ComStock Measure Documentation:

Geothermal Heat Pumps + High Efficiency Envelope + LED Lighting Package

Marlena Praprost

National Renewable Energy Laboratory

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List of Acronyms

AEDG	Advanced Energy Design Guide
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2e	carbon emissions equivalent
DEER	Database of Energy Efficiency Resources
DOAS	dedicated outdoor air system
GHP	geothermal heat pump
HVAC	heating, ventilating, and air conditioning
IEAD	insulation entirely above deck
LED	light-emitting diode
LPD	lighting power density
LRMER High RE	Long-Run Marginal Emissions Rate High Renewable Energy
MMT	million metric tons
PFP	parallel fan-powered
PSZ-AC	packaged single-zone air conditioner
PTAC	packaged terminal air conditioners
PVAV	packaged variable air volume
SHGC	solar heat gain coefficient
RTU	rooftop unit
TBtu	trillion British thermal units
VAV	variable air volume
XPS	extruded polystyrene

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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 are discussed in the ComStock Reference Documentation.

The goal of this work is to develop energy efficiency and demand flexibility measures that cover market-ready technologies and study their mass adoption impact on the baseline building stock. "Measures" refers to various "what-if" scenarios that can be applied to buildings. The results for the baseline and measure scenario simulations are published in public datasets the provide insight into buildings stock characteristics, operational behaviors, utility bill impacts, impacts to emissions, and annual and subhourly energy usage by fuel type and end use.

An upgrade package applies one or more ComStock measure scenarios to a single building model simulation. Because ComStock is a bottom-up physics-based model, an upgrade package will go beyond aggregating or summing the individual upgrade results and produce novel results by simulating interactions between the upgrades. For example, pairing an envelope upgrade with an energy efficiency upgrade would likely result in higher savings results than the sum of these upgrades individually. Additionally, the size of the heating, ventilating, and air-conditioning (HVAC) equipment may be reduced if the envelope upgrade reduces the loads significantly.

This documentation focuses on an upgrade package of seven measures—Central Hydronic Geothermal Heat Pump (GHP), Packaged GHP, Console GHP, Window Replacement, Exterior Wall Insulation, Roof Insulation, and LED Lighting—which we will refer to collectively as the "Comprehensive GHP + High Efficiency Envelope + LED Lighting" package.

This documentation contains the same ComStock baseline and measure approach information as in the documentation of the individual measures included in the package. However, package results will be unique, as they include interactions between the individual measures. More details on the individual upgrades can be found on the ComStock Measures Documentation page. 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.

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Table ES-1. Key Modeling Specifications

Package Title:	Comprehensive GHP + High Efficiency Envelope + LED Lighting Package
Technology Description	This package replaces existing HVAC systems with one of three GHP-based systems, as well as upgrades wall insulation, roof insulation, replaces windows, and replaces non-LED lighting in applicable models. It is a combination of seven upgrades: Hydronic GHP, Packaged GHP, Console GHP, New Windows, Wall Insulation, Roof Insulation, and LED Lighting.
Performance Assumptions	Some key performance assumptions of each measure include: • Packaged Water-to-Air GHP: Performance curves are based on a 10-ton distributed water-to-air heat pump. Modeled with variable speed supply fan operation; also incorporates demand control ventilation and air-side economizing. Modeled to meet the full heating and cooling load with no supplemental heat. • Central Hydronic Water-to-Water GHP: Performance curves are based on a 56-ton central water-to-water heat pump. Model implements a lower set point (135°F [57°C]) based on typical operating range of water-source heat pumps. Modeled to meet the full heating and cooling load with no backup heat. • Console Water-to-Air GHP: Performance curves are based on a 3-ton distributed water-to-air heat pump. Outdoor air is supplied directly through the heat pump unit. Modeled to meet the full heating and cooling load with no backup heat. • Window Replacement: New windows are double- or triple-pane with thermally broken aluminum frames. U-factor values range from 0.25–0.48 and solar heat gain coefficient (SHGC) values range from 0.21–0.38 based on climate zone, with better performance requirements for colder climates. • Exterior Wall Insulation: R-values of new wall insulation are determined by climate zone, ranging from R-13 in warmest climates to R-29 in coldest climates. • Roof Insulation: R-values of new roof insulation are determined by climate zone, ranging from R-21 in warmest climates to R-37 in coldest climates. • LED Lighting: Assumes Generation 5 LED Lighting, which results in an average building-level lighting power density (LPD) of 0.21–0.52 W/ft^2 depending on the building type.
Applicability	This package is applicable to approximately 84% of the stock floor area. For the package to be applicable, the model must meet the applicability criteria of one of the GHP measures and one or more of the envelope measures. • Packaged Water-to-Air GHP: Models with gas-fired or electric resistance packaged rooftop systems or packaged variable air volume systems (PVAV). This measure is applicable to approximately 62% of the ComStock floor area. • Central Hydronic Water-to-Water GHP: Models with central hydronic systems including variable air volume (VAV) systems and dedicated outdoor air systems (DOAS) that are served by a boiler and/or chiller. This measure is applicable to approximately 12% of the ComStock floor area. • Console Water-to-Air GHP: Models with minimal or no ductwork, including packaged terminal units, baseboard electric, and gas unit heaters, as well as residential-style systems. This measure is applicable to approximately 11% of the ComStock floor area.

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Package Title:	Comprehensive GHP + High Efficiency Envelope + LED Lighting Package
	• Window Replacement: All windows with assembly U-values greater than those proposed in the *Zero-Energy Small/Medium Office Advanced Energy Design Guide* (AEDG), and all windows with SHGCs greater than those proposed in the AEDG. This measure is applicable to more than 99% of the ComStock floor area. • Exterior Wall Insulation: Models with mass, steel-framed, or wood-framed walls. This measure is applicable to approximately 99% of the ComStock floor area. • Roof Insulation: Models with roof insulation R-values that are below those specified in the AEDG for the respective climate zone. This measure is applicable to more than 99% of the ComStock floor area. • LED Lighting: Models without LED lighting installed. This measure is applicable to approximately 64% of the ComStock floor area.
Release	2025 Release 1: 2025/comstock_amy2018_release_1/

National annual results for impacts to site energy, utility bills, and emissions, are summarized in Table ES-2, Table ES-3, and Table ES-4, respectively. In addition to these results, this report addresses the impacts on ground heat exchanger sizing and heat pump sizing when combining GHPs with envelope and lighting improvements. In summary, this package demonstrates that the number of boreholes is reduced by 24% and capacity of the geothermal heat pump is reduced by 21% (based on median) due to the addition of envelope and lighting measures. Based on the analysis described in this report, it was concluded that the envelope improvements have much more impact on the ground heat exchanger and heat pump sizing than the lighting improvements.

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

Fuel Type	Absolute Savings (TBtu)	Baseline Total, All Buildings (TBtu)	Percent Savings, All Buildings (%)	Baseline Total, Applicable Buildings Only (TBtu)	Percent Savings, Applicable Buildings Only (%)
Natural Gas	875.3	1,524.1	57.4%	1,378.3	63.5%
Electricity	614.4	3,173.4	19.4%	2,782.6	22.1%
Other Fuel*	41.0	53.7	76.3%	52.7	77.8%
Total	1,530.7	4,751.2	32.2%	4,213.6	36.3%

*combination of Fuel Oil and Propane annual site energy results

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

Fuel Type	Absolute Savings (Billion USD, 2022)	Baseline Total, All Buildings (Billion USD, 2022)	Percent Savings, All Buildings (%)	Baseline Total, Applicable Buildings Only (Billion USD, 2022)	Percent Savings, Applicable Buildings Only (%)
Natural Gas	9.7	17.4	55.6	15.7	61.7
Electricity	23.5	107.7	21.8	94.1	25.0
Fuel Oil	0.6	0.7	89.7	0.6	93.1
Propane	0.7	1.0	67.4	1.0	68.1
Total	34.5	126.8	27.2	111.4	30.9

Electricity bill savings in this table are calculated using the mean electricity rate available for each building. Other electricity rate structures are available in this report and in the public dataset.

