price in dollars per kilo British thermal unit (kBtu) [13].

Propane and fuel oil bills are estimated using 2022 EIA averages by state. Residential No. 2 Distillate Prices by Sales Type and 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 [14]. 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 were used directly. For other states, Petroleum-Administration-for-Defense-District-average pricing is used. For states where that level of pricing is not available, national average pricing is used.

The primary resource for ComStock electric utility rates is the Utility Rate Database (URDB) [15], which includes rate structures for about 85% of the buildings and 85% of the floor area in

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ComStock [3]. The URDB rates include detailed cost features such as time-of-use pricing, demand charges, ratchets, etc. ComStock only uses URDB rates that were entered starting in 2013, and a cost adjustment factor is applied such that the rates reflect 2022 U.S. dollars.

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

Many precautions are implemented to prevent less reasonable rates from being applied. This includes removing 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 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 [16]. 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

There are several modeling considerations to note when describing the implementation of this measure. First, as discussed in the Modeling Methodology section, the true behavior of occupancy sensors is difficult to capture in energy modeling because occupancy is modeled as a static schedule per space. In reality, the occupancy in each space will vary constantly as occupants move throughout the building, allowing occupancy sensors to control the lights in individual spaces. This measure was implemented by applying a flat LPD reduction to each space, as determined in ASHRAE 90.1-2019 Table G3.7 [11]. While this implementation does not capture the nuances of the controls, we believe that on an aggregate level it captures the energy impacts of occupancy sensors. This implementation could be improved in the future; however, for now this is the methodology chosen for this measure based on available research and data.

A second limitation relates to the way spaces and space types are modeled in ComStock, which is dependent on building size and type. Space types are represented within a rectangular geometry as "slices" through the building that correspond to the floor area fractions of each space type. In very small buildings, this can result in spaces that are unrealistically long and narrow for space types that make up only a small fraction of the building. This zoning is not ideal for daylighting analysis because it will result in thin slivers of window in some space types.

For larger buildings where the length and width are both greater than 37.5 feet, each space type is divided into core and perimeter thermal zones with a 15-foot perimeter depth. This approach better captures heat imbalances near windows and is therefore more realistic for approximating daylighting effects.

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In small, medium, and large offices, ComStock models a whole building office space type rather than more specific space types such as conference rooms, open office, closed office, restroom, etc. Therefore, occupancy sensors are applied using a flat 15% LPD reduction across the building (corresponding to the recommended LPD reduction for open offices). The only exception to this whole building space type is data center spaces, which are modeled separately and make up a small fraction of floor area in some medium and large offices. Similarly, daylighting controls are applied to these large whole building office spaces, but we do not break out into many individual spaces for applying lighting controls.

A third minor limitation to note is that in California buildings, some windows are modeled with automated blinds. Blinds help reduce internal heat gains during the hottest/sunniest periods of the day; however, they can counteract the effects of daylighting sensors, which are also most effective during these same parts of the day. The blinds in ComStock California buildings are modeled using sensors in the space, which we noticed caused unwanted interactions with the daylighting sensors added by this measure. For this reason, we made the decision not to add daylighting sensors to spaces with blinds. Realistically, the daylighting sensors would have very limited effect in these spaces, because the blinds would be down during the periods when the daylighting sensors would have been able to reduce lighting. Therefore, we decided this was a fair compromise; however, it must be noted in the limitations of this measure.

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4 Output Variables

Table 6 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 Interior Lighting Controls 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 6. Output Variables Calculated From the Measure Application

Variable Name	Description
Interior Lighting Generation	Lighting generation of the lights in the building (see Table 1)
Interior Lighting Power Density	Interior lighting power density (watt/square foot)
Interior Lighting Equivalent Full Load Hours (EFLH)	Annual interior lighting equivalent full load hours (hours)
Daylight Control Fraction	Fraction of building lighting by floor area that is controlled by daylight sensors

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5 Results

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

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

5.1 Single Building Measure Tests

This section demonstrates the impacts of the Interior Lighting Controls measure on a 90,000-square-foot warehouse test model in Denver, Colorado. This model has three space types— Bulk Storage, Fine Storage, and Office—and an 18% window-to-wall-ratio. The storage spaces make up most of the floor area. This section will walk through the checks that were done to ensure the measure is properly applied and evaluating the impacts of the individual lighting types of controls.

Four scenarios were run on this single model: Baseline, Daylighting Controls Only, Occupancy Controls Only, and Daylighting + Occupancy Controls (i.e., the implementation of the Interior Lighting Controls measure scenario). For each scenario, Table 7 shows the building's annual lighting, heating, and cooling energy for each scenario, as well as the electricity peak for the year. In this model, the occupancy controls have a larger impact on energy and peak savings compared with the daylighting controls.

Daylighting controls were added to all three space types. However, the effect of daylighting controls can be limited by the window-to-wall ratio, as well as the size of the zones. Because the bulk and fine storage spaces are very large and deep, the daylight can only penetrate through so much of the zone. Some of the artificial lighting needs to remain turned on in parts of those zones that cannot be easily daylit. On their own, the daylighting controls in this model save 1.5% building site energy and 13.7% lighting energy annually. There is also a 2.1% increase in heating energy and 1.7% reduction in cooling energy because less lighting energy means lower internal gains for the space. Internal gains from lighting can be useful during the winter but come with a penalty in the summer.

For occupancy controls, we can see in Table 3 that the Bulk and Fine storage spaces received a 45% LPD reduction, which is substantial for these large spaces. A 15% LPD reduction is applied to the office space; however, this space only makes up a small portion of the total building floor area. On their own, the occupancy controls in this model save 4.4% building site energy and

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42.8% lighting energy annually. There is also a 6.9% increase in heating energy and 4.2% reduction in cooling energy for the same reasons discussed earlier.

When combining the two types of lighting controls, we see building site energy savings of 5.2% and lighting savings of 51%. This comes with an 8.2% increase in heating energy, but a 5.2% decrease in cooling energy. Notably, lighting controls reduce the electricity peak in this building by nearly 12%, which is a result of reducing lighting energy (through LPD reductions and daylighting controls during the middle parts of the day), which in turn reduces cooling energy during the hottest parts of the year.