Table ES-4. Key Results for Annual Carbon Emissions Equivalent (CO_2e) Savings

Fuel Type	Absolute Savings (MMT CO_2e)	Baseline Total, All Buildings (MMT CO_2e)	Percent Savings, All Buildings (%)	Baseline Total, Applicable Buildings Only (MMT CO_2e)	Percent Savings, Applicable Buildings Only (%)
Natural Gas	58.5	101.8	57.4%	92.1	63.5%
Electricity	41.6	239.6	17.3%	212.0	19.6%
Fuel Oil	1.6	1.7	89.7%	1.7	93.0%
Propane	1.9	2.7	68.6%	2.7	69.3%
Total	103.5	345.9	29.9%	308.5	33.5%

Electricity emissions avoided in this table are calculated using Cambium Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year grid scenario. Other grid scenarios are presented in this report and in the public dataset.

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1 Technology Summary

1.1 Geothermal Heat Pumps

Geothermal heat pumps (GHPs), also known as ground-source heat pumps, are a potential solution to increase energy efficiency in buildings, with annual growth of 3% in the U.S. [1] Space heating is the top consumer of energy use in the buildings sector, representing 43% of site energy in the residential sector [2] and 32% of site energy in the commercial sector [3]. When combined with cooling, space conditioning is responsible for 52% of energy use in residential buildings [2] and 41% of energy use in commercial buildings [3]. GHPs leverage naturally stable ground temperatures to extract thermal energy used to heat and cool buildings. During the winter, GHPs extract heat from the ground by circulating the working fluid in the ground loop. The energy absorbed by the fluid is then transferred by the heat pump to heat to the building. During the summer, the system is reversed, cooling the building. Properly designed ground heat exchanger coupled heating and cooling systems can offer energy efficiency and resilience benefits compared to conventional heating, ventilating, and air-conditioning (HVAC) systems.

GHPs can be configured as water-to-air or water-to-water, depending on whether the building uses air-based distribution or hydronic distribution. The Packaged GHP and Console GHP measures are configured as water-to-air heat pumps, whereas the Hydronic GHP measure is a water-to-water heat pump. Water-to-air heat pumps are the most common form of ground-coupled heat pump and are commonly available as packaged options in capacities ranging from 0.5 to 30 tons. The Packaged GHP measure is modeled as a retrofit for packaged single zone rooftop units, while the Console GHP measure is a retrofit for non-ducted or minimally ducted systems serving individual spaces. Hydronic HVAC systems are also common in commercial buildings and often use boilers and chillers as the primary equipment for heating and cooling. The Hydronic GHP measure focuses on the retrofit of hydronic HVAC systems to use central, ground-coupled, water-to-water heat pumps as primary equipment for both heating and cooling. For details about each of the three technologies, reference their individual measure documentation: Central Hydronic GHP, Packaged GHP, and Console GHP.

1.2 Envelope

The building envelope refers to the physical barrier between the external environment and the conditioned spaces of a building. It includes a building's windows, walls, roofs, doors, insulation, exterior cladding systems, as well as air, vapor, and moisture barriers. According to Better Buildings, these technologies are responsible for 30% of primary energy consumed in residential and commercial buildings due to their direct impact the heating and cooling requirements of a building [4]. Improving the performance of the building envelope can therefore have a substantial impact on whole-building energy consumption.

This upgrade package includes three envelope measures: windows, walls, and roofs. The upgrade package applies the Window Replacement, Exterior Wall Insulation, and/or Roof Insulation measures based on the applicability criteria of each individual measure. A model will have all, some, or none of the upgrades applied, depending on how the model's characteristics align with each measure's applicability criteria. For details about each of the three technologies, reference their individual measure documentation: Window Replacement, Exterior Wall Insulation, and Roof Insulation.

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1.3 LED Lighting

LED lighting is now the most common technology in new and retrofit interior lighting systems. Most lighting in commercial buildings is currently in the form of linear fluorescents and fluorescent troffer-style luminaires. There are direct one-to-one LED linear lamp replacements, as well as LED troffers. This measure does not distinguish between lamp and luminaire replacements. Additionally, this measure does not make any changes to the lighting controls in a building.

This upgrade package includes the LED Lighting measure, which replaces all non-LED lighting in a building with Generation 5 LEDs. Some buildings in the stock may not receive this measure if the building already has LED Lighting. For more details about the measure, reference the individual measure documentation: LED Lighting.

1.4 Summary

The building envelope and internal loads of a building can impact the performance and required capacity of HVAC equipment in a building. For this reason, this package pairs the GHP upgrades with envelope and lighting upgrades to understand the combined impacts of these measures. By comparing the standalone GHP upgrades with the packages that include envelope and lighting upgrades, we can analyze how much improving the envelope and lighting of a building can impact the performance and size requirements of the GHP system.

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2 ComStock Baseline Approach

The following sections provide high-level summaries of the ComStock baseline approach for HVAC systems, windows, walls, roofs, and lighting. For more details about how these systems are modeled in the ComStock baseline, including data sources, reference the ComStock documentation [5].

2.1 HVAC Systems

Of the buildings represented in ComStock, about 17% are served by hydronic HVAC systems, 43% are served by rooftop units (RTU), 24% are served by packaged variable air volume (PVAV) systems, and 8% are served by packaged terminal air conditioners (PTACs) or packaged terminal heat pumps (PTHPs). These totals exclude buildings served by district energy systems. The remaining 8% of buildings in ComStock are served by a variety of other HVAC systems with relatively low prevalence. GHPs are currently represented in the baseline stock, making up roughly 1% of ComStock floor area.

The GHP measures do not apply to buildings served by district energy (heating hot water or chilled water) systems, as this retrofit is intended to represent the installation of a ground heat exchanger to serve a single building's load. Other system types not applicable include direct evaporative coolers, variable refrigerant flow systems, and some dedicated outdoor air systems (DOAS). The applicability for each measure was determined based on thorough research into the ease and practicality of retrofit, and discussions with industry experts as part of a Technical Advisory Group. More details about the modeling approach for each measure can be found in the individual measure documentation. Table 1 summarizes the HVAC system types that were applicable to each of the GHP measures and their corresponding percentage of the ComStock floor area. Of the 29 HVAC systems modeled in ComStock, 18 systems received one of the three GHP measures.

While the total floor area of eligible systems in Table 1 adds up to 95% of the floor area, only approximately 84% of the stock floor area had one of the GHP measures successfully applied. There are several reasons for this discrepancy. The largest reason is a known issue with California warehouses, in which they are assigned an HVAC system in the model, but they are effectively unconditioned. Therefore, the GHP measures are not actually applied to any warehouses in California. In addition, a small percentage of models failed during simulation for various reasons, while others were unsuccessfully able to apply the GHP due to limitations of the ground heat exchanger sizing algorithm. This was typically only the case for very large buildings with high loads (such as hospitals or outpatient buildings), as the ground heat exchanger sizing algorithm imposes a limit on the size of the ground heat exchanger.

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Table 1. GHP Upgrade Applicability by Baseline HVAC System and Percent of Floor Area

Baseline HVAC System Type	Applicable GHP Upgrade	Percent of ComStock Floor Area	Total Percent of Floor Area by Upgrade
Packaged single-zone air conditioner (PSZ-AC) with electric heat	Packaged	13.0%	67.6%
PSZ-AC with gas boiler	Packaged	1.8%	
PSZ-AC with gas heat	Packaged	25.7%	
PSZ-heat pump	Packaged	3.0%	
PVAV with gas boiler reheat	Packaged	9.7%	
PVAV with gas heat with electric reheat	Packaged	5.3%	
PVAV with parallel fan-powered (PFP) boxes	Packaged	9.1%	
PTAC with electric coil	Console	3.2%	11.9%
PTAC with gas boiler	Console	1.3%	
PTAC with gas coil	Console	0.5%	
PTHP	Console	3.3%	
Residential AC with residential forced air furnace	Console	3.6%	
DOAS with fan coil air-cooled chiller with boiler	Hydronic	1.1%	15.1%
DOAS with fan coil chiller with boiler	Hydronic	0.6%	
VAV air-cooled chiller with gas boiler reheat	Hydronic	4.2%	
VAV air-cooled chiller with PFP boxes	Hydronic	0.1%	
VAV chiller with gas boiler reheat	Hydronic	6.5%	
VAV chiller with PFP boxes	Hydronic	2.6%	

2.2 Windows

The ComStock baseline uses a mix of wood-framed and aluminum-framed windows with or without a thermal break. They range from single-pane to triple-pane and can be clear/tinted or low-emissivity (low-e). The properties were informed by a variety of data sources, described in the ComStock Reference Documentation and shown in Table 2 [5].