Note that the savings for the Daylighting + Occupancy scenario are lower than the sum of the individual scenarios. This indicates that the controls are interacting or overlapping during some parts of year. For example, an LPD reduction from the occupancy controls will have no impact during periods when the lights are already off due to daylighting controls. Therefore, the combined scenario will not be the sum of the savings from the individual scenarios.

Table 7. Analysis of Impacts of Lighting Controls on the Single Model Example

Field	Baseline	Daylighting Only	Occupancy Only	Daylighting + Occupancy
Annual Site Energy (million British thermal units [MBtu])	2,732.1	2,692.4	2,612.9	2,590.5
% Site Energy Savings		1.5%	4.4%	5.2%
Lighting Energy (kWh)	114,079.4	98,473.4	65,220.8	55,969.3
% Lighting Energy Savings		13.7%	42.8%	50.9%
Natural Gas Heating Energy (MBtu)	851.0	868.9	909.4	920.9
% Heating Energy Savings		-2.1%	-6.9%	-8.2%
Cooling Energy (kWh)	61,172.1	60,101.8	58,587.6	57,965.3
% Cooling Energy Savings		1.7%	4.2%	5.2%
Electricity Peak (kilowatts)	185.8	178.0	169.0	164.1
% Electricity Peak Reduction		4.2%	9.0%	11.7%

5.2 Stock Energy Impacts

The Interior Lighting Controls measure demonstrates 1.9% total site energy savings (93 trillion British thermal units [TBtu]) for the U.S. commercial building stock modeled in ComStock. The savings contributions by end use and fuel type are summarized in Table 8 and are illustrated in Figure 1. Because this measure is applicable to 100% of the stock, the percent savings for the full stock and applicable buildings are the same.

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Table 8. Summary of Site Energy Savings From Interior Lighting Controls 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 (Trillion British Thermal Units)
Interior Lighting	24.2%	24.2%	109.6
Total Natural Gas	-1.5%	-1.5%	-24.0
Total Electricity	3.6%	3.6%	118.3
Total Heating	-2.5%	-2.5%	-33.7
Natural Gas Heating	-2.4%	-2.4%	-24.0
Electric Heating	-2.8%	-2.8%	-7.6
Total Cooling	1.7%	1.7%	14.2
Electric Cooling	1.8%	1.8%	13.3
Electric Fans	0.5%	0.5%	3.0
Total Site Energy	1.9%	1.9%	93.4

This measure scenario primarily affects the interior lighting end use, demonstrating 24% lighting energy savings after implementing daylighting and occupancy controls to all models. Along with these lighting energy savings, we also see some minor changes in heating and cooling end uses, with a 2.5% increase in annual heating energy and 1.7% decrease in annual cooling energy. Interior lights contribute heat gains to a space, which is beneficial during the winter but not during the summer. Therefore, when we reduce the lighting power in a building, we lose some of those additional internal gains, resulting in cooling savings during the summer but a heating penalty during the winter. The cooling savings also come with some minor (0.5%) fan savings. All other end uses remain unchanged by this measure.

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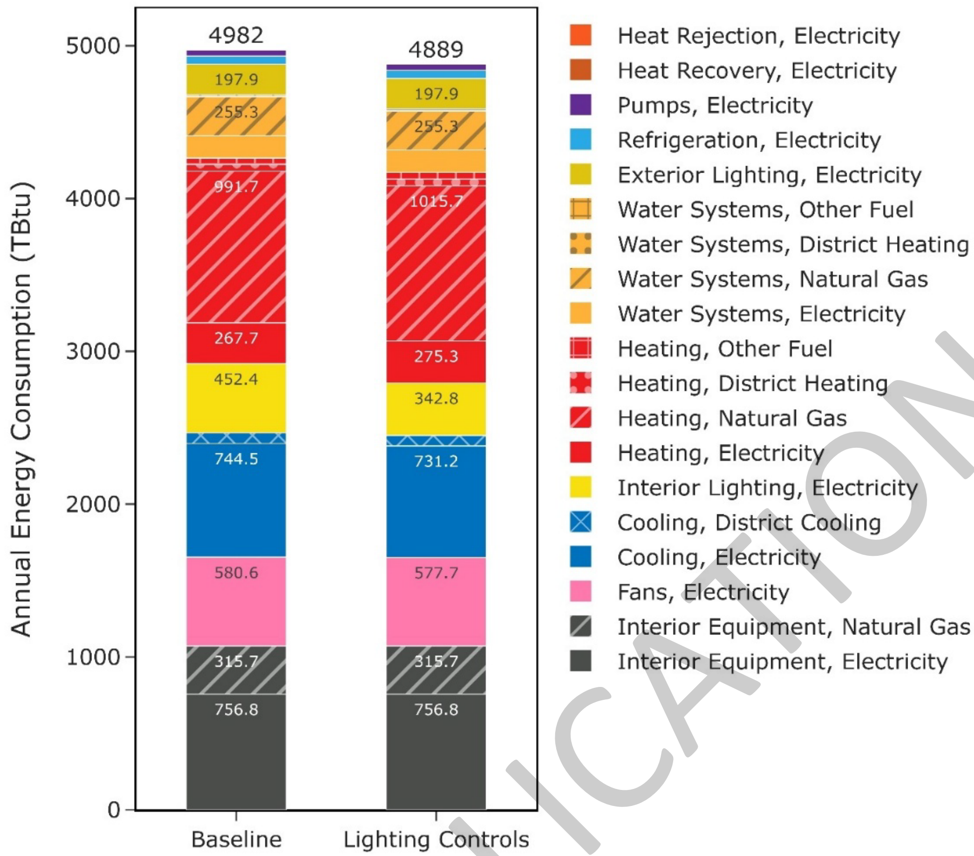

Figure 1. Comparison of annual site energy consumption between the ComStock baseline and the Interior Lighting Controls measure scenario

5.3 Stock Utility Bill Impacts

This section includes a comparison of national-level annual utility bills of the stock across different fuel sources (i.e., electricity, natural gas, propane, and fuel oil). ComStock uses utility region mapping to determine all associated electricity rates that can be used by a building in that region. Therefore, the results can include many annual utility rates per building. The comparison in this section highlights three statistics—maximum, mean, and minimum—across all possible electric utility rates in each location. For more information about the utility bill methodology in ComStock, see the ComStock Reference Documentation [3].