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Table 2. ComStock Baseline Window Properties

Number of Panes	Glazing Type	Frame Material	Low-E Coating	Assembly U-Factor IP (Btu/h ft^2 F)	SHGC	VLT*
Single	Clear	Aluminum	No	1.178	0.744	0.754
Single	Tinted/Reflective	Aluminum	No	1.178	0.579	0.455
Single	Clear	Wood	No	0.910	0.683	0.723
Single	Tinted/Reflective	Wood	No	0.910	0.525	0.436
Double	Clear	Aluminum	No	0.746	0.646	0.671
Double	Tinted/Reflective	Aluminum	No	0.749	0.484	0.411
Double	Clear	Aluminum	Yes	0.559	0.386	0.591
Double	Clear	Aluminum With Thermal Break	Yes	0.499	0.378	0.591
Double	Tinted/Reflective	Aluminum	Yes	0.557	0.274	0.359
Double	Tinted/Reflective	Aluminum	Yes	0.496	0.266	0.359
Triple	Clear	Aluminum	Yes	0.300	0.328	0.527
Triple	Tinted/Reflective	Aluminum	Yes	0.299	0.224	0.320

*VLT stands for visible light transmission.

2.3 Walls

The ComStock baseline uses a mix of mass, metal building, steel-framed, and wood-framed or other walls. The properties and distribution of the wall types were informed by a variety of data sources described in the ComStock Reference Documentation [5]. R-value values by climate zone and wall type are shown in Table 3 (outside California) and Table 4 (inside California).

Table 3. Wall Assembly Thermal Performance (Outside California)

Whole Wall Assembly R-Value by ASHRAE Climate Zone (ft^2*F*hr/Btu) Includes interior and exterior air films															
Wall Type	Energy Code	ASHRAE Climate Zone													
		1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Mass	Pre-1980	4.3	4.3	4.3	4.4	4.3	4.5	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8.0
	1980-2004	1.0	2.9	2.4	3.4	3.4	2.0	8.3	5.3	10.0	10.0	7.1	7.1	14.1	16.4	21.3
	90.1-2004	1.7	1.7	1.7	6.6	6.6	6.6	6.6	6.6	6.6	8.1	8.1	9.6	9.6	11.1	12.5
	90.1-2007	1.7	6.6	6.6	8.1	8.1	8.1	9.6	9.6	9.6	11.1	11.1	12.5	12.5	14.1	14.1
	90.1-2010	1.7	6.6	6.6	8.1	8.1	8.1	9.6	9.6	9.6	11.1	11.1	12.5	12.5	14.1	14.1
	90.1-2013	1.7	6.6	6.6	8.1	8.1	8.1	9.6	9.6	9.6	11.1	11.1	12.5	12.5	14.1	20.8
Metal Building	Pre-1980	4.3	4.3	4.3	4.4	4.3	4.5	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8.0
	1980-2004	1.0	6.7	4.2	7.7	6.3	7.7	11.2	10.0	10.9	12.2	12.2	15.4	13.9	17.2	22.2
	90.1-2004	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	17.5	17.5
	90.1-2007	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	17.5	17.5
	90.1-2010	10.8	10.8	10.8	11.9	11.9	11.9	11.9	11.9	11.9	14.5	14.5	14.5	14.5	17.5	17.5
	90.1-2013	10.6	10.6	10.6	10.6	10.6	10.6	16.7	16.7	16.7	20.0	20.0	20.0	20.0	22.7	25.6
Steel Framed	Pre-1980	4.3	4.3	4.3	4.4	4.3	4.5	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8.0
	1980--2004	1.0	6.7	4.2	7.7	6.3	7.7	11.2	10.0	10.9	12.2	12.2	15.4	13.9	17.2	22.2
	90.1-2004	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	11.9	11.9	11.9	11.9	15.6	15.6
	90.1-2007	8.1	8.1	8.1	11.9	11.9	11.9	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
	90.1-2010	8.1	8.1	8.1	11.9	11.9	11.9	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
	90.1-2013	8.1	11.9	11.9	13.0	13.0	13.0	15.6	15.6	15.6	18.2	18.2	20.4	20.4	20.4	27.0
Wood Framed	Pre-1980	4.3	4.3	4.3	4.4	4.3	4.5	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8.0
	1980-2004	1.0	6.7	4.2	7.7	6.3	7.7	11.2	10.0	10.9	12.2	12.2	15.4	13.9	17.2	22.2
	90.1-2004	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	19.6
	90.1-2007	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	15.6	15.6	19.6	19.6	19.6	27.8
	90.1-2010	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	15.6	15.6	19.6	19.6	19.6	27.8
	90.1-2013	11.2	11.2	11.2	11.2	11.2	11.2	15.6	15.6	15.6	19.6	19.6	19.6	19.6	19.6	31.3

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Table 4. Wall Assembly Thermal Performance (Inside California)

Whole Wall Assembly R-Value by CEC Climate Zone (ft^2*F*hr/Btu) Includes interior and exterior air films																	
Wall Type	Energy Code	CEC Climate Zone															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Mass	DEER Pre-1975	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	DEER 1985	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	DEER 1996	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	DEER 2003	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	DEER 2007	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	DEER 2011	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	5.4	4.0	4.7	5.4	5.4	6.3
	DEER 2014	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	5.4	4.0	4.7	5.4	5.4	6.3
	DEER 2015	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	5.4	4.0	4.7	5.4	5.4	6.3
	DEER 2017	4.0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	5.4	4.0	4.7	5.4	5.4	6.3
Metal Building	DEER Pre-1975	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
	DEER 1985	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3
	DEER 1996	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	11.3	11.3	12.5	12.5	12.5	12.5	12.5	12.5
	DEER 2003	12.5	12.5	11.3	11.3	11.3	11.3	11.3	11.3	11.3	12.5	12.5	12.5	12.5	12.5	12.5	12.5
	DEER 2007	12.5	12.5	11.3	11.3	11.3	11.3	11.3	11.3	11.3	12.5	12.5	12.5	12.5	12.5	12.5	12.5
	DEER 2011	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9
	DEER 2014	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9
	DEER 2015	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9
	DEER 2017	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9
Steel Framed	DEER Pre-1975	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
	DEER 1985	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
	DEER 1996	8.0	8.0	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.4	8.0	8.0	8.0	8.0	8.0	8.0
	DEER 2003	8.0	8.0	7.4	7.4	7.4	7.4	7.4	7.2	7.2	7.2	8.0	8.0	8.0	8.0	8.0	8.0
	DEER 2007	8.0	8.0	7.4	7.4	7.4	7.4	7.4	7.2	7.2	7.2	8.0	8.0	8.0	8.0	8.0	8.0
	DEER 2011	10.2	16.1	12.2	16.1	16.1	10.2	10.2	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
	DEER 2014	10.2	16.1	12.2	16.1	16.1	10.2	10.2	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
	DEER 2015	10.2	16.1	12.2	16.1	16.1	10.2	10.2	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
	DEER 2017	10.2	16.1	12.2	16.1	16.1	10.2	10.2	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
Wood Framed	DEER Pre-1975	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
	DEER 1985	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3	11.3
	DEER 1996	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	11.3	11.3	12.5	12.5	12.5	12.5	12.5	12.5
	DEER 2003	12.5	12.5	11.3	11.3	11.3	11.3	11.3	11.3	11.3	12.5	12.5	12.5	12.5	12.5	12.5	12.5
	DEER 2007	12.5	12.5	11.3	11.3	11.3	11.3	11.3	11.3	11.3	12.5	12.5	12.5	12.5	12.5	12.5	12.5
	DEER 2011	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9
	DEER 2014	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9
	DEER 2015	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9
	DEER 2017	12.5	16.9	11.3	16.9	11.3	11.3	11.3	11.3	16.9	16.9	16.9	16.9	16.9	16.9	23.8	16.9

2.4 Roofs

Roofs in ComStock are modeled as flat roofs. For buildings outside of California, we chose a single roof construction type for each building type. As shown in Table 5, most buildings are assumed to use insulation entirely above deck (IEAD) roofs, which is consistent with the assumption of flat roofs. For buildings in California, we used the construction types from the California Public Utilities Commission's Database of Energy Efficiency Resources (DEER) prototype buildings.