As shown in Table 9, when combining all fuels, the Interior Lighting Controls measure scenario resulted in $3.6 billion (2.8%) total utility bill savings across the building stock when using the mean electricity rate. Electricity bills show $3.9 billion in savings (3.5%) due to the lighting and cooling savings resulting from this measure. However, natural gas bills see a $0.3 billion increase (1.5%) due to the heating penalties from adding lighting controls. Fuel oil and propane bills show a slight (1.2%–2.5%) increase; however, these fuels are not very common in the building stock so there is almost no change in absolute bills at the national level. Because this measure is applicable to 100% of the stock, the percent savings for the full stock and applicable buildings are the same.

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Table 9. Summary of Key Results for Annual Utility Bill Savings.

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

End Use/Fuel Type	Percent Savings (All Buildings)	Percent Savings (Applicable Buildings Only)	Absolute Savings (Million USD, 2022)
Natural Gas	-1.5%	-1.5%	-0.3
Electricity	3.5%	3.5%	3.9
Fuel Oil	-2.5%	-2.5%	<0.0
Propane	-1.2%	-1.2%	<0.0
Total	2.8%	2.8%	3.6

In Figure 2, we can see the utility bill savings for a range of electricity rates. Note that this figure rounds to the nearest billion. The total bill savings across all fuels are \$3 to \$4 billion depending on the electricity rate used. Electricity bills are reduced by \$3 billion when using the minimum rate, and \$4 billion when using the maximum rate. Natural gas bills see an increase of \$0.3 billion (Table 9), but this is not shown in Figure 2. Annual utility bill impacts using the maximum, mean, and minimum bills across available rate structures for buildings for the Interior Lighting Controls measure scenario, which rounds to the nearest \$1 billion. Similarly, propane and fuel oil bills show a very minor increase at the national level, but this increase cannot be seen in Figure 2.

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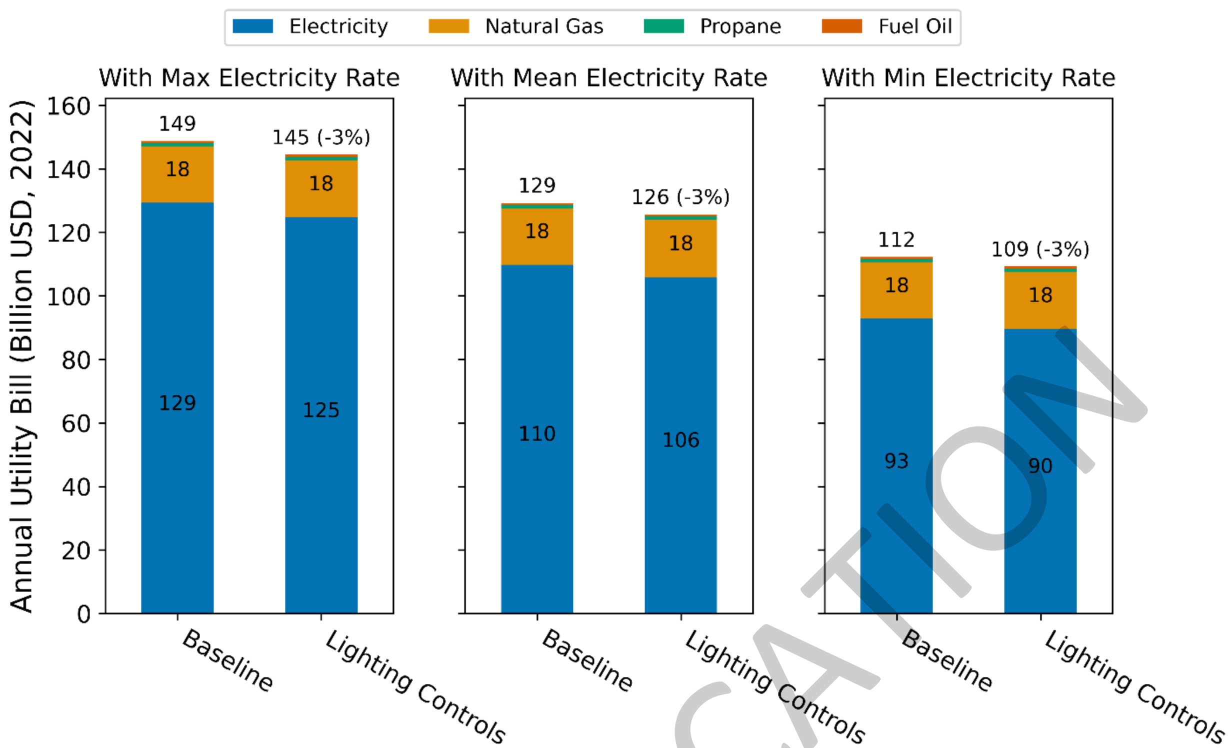

Figure 2. Annual utility bill impacts using the maximum, mean, and minimum bills across available rate structures for buildings for the Interior Lighting Controls measure scenario

5.4 Site Energy Savings Distributions

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

Figure 3 shows the percentage savings distributions of the baseline ComStock models versus the Interior Lighting Controls measure by end use and fuel type for applicable models. In other words, each data point in the distribution represents the percentage energy savings between a baseline ComStock model and the corresponding model with measures applied.

The highest percentage savings are seen in interior lighting, with median savings near 25%. Buildings on the upper end of the distribution can save 50% or more lighting energy. The cooling electricity, district cooling, fan electricity, and heat rejection end uses show small positive savings, with savings up to 5% for most buildings in the distribution. All the heating end uses, including electricity, natural gas, district, and other fuel, show negative savings (i.e., an increase in energy) up to 5% in most buildings in the distribution. As stated previously, the Interior Lighting Controls measure primarily affects the lighting end use but also results in cooling savings and heating penalties due to the changes in internal heat gains.

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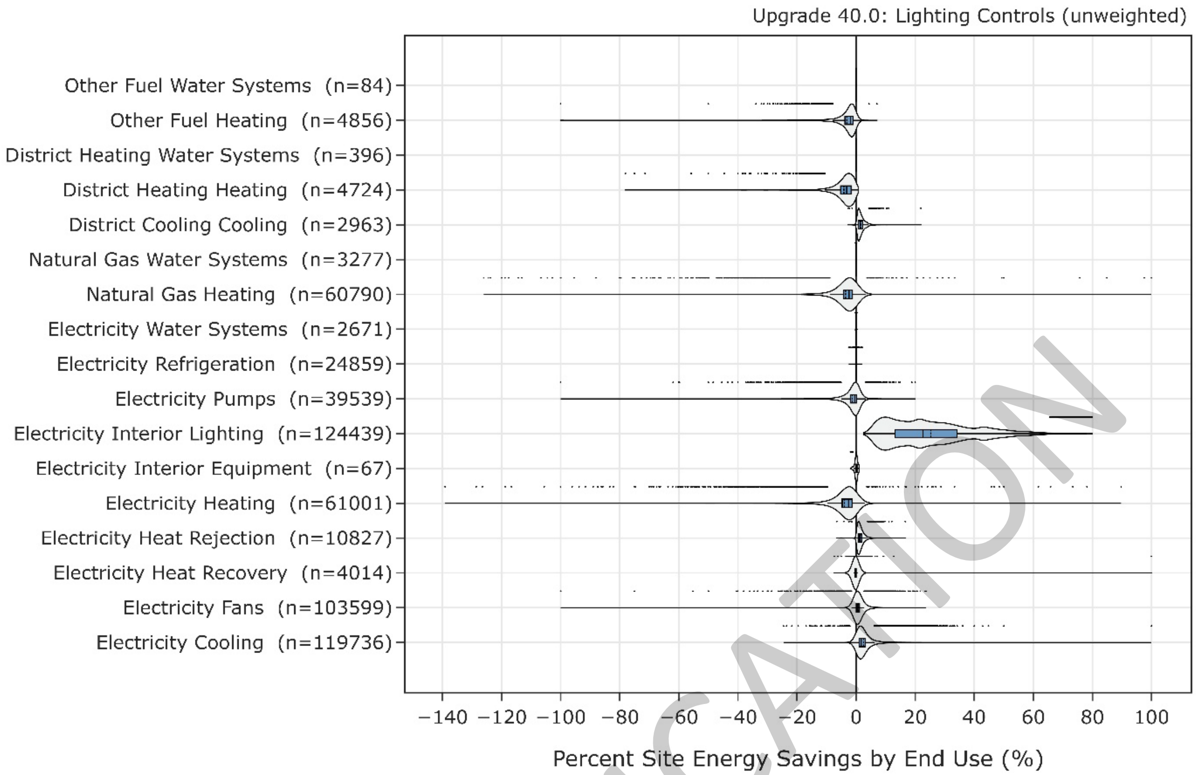

Figure 3. Percent site energy savings distribution for ComStock models with applied measure scenario by end use and fuel type.

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 4 shows the site energy savings distributions by building type. The building types in ComStock can have vastly different lighting types and lighting intensity, therefore savings by building type show us a closer look at the impact of this measure. Warehouses by far show the highest savings when applying this measure, with median site energy savings of 7%. Warehouses are typically large in floor area, but much of the space is not occupied by people. In addition, some warehouses in ComStock are modeled to be effectively unconditioned, so lighting makes up a larger portion of the building load. Therefore, occupancy sensors can have a big impact on this building type in reducing lighting energy in those unoccupied storage spaces for much of the day. Warehouses typically have lower window-to-wall ratios, so daylighting sensors likely do not contribute as much to the higher savings in this building type. After warehouses, offices, schools, small hotels, and stand-alone retail show the next highest savings, with median site energy savings around 2%–3%. Restaurants tend to show the lowest savings as it can be difficult to implement lighting controls in a restaurant during business hours.

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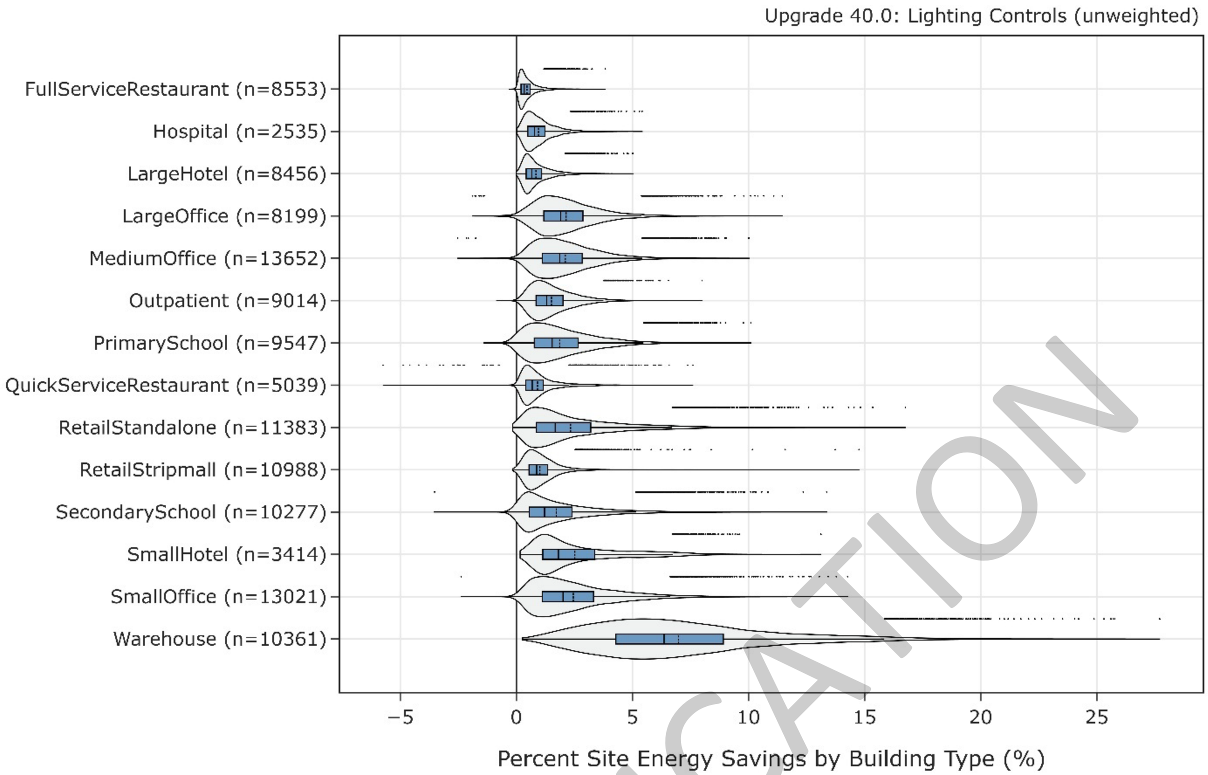

Figure 4. Percent site energy savings distribution for ComStock models with the applied measure scenario by building type.