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Table 5. Roof Construction Types

	U.S. DOE Ref and ASHRAE 90.1		DEER (CA ONLY)	
Building Type	**Construction Type**	**Building Category for Exterior Roofs**	**Construction Type**	**Building Category for Exterior Roofs**
Full-Service Restaurant	IEAD	Nonresidential	Wood Framed	Nonresidential
Hospital	IEAD	Nonresidential	Mass	Nonresidential
Large Hotel	IEAD	Residential	IEAD	Residential
Large Office	IEAD	Nonresidential	Mass	Nonresidential
Medium Office	IEAD	Nonresidential	Mass	Nonresidential
Outpatient	IEAD	Nonresidential	Mass	Nonresidential
Primary School	IEAD	Nonresidential	Wood Framed	Nonresidential
Quick-Service Restaurant	IEAD	Nonresidential	Wood Framed	Nonresidential
Retail	IEAD	Nonresidential	IEAD	Nonresidential
Secondary School	IEAD	Nonresidential	Wood Framed	Nonresidential
Small Hotel	IEAD	Residential	Wood Framed	Residential
Small Office	IEAD	Nonresidential	Wood Framed	Nonresidential
Strip Mall	IEAD	Nonresidential	Wood Framed	Nonresidential
Warehouse	Metal*	Semi-heated*	Wood Framed	Nonresidential

*Except pre-1980, which assumes IEAD and nonresidential for all years.

2.5 Interior Lighting

ComStock interior lighting 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 (additional lighting), and Wall Wash (illuminates vertical surface). The lighting technologies used in each category across the ComStock lighting generations are listed in Table 6. 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. ComStock currently only includes Generations 1 through 5 in its model, though Generations 6 through 8 could be added in the future.

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Table 6. Lighting Generations and Associated Technologies

Lighting Generation	General Lighting Technology	General Lighting (High Bay) Technology	Task Lighting Technology	Supplemental Lighting Technology	Wall Wash Lighting Technology
Gen 1	T12 Linear Fluorescent	High-Intensity Discharge Mercury Vapor	Incandescent A-Shape	Incandescent Decorative	Incandescent Decorative
Gen 2	T8 Linear Fluorescent	High-Intensity Discharge Metal Halide	Halogen A-Shape	Halogen Decorative	Halogen Decorative
Gen 3	T5 Linear Fluorescent	High-Intensity Discharge Metal Halide	Compact Fluorescent Screw	Compact Fluorescent Pin	Compact Fluorescent Pin
Gen 4–8	LED Linear	LED High Bay Luminaire	LED General Purpose	LED Decorative	LED Directional

ComStock uses a similar approach to the ASHRAE 90.1 Lighting Subcommittee for determining the lighting power density (LPD) allowance for a given space type. Table 7 provides the average installed building-level LPDs in ComStock by building type and lighting generation.

Table 7. Average Building-Level Lighting Power Densities (W/ft^2) by Lighting Generation and Building Type

Building Type	Gen1	Gen2	Gen3	Gen4	Gen5
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

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3 Modeling Approach

The following subsections briefly summarize the modeling approach and applicability for the three measures included in the Comprehensive GHP package. For more detailed descriptions, reference the individual upgrade documentation. Overall, this package is applicable to approximately 84% of the ComStock floor area.

3.1 Central Hydronic Water-to-Water Geothermal Heat Pump

The Hydronic GHP upgrade replaces existing hydronic HVAC systems with a central water-to-water GHP. For each hydronic HVAC loop that currently exists in the building, the measure removes the existing primary equipment from the loop and replaces it with a water-to-water heat pump, with separate, dedicated heat pumps for supplying hot water and chilled water. The source side of each heat pump is tied to a common ground loop. This measure implements a lower supply temperature set point (135°F [57°C]) based on typical operating range of water-source heat pumps. Components such as coils are resized to accommodate the lower supply temperatures. Based on discussions with design practitioners who have experience in GHP retrofits, in buildings with hydronic HVAC systems, existing air-side ductwork is generally sufficient for a reduction in hydronic supply temperatures in heating, while hydronic pipes and coils are more likely to be the limiting factor.

In air handlers performing space conditioning (as opposed to DOAS units), the measure will replace any direct expansion cooling or gas or electric resistance heating coils with hydronic coils and create new plant loops served by water-source heat pumps to condition these loops as necessary. Existing electric baseboard systems will be replaced with hot water fan coils. Existing hot water baseboard systems are not addressed by this measure.

This measure will replace any natural gas coils in DOAS with electric coils to ensure compatibility with the lower hot water supply temperatures (135°F—140°F [57°FC—60°C]) provided by the water-to-water GHP. Existing electric resistance heating coils in DOAS units will be left as-is. Air-side distribution systems (fans, dampers, etc.) are not affected by this measure. Existing systems for providing outdoor air will be preserved. This approach was selected to reflect practical constraints in existing buildings and isolate the effects of this retrofit measure. Details of the sizing approach for this measure are discussed in the individual measure documentation.

Real performance data were used to model each of the three GHP configurations. The Hydronic GHP uses performance data for a 56-ton Carrier 60WG/30WG Series unit. More details can be found in the individual measure documentation.

3.1.1.1 Applicability

This measure is applicable to buildings with hydronic HVAC systems supplying heating or cooling or both, except for (1) buildings served by hydronic baseboards (due to their high temperature requirements) and (2) district thermal energy systems. This includes central VAV systems with chilled water coils, and fan coil-based systems, among other system types. Table 1 summarizes the HVAC system types that received the Hydronic GHP measure and their corresponding percent of the ComStock floor area. In total, this measure was applicable to 12% of the ComStock floor area.

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3.2 Packaged Water-to-Air Geothermal Heat Pump

The Packaged GHP upgrade replaces RTUs and PVAV systems with packaged water-to-air GHPs. Specifically, this measure implements single-zone water-to-air heat pump systems with the source-side loop connected to a ground heat exchanger. The heat pump coils are configured with their load side as part of the existing air handling units, and their source side tied to a condenser loop that is configured to draw heat from and reject heat to a ground heat exchanger. Packaged water-to-air heat pumps can have variable-speed supply fans and can incorporate air- or water-side economizing as well as demand-controlled ventilation. These units can also incorporate hot gas reheat (which uses heat recovered from the refrigeration cycle) to reheat dehumidified air. Because water-source heat pump coils often have relatively high minimum entering air temperatures (50°F–55°F [10°C–13°C]), as specified by the manufacturers, gas or electric coils must be used to precondition outdoor air in cold conditions if the units are providing outdoor air [6], [7]. Packaged water-to-air heat pumps are connected both to ductwork (for air distribution) and to condenser water serving the heat pumps. The Packaged GHP configuration also incorporates additional efficiency features including demand-controlled ventilation and economizers.

Real performance data were used to model each of the three GHP configurations. The Packaged GHP uses performance data for a 10-ton Trane Axion GWS unit. More details can be found in the individual measure documentation.

3.2.1.1 Applicability

This measure is applicable to most buildings that have an existing packaged single-zone RTU system. The exception is RTU systems that operate using district chilled water or district hot water, to which this measure is not applicable. Table 1 summarizes the HVAC system types that received the Packaged GHP measure and their corresponding percent of the ComStock floor area. In total, this measure was applicable to 62% of the ComStock floor area.

3.3 Console Water-to-Air Geothermal Heat Pump

The Console GHP upgrade replaces PTACs, PTHPs, and residential-style systems with console water-to-air GHPs. Console water-to-air heat pumps are generally non-ducted or have minimal ducting and are intended to serve relatively small spaces. They are available in sizes from 0.5 to 3 tons [7], [8]. Some console water-to-air heat pumps offer outdoor air dampers, and others do not [7], [9]. This measure will supply ventilation directly through the water-to-air heat pump, as opposed to separately through a DOAS. Console (and other) water-to-air heat pumps that are configured for providing outdoor air have relatively high minimum entering air temperature requirements. Thus, this measure will configure console units that are tempering outdoor air with an electric preheat coil.

Real performance data were used to model each of the three GHP configurations. The Console GHP uses performance data for a 3-ton Trane Axion GWS unit. More details can be found in the individual measure documentation.