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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5.5 Utility Bill Savings Distributions

Figure 5 shows the percentage utility bill savings distributions of the baseline ComStock models versus the Interior Lighting Controls measure by fuel type for applicable models. In other words, each data point in the distribution represents the percentage utility bill savings between a baseline ComStock model and the corresponding model with the measure applied.

The overall impact on utility bills is minimal, with a 5% or lower change in total bills in most buildings. Electricity bills see some positive savings, whereas natural gas, propane, and fuel oil bills see a slight increase (negative savings). A small number of buildings experience an increase in total utility bills (which is typically accompanied by an increase in total site energy). After investigation, we noticed that almost all the buildings with negative energy or bill savings are in California. As noted in Section 3.4, we do not apply daylighting sensors to spaces in California models that already have blinds, so this reduces the lighting and cooling savings potential of this measure. In addition, many of these California buildings with negative savings were schools. Schools follow a nontraditional schedule in which occupancy, lighting, and heating, ventilating, and air conditioning loads are heavily reduced during the summer months when schools are typically unoccupied. Therefore, the lighting controls are mainly impacting shoulder and winter months and having minimal effects in summer months. This will exacerbate the heating penalty and minimize the cooling savings that are often a result of adding lighting controls.

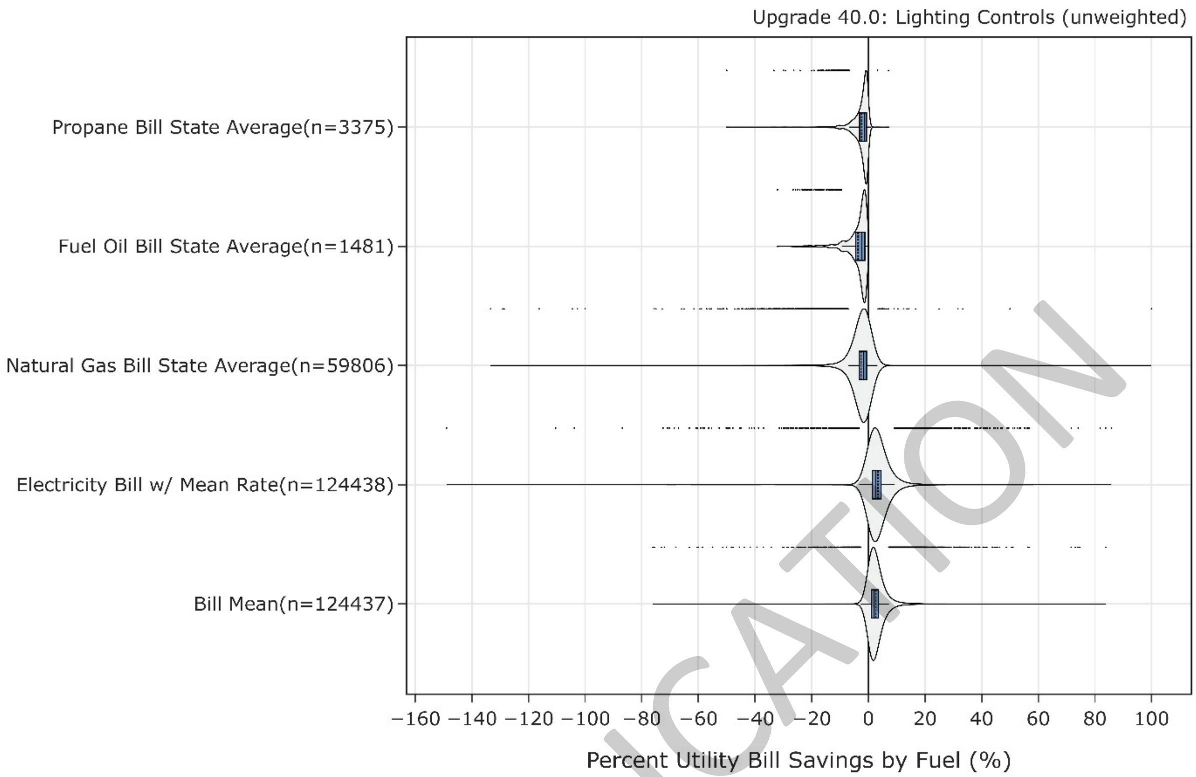

Figure *5. Percent annual utility bill savings distribution for ComStock models with the Interior Lighting Controls measure scenario by fuel type.*

Note: Results shown in this plot are the savings for the average available utility rate per building. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of unweighted ComStock models that were applicable for energy savings for the fuel type category.

Figure 6 shows the percentage utility bill savings distributions of the baseline ComStock models versus the Interior Lighting Controls measure by climate zone for applicable models. Climate zone appears to have very little impact on the total site energy savings distributions of buildings when adding lighting controls. Colder climate zones have slightly lower savings than warmer climate zones, which is linked to the heating penalty that counteracts some of the cooling savings. However, it can be concluded that lighting controls will typically benefit all climate zones equally.

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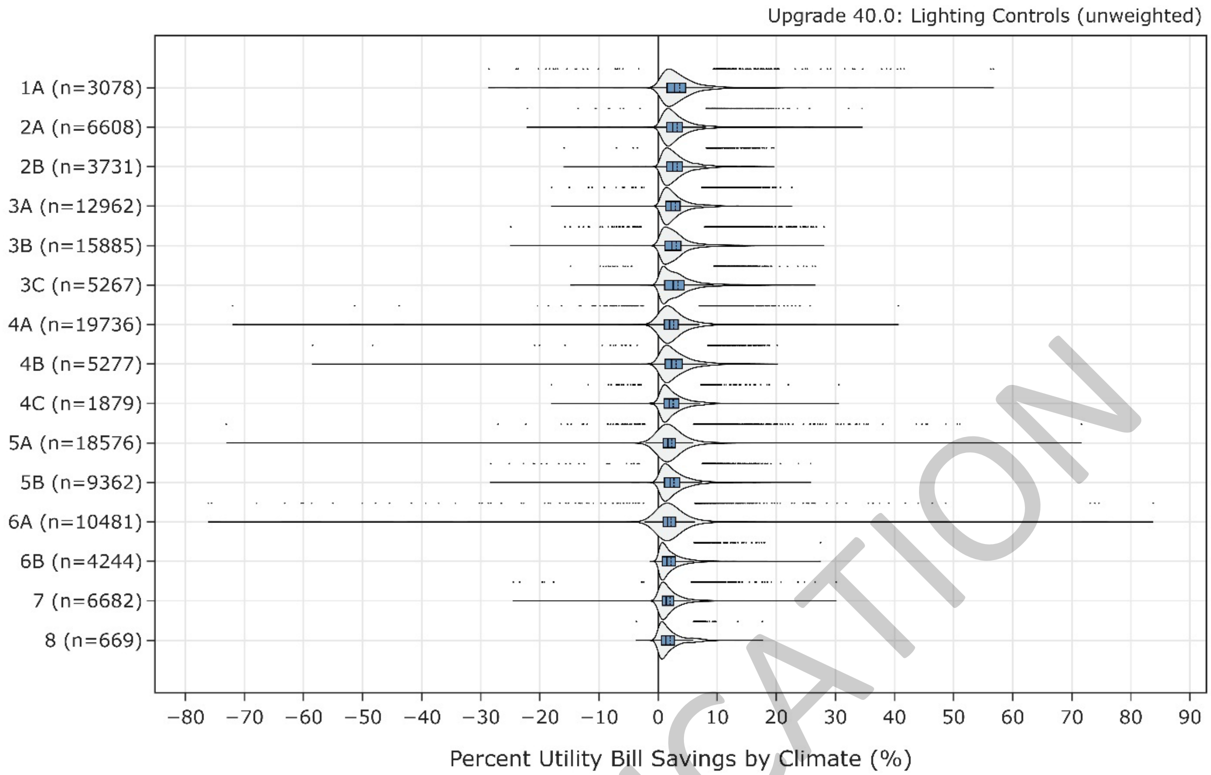

Figure 6. Percent annual utility bill savings distribution for ComStock models with the Interior Lighting Controls measure scenario by climate zone.

Results shown in this plot are the savings for the average available utility rate per building. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of unweighted ComStock models that were applicable for energy savings for the fuel type category.

5.6 Impacts of Individual Versus Combined Controls

While developing and testing this measure, we wanted to understand the impacts of daylighting controls and occupancy sensors individually before combining them together into the "Lighting Controls" measure. We ran a medium-scale test run (~13,000 models) with three measure scenarios:

1. Only Daylighting Controls
2. Only Occupancy Controls
3. Lighting Controls (Daylighting Controls + Occupancy Controls).

This testing can help us understand which lighting control technology has the largest impact on energy savings, as well as looking further into which buildings benefit more from one technology or the other. When evaluating site energy savings at the stock level in Figure 7, the Daylighting Controls measure saved 0.7% (35 TBtu), the Occupancy Controls measure saved 1.2% (60 TBtu), and the Lighting Controls measure saved 1.8% (89 TBtu). Based on these results, we can conclude that the occupancy sensors are saving more energy at the stock than the daylighting controls. However, this may not be the case in every single building, which we will investigate further in this section. The Lighting Controls savings of 89 TBtu are less than the

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sum of the two individual control measures (35 + 60 = 95 TBtu), indicating that there is some interaction between the controls. For example, the occupancy sensor LPD reduction is less impactful during periods when the daylighting controls are also in effect because the LPD would be zero during those timesteps if the lights have been turned off. Therefore, we cannot expect that the savings for the Lighting Controls measure will be the same or higher than the sum of the individual control measures.