3.3.1.1 Applicability

This measure is applicable to buildings that have an existing packaged terminal system, including PTACs and PTHPs. In addition to packaged terminal systems, console water-to-air

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heat pumps are an appropriate retrofit for other non-ducted systems, such as baseboard heaters and unit heaters, or for residential-style systems. In some cases, the existing system in the baseline does not currently have cooling. Retrofitting a heating-only or cooling-only system with a GHP could result in extreme load imbalance and negatively affect the performance of the ground heat exchanger over time [10]. Therefore, the heat pump will supply both heating and cooling to the building, and cooling will be added to heating-only systems via the console heat pump retrofit. Table 1 summarizes the HVAC system types that received the Console GHP measure and their corresponding percent of the ComStock floor area. In total, this measure was applicable to 11% of the ComStock floor area.

3.4 Window Replacement

The Window Replacement upgrade replaces the windows of a model with new windows with thermal and tinting properties that align with the properties specified in the *Zero Energy Small/Medium Office* AEDG (Table 8). The upgrade will first identify the existing window properties for each ComStock baseline model. In cases where the U-value (thermal transmittance) and/or SHGC underperform those specified in the AEDG, the windows will be replaced with AEDG-compliant windows.

Table 8. AEDG Target Properties for Window Replacements [11]

	ASHRAE Climate Zone								
	0	1	2	3	4	5	6	7	8
Number of Panes	Double							Triple	
Fill	Air				Argon or vacuum				
Thermal Breaks	~1				>1				
Maximum Assembly U-Factor (Btu/hr ft^2 F)	0.48	0.48	0.43	0.40	0.34	0.34	0.32	0.28	0.25
Maximum SHGC	0.21	0.22	0.24	0.24	0.34	0.36	0.36	0.38	0.38

3.4.1 Applicability

This upgrade is applicable to models of all building types with existing windows. Triple-pane windows are excluded from this analysis because they are already high-performing. However, triple-pane windows are a very low percentage of windows in the commercial building stock.

When run as a standalone measure, this upgrade is applicable to over 99% of ComStock floor area. However, in this package, it will only be applied in buildings that received one of the three GHP measures.

3.5 Exterior Wall Insulation

The Exterior Wall Insulation upgrade applies extruded polystyrene (XPS) insulation to applicable building models. First, it determines the thickness of XPS required to meet the specified R-value, determined from the *Zero Energy Small/Medium Office* AEDG target assembly performance for each climate zone (Table 9). Second, it finds all the constructions used by exterior walls in the model, clones them, adds a layer of insulation to the cloned

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constructions, and then assigns the construction back to the wall. Based on the baseline, the updated wall properties may be close to the target values, but exact target values may not be achieved.

Table 9. AEDG Overall Wall Assembly Performance Characteristics by Climate Zone [11]

ASHRAE Climate Zone	1	2	3	4	5	6	7	8
R-Value (hr ft^2 F/Btu)	13	13	16	16	19	21	21	29

3.5.1 Applicability

Based on many examples readily identified through a cursory search, it appears that exterior insulation is readily applied to mass, wood-framed, and steel-framed walls. For metal buildings, interior insulation is a more practical and likely retrofit; this upgrade is therefore not applicable to metal buildings.

For modeling purposes, we calculate the thickness of XPS insulation necessary to bring the wall assembly up to the AEDG recommendation for each climate zone. When the existing walls already meet or exceed the AEDG recommendations, this upgrade is not applicable. When the required insulation thickness is less than 0.5 in., this upgrade is not applicable. For required thicknesses greater than 0.5 in., the selected thickness is rounded to the nearest inch using standard rounding to reflect commonly available products.

When run as a standalone measure, this upgrade is applicable to 99% of the ComStock floor area. However, in this package, it will only be applied in buildings that received one of the three GHP measures.

3.6 Roof Insulation

The Roof Insulation upgrade increases the insulation value of roof surfaces in the models such that the final applied insulation value meets the specified R-value, determined from the *Zero Energy Small/Medium Office* AEDG target assembly performance for each climate zone (Table 10), skipping roof surfaces that already meet or exceed these values. To better align with how insulation is often sold, the applied thickness of additional insulation is rounded up to the nearest inch, which may cause some buildings to slightly exceed the AEDG values. The upgrade assumes XPS insulation with a thermal resistance of R-5/inch.

Table 10. AEDG Overall Target Roof Assembly Performance Characteristics by Climate Zone [11]

ASHRAE Climate Zone	1	2	3	4	5	6	7	8
R-Value (hr ft^2 F/Btu)	21	26	26	33	33	33	37	37

3.6.1 Applicability

The roof insulation upgrade is applicable to all roof surfaces with R-values below the target AEDG R-values. For ComStock, only roofs that follow the ASHRAE 90.1-2013 energy code during the last roof replacement (or installation) have R-values that meet or exceed the AEDG suggestions.

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When run as a standalone measure, this upgrade is applicable to over 99% of the ComStock floor area. However, in this package, it will only be applied in buildings that received one of the three GHP measures.

3.7 Interior Lighting

The LED Lighting upgrade replaces model interior lighting with Generation 5 LED lighting, where applicable. The upgrade will first identify whether the upgrade is applicable to the model. If applicable, it will cycle through each of the spaces in the model, changing the lighting to the appropriate technology based on the space type's lighting category (the lighting categories are shown in Table 6).

3.7.1 Applicability

The purpose of this upgrade is to model the energy impact of 100% LEDs in the commercial building stock. To capture this, in all models without LEDs (Generations 1–3), all interior lighting categories will be retrofitted with Generation 5 lighting. Models with Generation 4 LEDs are not retrofitted with Generation 5 LEDs, as it is not realistic to replace Generation 4 LEDs with a newer technology if the lamps still have many years of usable life left (lifespan of LEDs can be 10+ years). Models with Generation 5 LEDs will also remain unchanged. This upgrade is applicable to 64% of the ComStock floor area.

3.8 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 [5]. Summary [12] statistics from this implementation are shown in Table 11. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 11. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural gas	$0.007/kBtu ($0.70/therm)	$0.012/kBtu ($1.20/therm)	$0.048/kBtu ($4.80/therm)
Propane	$0.022/kBtu ($2.20/therm)	$0.032/kBtu ($3.20/therm)	$0.052/kBtu ($5.20/therm)
Fuel oil	$0.027/kBtu ($2.70/therm)	$0.033/kBtu ($3.30/therm)	$0.036/kBtu ($3.60/therm)
Electricity	$0.003/kBtu ($0.01/kWh)	$0.035/kBtu ($0.12/kWh)	$3.530/kBtu ($12.04/kWh)

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 [13].

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 [14]. Residential prices are used because commercial prices are only available at the national resolution. Additionally, most commercial buildings using these fuels are assumed

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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) [15], which includes rate structures for approximately 85% of the buildings and 85% of the floor area in ComStock [5]. The URDB rates include detailed cost features, such as time-of-use pricing, demand charges, and ratchets. 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 in [16]. Although this method does not reflect the detailed rate structures and demand charges, it is a fallback for the 15% of buildings in ComStock with no utility assigned.

3.9 Carbon Emissions Equivalent

Three electricity grid scenarios are presented to compare the emissions of the ComStock baseline and the Comprehensive GHP scenario. The choice of grid scenario will impact the grid emissions factors used in the simulation, which determines the corresponding emissions produced per kilowatt-hour. Two scenarios—Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year and LRMER Low RE Cost 15-Year—use the Cambium dataset, and the last uses the eGRID dataset [17], [18]. All three scenarios vary the emissions factors geospatially to reflect the variation in grid resources used to produce electricity across the United States. The Cambium datasets also vary emissions factors seasonally and by time of day. This study does not imply a preference for any grid emissions scenario, but other analysis suggests that the choice of grid emissions scenario can impact results [19]. Emissions due to on-site combustion of fossil fuels use the emissions factors shown in Table 12, which are from Table 7.1.2(1) of draft American National Standards Institute/Residential Energy Services Network/International Code Council 301 [20]. To compare total emissions due to both on-site fossil fuel consumption and grid electricity generation, the emissions from a single electricity grid scenario should be combined with all three on-site fossil fuel emissions.

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Table 12. On-Site Fossil Fuel Emissions Factors

Natural gas	147.3 lb/MMBtu (228.0 kg/MWh)[a]
Propane	177.8 lb/MMBtu (275.7 kg/MWh)
Fuel oil	195.9 lb/MMBtu (303.2 kg/MWh)

[a] lb = pound; MMBtu = million British thermal units; kg = kilogram; MWh = megawatt-hour

3.10 GHEDesigner Workflow

GHEDesigner is a software tool available as a Python package for designing ground heat exchangers used with GHP systems [21]. The GHP upgrade measures leverage GHEDesigner for sizing the vertical ground heat exchangers used in the ComStock models. GHEDesigner is executed within the GHP measures. Figure 1 shows the full ComStock GHP measure workflow. First, the GHP measure is applied, which replaces the existing system with one of the GHP configurations. An initial sizing run determines the annual loads the ground heat exchanger needs to supply. The ground loads are exported to GHEDesigner in the form of a JavaScript Object Notation (JSON) file. GHEDesigner then performs calculations to determine the size of the ground heat exchanger in the model. A final EnergyPlus® simulation is performed with the ground heat exchanger size set to the value determined by GHEDesigner. See the individual measure documents (Central Hydronic GHP, Packaged GHP, Console GHP) for more detail about the GHEDesigner workflow.

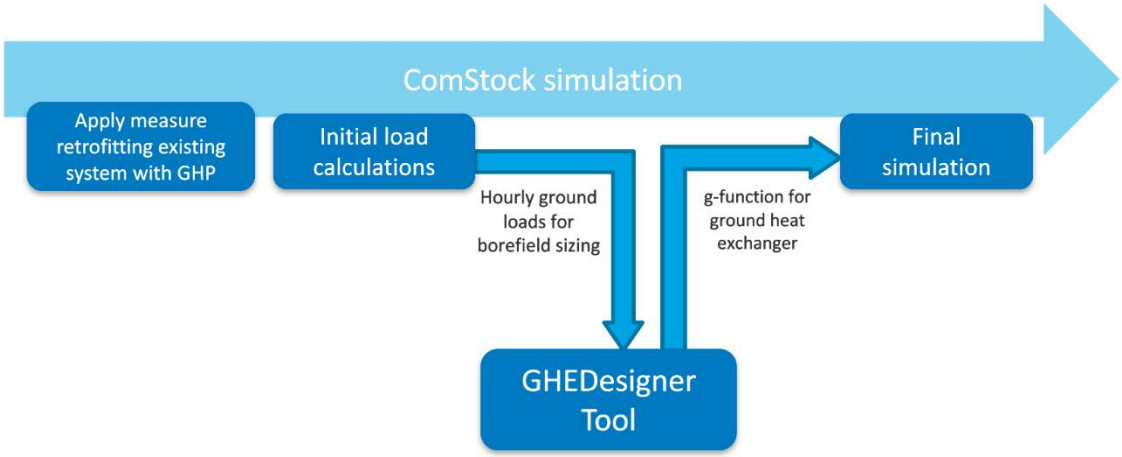

Figure 1. ComStock GHEDesigner workflow

All figures created by the authors, unless noted otherwise.

3.11 Limitations and Concerns

3.11.1 GHP Measures

The representation of heat pump performance in EnergyPlus relies on data obtained from manufacturers. Only one set of performance data was used for each of the three GHP configurations. These data are not fully representative of all heat pumps of this type available in the United States. Field demonstrations to document the reasonableness of the curves have not been performed.

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For the Packaged GHP measure, available space is a consideration in the feasibility of the retrofit. Newer RTUs and heat pumps may require a larger footprint than older models with direct-expansion cooling and gas or electric heating [12].

3.11.2 Envelope Measures

Window assembly U-value is often a function of the ratio of frame area to glass area. ComStock currently uses the EnergyPlus simple glazing object, which accepts a constant U-value input regardless of window size and therefore does not capture U-value differences with window size. Furthermore, ComStock does not differentiate between punched windows, curtainwall, storefront, etc., which can have different performance characteristics. Neither of these limitations are expected to impact stock-level analysis in a substantial way.

In general, real buildings may have limitations beyond what has been included in the upgrades' applicability criteria that could affect the upgrade results. Examples could include existing structural limitations, the presence of hazardous materials such as asbestos, or aesthetic/historical requirements that preclude certain upgrades.

3.11.3 LED Lighting Measure

There are no major limitations or concerns associated with the LED Lighting upgrade.

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4 Output Variables

Table 13 includes a list of output variables that are provided by ComStock. These variables are important to understand the differences between buildings with and without the Comprehensive GHP + High Efficiency Envelope package applied. Additionally, these output variables can be used for understanding the economics (e.g., return on investment) of the upgrade if cost information (i.e., material, labor, and maintenance cost for technology implementation) is available.

Table 13. Output Variables Calculated From the Measure Application

Upgrade	Variable Name	Description
GHP Measures	Ground heat exchanger borehole depth	Borehole depth calculated from GHEDesigner (feet)
	Ground heat exchanger design flow rate	Ground heat exchanger flow rate (cubic feet per minute)
	Ground heat exchanger number of boreholes	Number of boreholes calculated from GHEDesigner
	WA HP Cooling Capacity	Water-to-air heat pump cooling capacity (Watts)
	WA HP Heating Capacity	Water-to-air heat pump heating capacity (Watts)
	WA HP Cooling Average COP	Water-to-air heat pump cooling coefficient of performance
	WA HP Heating Average COP	Water-to-air heat pump heating coefficient of performance
	Heat Pump Cooling Average COP	Water-to-water heat pump cooling coefficient of performance
	Heat Pump Heating Average COP	Water-to-water heat pump heating coefficient of performance
Window Replacement	Window-to-Wall Ratio	Ratio of window area to exterior wall area for the building model.
	Window Type	Name of window construction type, as described in Table 2.
	Average Window SHGC	Average SHGC of all the windows in the building model.
	Average Window U-Value	Average thermal conductance of all the windows in the building model (Btu/hr ft^2 F).
	Window Area	Total window area replaced by the upgrade (ft^2).
Exterior Wall Insulation	Target R-value	Target insulation R-value based on climate zone (ft^2-hr-R/Btu).
	Insulation R-value per Inch	XPS R-value per inch (hr ft^2 R/Btu per inch).
	Required Insulation Thickness	Insulation thickness required to meet target R-value (in.).

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Upgrade	Variable Name	Description
	Exterior Wall Insulation Area	Area of insulation added (ft^2).
Roof Insulation	Energy Code Followed During Last Roof Replacement	The energy code followed during the last roof replacement (or installation) for a building model, which dictates the roof performance properties for the ComStock baseline models.
	Average Roof Absorptance	The average absorptance of all roof surfaces for a building model.
	Average Roof U-Value	The average thermal conductivity of all roof surfaces for a building model (Btu/hr ft^2 F).
	Roof Area	The exterior roof area for a building model (ft^2).
LED Lighting	Initial Lighting Power	Initial power by lighting technology (W)
	Initial LPD	Average building LPD before upgrade is applied (W/ft^2)
	Final Lighting Generation	Lighting generation after upgrade is applied (should be Generation 5 if upgrade is applicable)
	Final Lighting Power	Final lighting power by technology (W)
	Final LPD	Average building LPD after upgrade is applied (W/ft^2)

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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 upgrade. 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 Comprehensive GHP + High Efficiency Envelope + LED Lighting upgrade package.

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, cost savings, or emissions reductions. This is especially important when an upgrade 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 Realized Applicability

Figure 2 provides a breakdown of the applicability of the Comprehensive GHP + High Efficiency Envelope + LED Lighting package by upgrade combination. As a reminder, the wall, roof, window, and lighting measures were only applied if one of the three GHP measures was applicable. The most common scenario was the Packaged GHP + Walls + Roof + Windows + LED Lighting, making up 40.1% of floor area. The next most common combinations were Packaged GHP + Walls + Roof + Windows (20.6% of floor area), Hydronic GHP + Walls + Roof + Windows + LED Lighting (7.2% of floor area), and Console GHP + Walls + Roof + Windows + LED Lighting (7.0% of floor area). There are many other upgrade combinations making up less than 5% of floor area each. Upgrade combinations that make up less than 0.1% of floor area are not shown in the figure. In total, the package was applicable to 84% of the stock floor area, leaving 16% of floor area not applicable to any measures in the package.