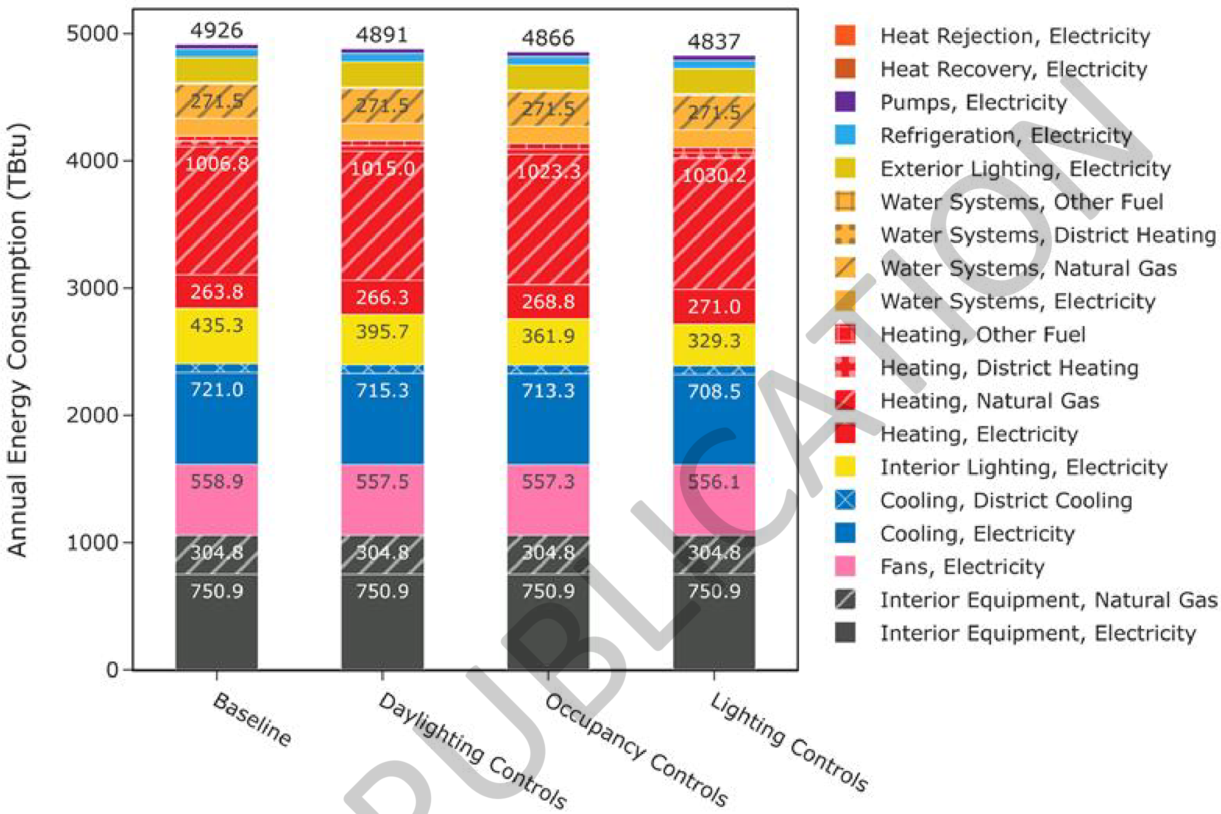

Figure 7. Comparison of annual site energy consumption between the ComStock baseline, Daylighting Controls, Occupancy Controls, and Lighting Controls measure scenarios

When comparing the impacts on utility bills (Figure 8), we see that across all three electricity rate scenarios, the daylighting controls are saving \$1 billion, the occupancy controls are saving \$2 billion, and the combined lighting controls measure is saving \$3 billion. The numbers in this figure are rounded to the nearest billion dollars, so some precision is lost. However, we can conclude that the occupancy sensors are contributing more to bill savings than daylighting controls at the stock level.

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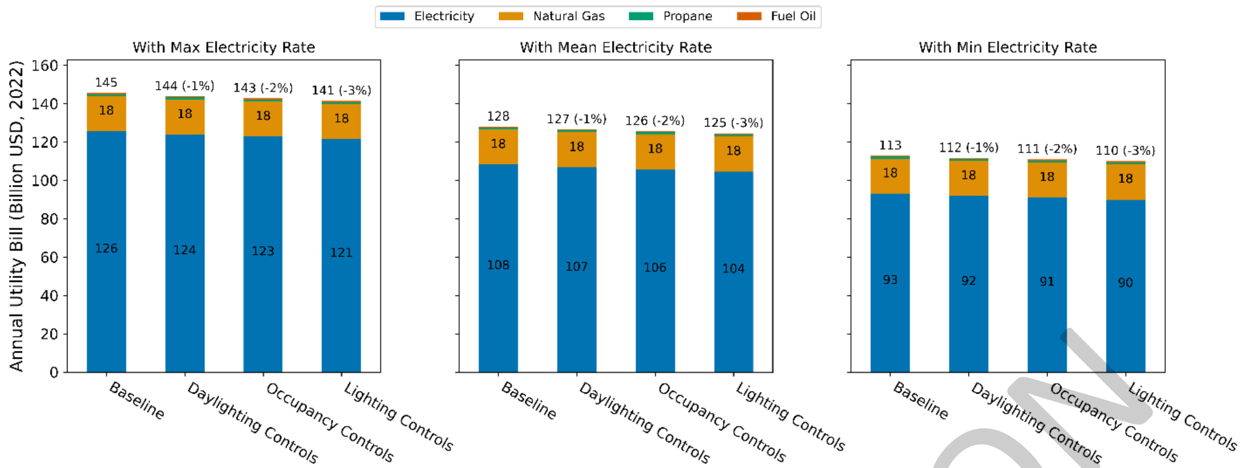

Figure 8. Comparison of annual utility bills between the ComStock baseline, Daylighting Controls, Occupancy Controls, and Lighting Controls measure scenarios

Figure 9. Median percent lighting energy savings and absolute lighting energy savings by building type and lighting control type shows both the median percent lighting energy savings and absolute lighting energy savings by building type and lighting control type. From this plot we can see that warehouses demonstrate the highest lighting energy savings (48%) when both daylighting and occupancy controls are applied. We can also see that the occupancy controls are contributing much more of the savings in warehouses then daylighting. This is because warehouses typically have a lot of unoccupied floor space that could benefit from occupancy sensors, but they also do not have large window-to-wall ratios, so it is difficult to get enough natural light for daylighting sensors to be effective. When looking at the absolute lighting energy savings on the right side of the plot, we can see that warehouses contribute by far the most to the stock lighting energy savings from this measure. Warehouses make up a large amount of square footage in the stock, therefore there is a lot of potential for reducing lighting energy in this building type.

One could do a similar analysis for each of the other building types to make conclusions about which lighting controls technology is most effective in determining how much lighting energy savings potential it has in the building stock. In all building types except offices, hospitals, large hotels, and stand-alone retail, occupancy controls are saving more energy than the daylighting controls. This outcome is influenced by many factors, including the presence of existing controls, occupancy sensor LPD reductions defined by ASHRAE 90.1-2019, compliance with daylighting controls criteria, and more.

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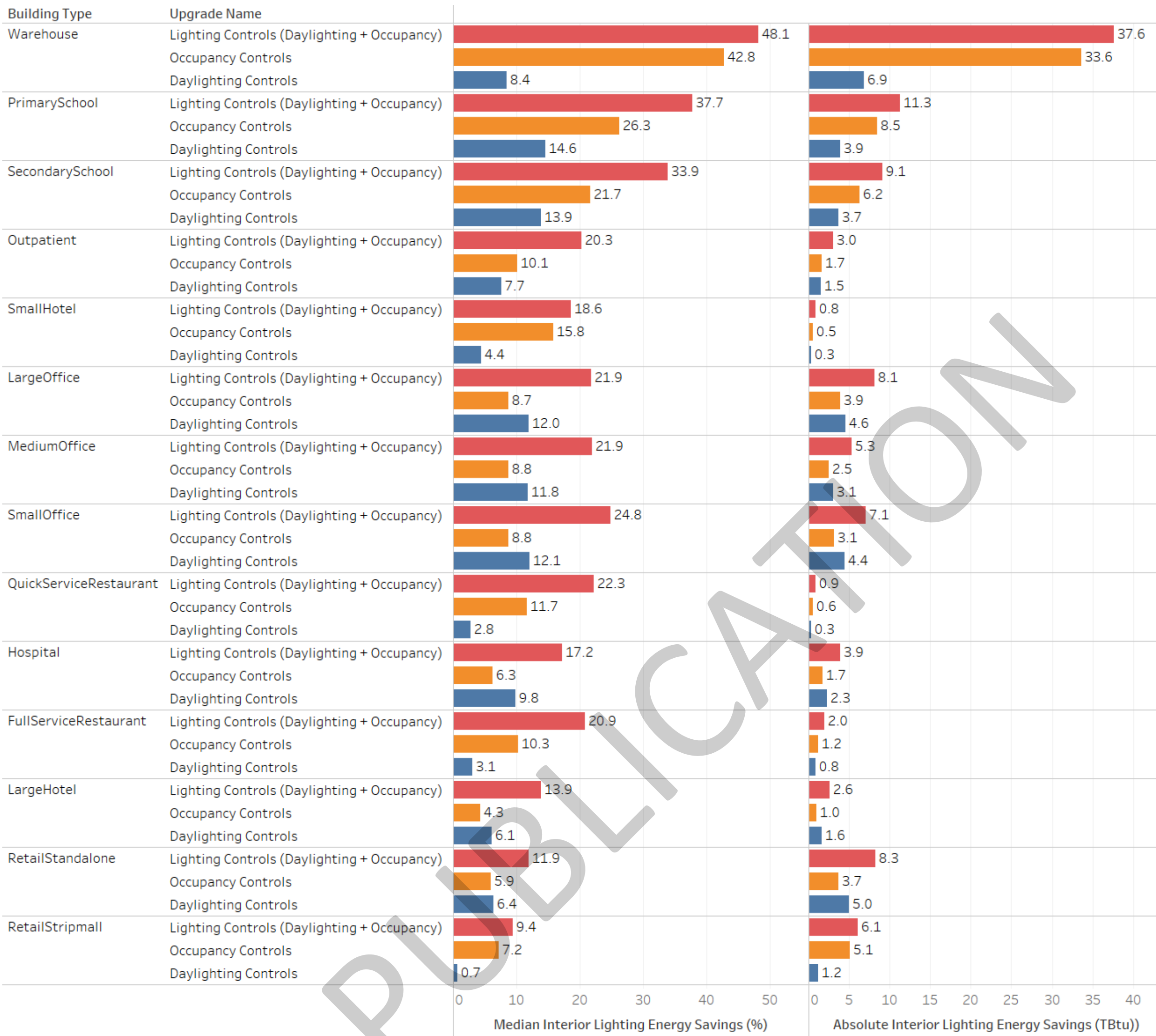

Figure 9. Median percent lighting energy savings and absolute lighting energy savings by building type and lighting control type

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References

[1] U.S. Department of Energy, "Lighting Controls," [Online]. Available: https://www.energy.gov/energysaver/lighting-controls.

[2] Amazon, "Open Energy Data Inititative," 2024. [Online]. Available: https://data.openei.org/s3_viewer?bucket=oedi-data-lake&prefix=nrel-pds-building-stock%2Fend-use-load-profiles-for-us-building-stock%2F.

[3] A. Parker, H. Horsey, M. Dahlhausen, M. Praprost, C. CaraDonna, A. LeBar and L. Klun, "ComStock Reference Documentation: Version 1," National Renewable Energy Laboratory, Golden, 2023.

[4] A. V. Sant, C. CaraDonna and A. Parker, "End-Use Savings Shapes Measure Documentation: LED Lighting," National Renewable Energy Laboratory, Golden, Colorado, 2023.

[5] American Society of Heating, Refrigerating and Air Conditioning Engineers, "Standard 90.1-2022 — Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings," [Online]. Available: https://www.ashrae.org/technical-resources/bookstore/standard-90-1. [Accessed July 2025].

[6] California Public Utilities Commission, "California Energy Data and Reporting System (CEDARS) MASControl," 2024. [Online]. Available: https://cedars.cpuc.ca.gov/deer-resources/tools/mas-control/. [Accessed November 2024].

[7] California Public Utilities Commission, "Cedars California Energy Data and Reporting System," 2025. [Online]. Available: https://cedars.cpuc.ca.gov/deer-resources/. [Accessed July 2025].

[8] International Code Council, "ICC Digital Codes - Chapter 4 [CE] Commercial Energy Efficiency," 2025. [Online]. Available: https://codes.iccsafe.org/content/iecc2018/chapter-4-ce-commercial-energy-efficiency. [Accessed July 2025].

[9] International Code Council, "9.4.1.1 Interior Lighting Controls," 2025. [Online]. Available: https://codes.iccsafe.org/s/MNEC2024P1/9-lighting/MNEC2024P1-Ch09-Sec9.4.1.1. [Accessed July 2025].

[10] National Renewable Energy Laboratory, "openstudio-standards," Github, 2025. [Online]. Available: https://github.com/NREL/openstudio-standards. [Accessed July 2025].

[11] American Society of Heating, Refrigerating and Air-Conditioning Engineers, "Energy Standard for Buildings Except Low-Rise Residential Buildings," ASHRAE, Atlanta, Georgia, 2019.

[12] Lighting Controls Assocation, "Daylight Zones: Sidelighted Spaces," 2025. [Online]. Available: https://lightingcontrolsassociation.org/2011/10/12/daylight-zones-sidelighted-spaces/. [Accessed July 2025].

[13] U.S. Energy Information Administration, "Natural Gas Explained," 28 April 2023. [Online]. Available: https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php.

[14] U.S. Energy Information Administration, "Petroleum and Other Liquids," 1 June 2022. [Online]. Available: https://www.eia.gov/dnav/pet/pet_pri_dist_a_epd2_prt_dpgal_a.htm.

PRE-PUBLICATION

[15] S. Ong and R. McKeel, "National Utility Rate Database," in *2012 World Renewable Energy Forum*, Denver, Colorado, 2012.

[16] U.S. Energy Information Administration, "Monthly Energy Review," 29 July 2024. [Online]. Available: https://www.eia.gov/totalenergy/data/monthly/.

PRE-PUBLICATION