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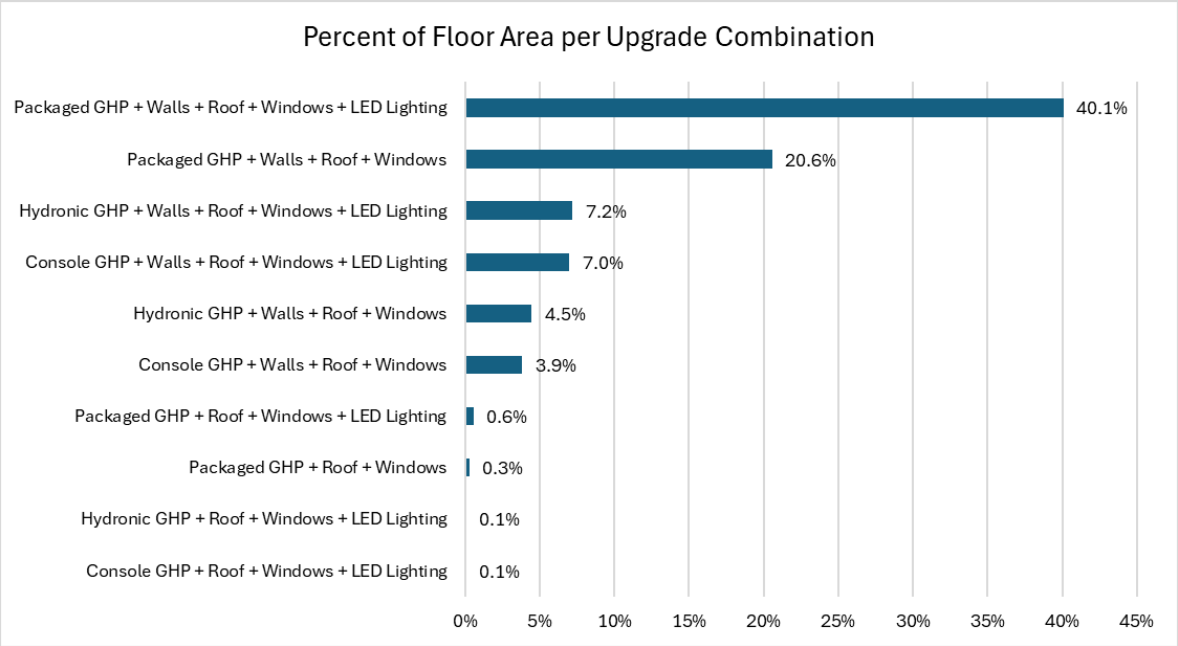

Figure 2. Applicability for the Comprehensive GHP + High Efficiency Envelope + LED Lighting package by upgrade combination

5.2 Stock Energy Impacts

The Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates 31.4% total site energy savings (1,530 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 14.

Table 14. Site Energy Savings from Comprehensive GHP + High Efficiency Envelope + LED Lighting Package Versus ComStock Baseline

End Use / Fuel Type	Absolute Savings (TBtu)	Baseline Total, All Buildings (TBtu)	Percent Savings, All Buildings (%)	Baseline Total, Applicable Buildings Only (TBtu)	Percent Savings, Applicable Buildings Only (%)
Total natural gas	875.2	1,524.1	57.4%	1,413.1	61.9%
Total electricity	613.7	3,172.9	19.3%	2,828.9	21.7%
Total heating	885.2	1,309.0	67.6%	1,192.0	74.3%
Gas heating	875.2	965.2	90.7%	909.8	96.2%
Electric heating	-31.1	260.1	-12.0%	240.1	-13.0%
Electric fans	151.9	568.5	26.7%	512.1	29.7%
Electric cooling	408.7	727.0	56.2%	655.5	62.3%
Electric interior lighting	121.0	440.4	27.5%	392.5	30.8%
Total	1,530.0	4,865.0	31.4%	4,295.0	35.6%

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Throughout the subsequent results sections, the results of the Comprehensive GHP + High Efficiency Envelope + LED Lighting package will be compared to the baseline, the Comprehensive GHP package, and the Comprehensive GHP + High Efficiency Envelope package. A summary of these three packages is as follows:

- **Comprehensive GHP:** Packaged GHP + Hydronic GHP + Console GHP
- **Comprehensive GHP + High Efficiency Envelope:** Packaged GHP + Hydronic GHP + Console GHP + New Windows + Wall Insulation + Roof Insulation
- **Comprehensive GHP + High Efficiency Envelope + LED Lighting:** Packaged GHP + Hydronic GHP + Console GHP + New Windows + Wall Insulation + Roof Insulation + LED Lighting.

The assumptions and applicability of the GHP measures in both packages are the same. With the application of envelope and lighting measures, we can analyze the impacts of these upgrades on both the stock level impacts of the combined technologies, as well as the sizing and performance impacts on the GHPs. The savings contributions of the three packages by fuel type and end use are illustrated in Figure 3.

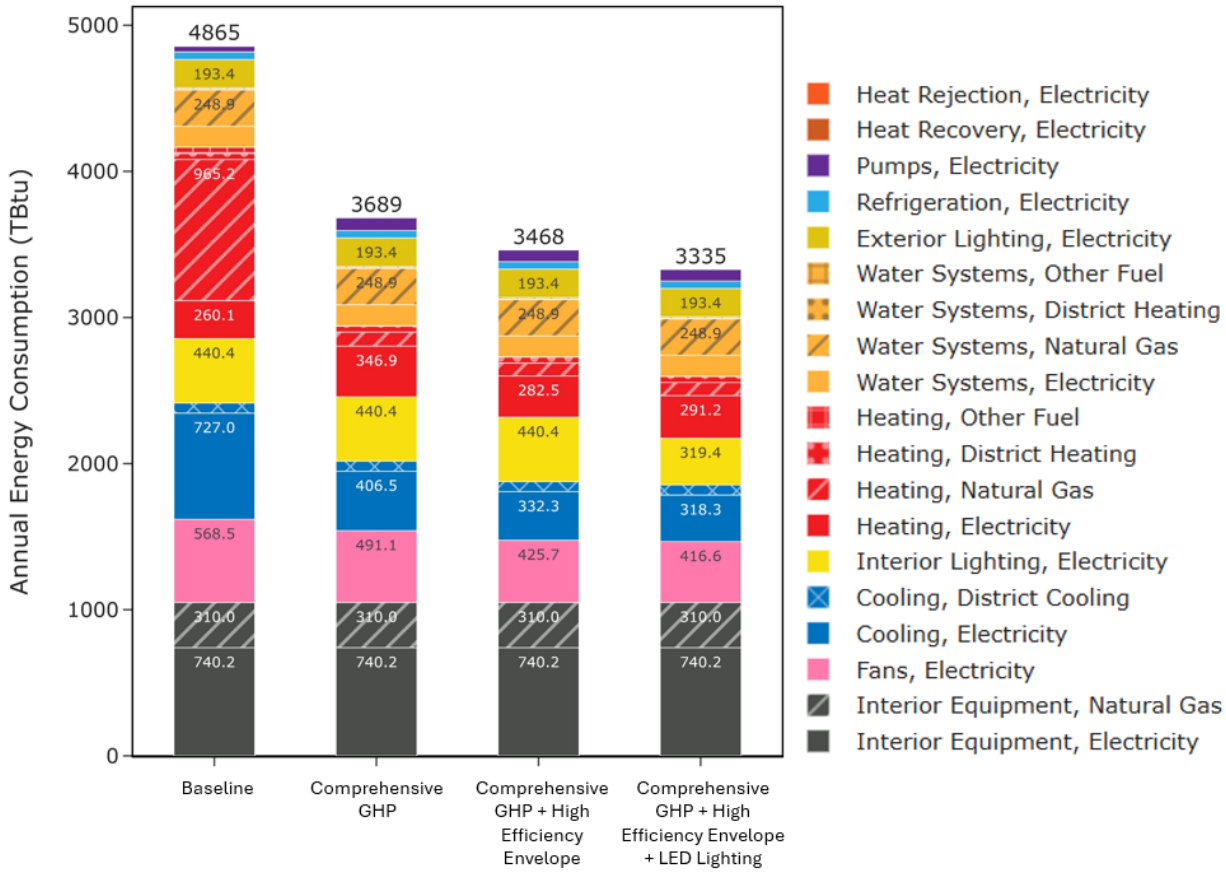

Figure 3. Comparison of annual site energy consumption between the ComStock baseline, Comprehensive GHP scenario, Comprehensive GHP + High Efficiency Envelope scenario, and Comprehensive GHP + High Efficiency Envelope + LED Lighting

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

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A comparison of the results for the three packages is summarized in Table 15:

Table 15. Energy Savings Comparison Between Comprehensive GHP + High Efficiency Envelope + LED Lighting Package and the Other Two Comprehensive GHP Packages

Compared to the *Comprehensive GHP* package, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates:	**Compared to the *Comprehensive GHP + High Efficiency Envelope* package**, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates:
9.6% stock **site energy** savings (354.0 TBtu)	**3.8%** stock **site energy** savings (133.0 TBtu)
21.7% stock **cooling electricity** savings (88.2 TBtu)	**4.2%** stock **cooling electricity** savings (14.0 TBtu)
15.2% stock **fan electricity** savings (74.5 TBtu)	**2.1%** stock **fan electricity** savings (9.1 TBtu)
16.1% stock **heating electricity** savings (55.7 TBtu)	**-3.1%** stock **heating electricity** savings (-8.7 TBtu)
9.2% stock **pump electricity** savings (8.1 TBtu)	**0.4%** stock **pump electricity** savings (0.3 TBtu)
5.6% stock **heating natural gas** savings (5.3 TBtu)	**-2.9%** stock **heating natural gas** savings (-2.5 TBtu)
27.5% stock **lighting electricity** savings (121.0 TBtu)	**27.5%** stock **lighting electricity** savings (121.0 TBtu)

The energy savings trends of the Comprehensive GHP + High Efficiency Envelope + LED Lighting package are largely similar to those of the Comprehensive GHP + High Efficiency Envelope package. See the measure documentation (Central Hydronic GHP, Packaged GHP, Console GHP) for the Comprehensive GHP + High Efficiency Envelope package for a detailed discussion on the savings by end use.

Lighting energy is the main end use contributing to the additional savings in the Comprehensive GHP + High Efficiency Envelope + LED Lighting package. The reduced lighting load is also contributing to changes in HVAC end uses. The package with LED Lighting sees additional cooling and fan savings because the more efficient lights emit lower internal gains to the building during hotter months, hence reducing the cooling and fan load required. For the same reason, the lower internal gains from the LED Lighting are resulting in higher heating loads required during winter (when internal gains are advantageous). Altogether, the cooling and fan savings outweigh the heating penalty, indicating that LED Lighting does save HVAC energy at the stock level.

5.3 Stock Utility Bill Impact

This section includes a comparison of national-level annual utility bills of the stock across different fuel sources (i.e., electricity, natural gas, propane, 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 (i.e., maximum, mean, and minimum) across all possible electric utility rates in a given location. For more information about the utility bill methodology in ComStock, see the ComStock Reference Documentation [5].

When combining all fuel types, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package resulted in $32–$37 billion nationally of utility bills savings (26%–29% reduction) compared to the baseline, depending on the electricity rate used (Figure 4). Natural gas bills are reduced by $9 billion (53%) as a result of fuel switching much of the space heating

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load. The natural gas rates used are fixed by state and therefore remain constant across all three scenarios shown.

Electricity rates are determined based on the utility region of each building in the dataset. For the Comprehensive GHP + High Efficiency Envelope + LED Lighting package, the electricity bills showed a $22–$26 billion reduction in electricity bills nationally depending on the rate chosen.

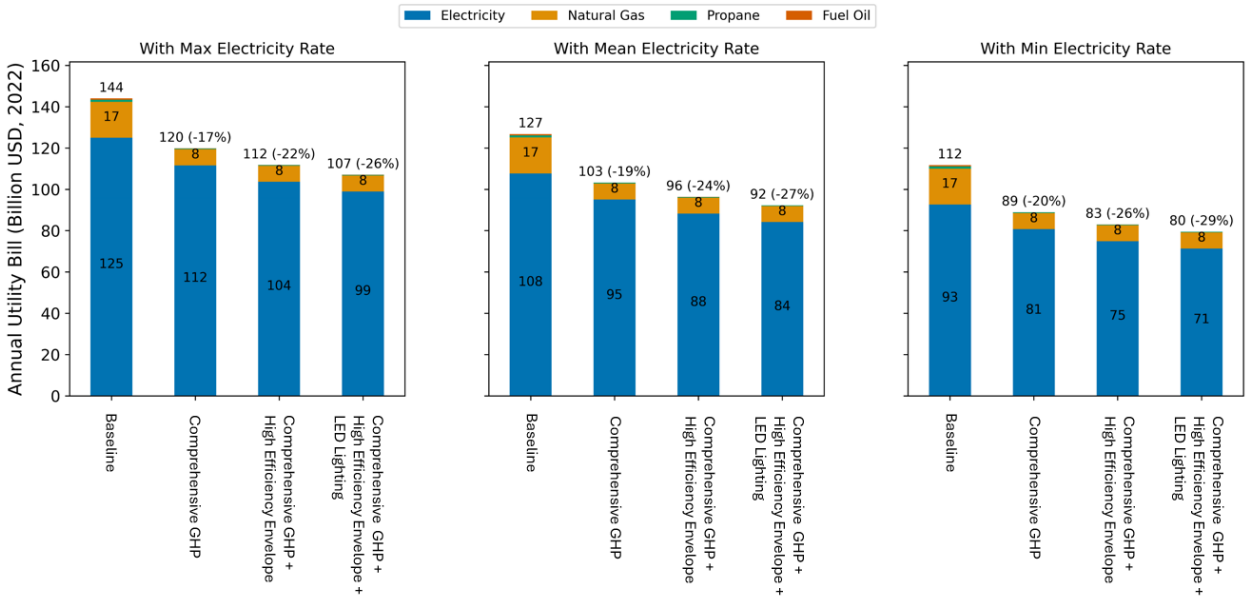

Figure 4. National annual utility bills comparison of the ComStock baseline, Comprehensive GHP scenario, Comprehensive GHP + High Efficiency Envelope scenario, and Comprehensive GHP + High Efficiency Envelope + LED Lighting scenario using maximum, mean, and minimum electricity rates

A comparison of the utility bill results for the three Comprehensive GHP packages is summarized in Table 16:

Table 16. Utility Bill Savings Comparison Between Comprehensive GHP + High Efficiency Envelope + LED Lighting Package and the Other Two Comprehensive GHP Packages, Using the Mean Electricity Rate

Compared to the *Comprehensive GHP* package, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates:	Compared to the *Comprehensive GHP + High Efficiency Envelope* package, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates:
11.5% total utility bill savings across all fuels ($11 billion USD nationally)	**4.2% total utility bill** savings across all fuels ($4 billion USD nationally)
12.5% electricity utility bill savings ($11 billion USD nationally)	**4.5% electricity utility bill** savings ($4 billion USD nationally)
No change in natural gas utility bill savings	**No change in natural gas utility bill savings**
No change in propane and fuel oil utility bill savings	**No change in propane and fuel oil utility bill savings**

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When the LED Lighting measure is added into the package, we see additional utility bill savings nationally. The utility bill savings are seen only in electricity bills, which is a result of replacing lighting with more efficient LEDs. The natural gas and other fuel bills do not change substantially at the stock level, indicating that the internal load reductions from the LED lights have minimal effect on natural gas bills. Individual buildings or smaller geographic regions could see changes in natural gas, propane, or fuel oil bills (due to changes in HVAC load when installing more efficient lighting with lower internal gains). However, at the stock level, we only see additional utility bill savings for electricity bills.

5.4 Stock Emissions Impact

ComStock simulation results show avoided emissions across all three electricity grid scenarios and all on-site combustion fuel types (Figure 5) compared to the ComStock baseline. When combining all fuel types, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package resulted in 81 to 127 million metric tons (MMT) of carbon emissions equivalent (CO_2e) avoided (28%–33% reduction) depending on the grid scenario.

The emissions from natural gas are reduced by 59 MMT CO_2e (58%) as a result of fuel switching much of the heating end use. The natural gas results remain consistent across all three grid scenarios, as these scenarios exclusively pertain to modifications within the electricity grid, without affecting natural gas outcomes.

Avoided electricity emissions from the electricity grid vary depending on the scenario chosen. The eGRID 2021 scenario represents the makeup of the grid as it was in 2021, while the LRMER scenarios project the future grid makeup by assuming different levels of renewable energy penetration. For the Comprehensive GHP + High Efficiency Envelope + LED Lighting package, the LRMER Low RE Cost and High RE Cost scenario show a 19 MMT CO_2e and 42 MMT CO_2e decrease in electricity emissions, respectively. The eGRID scenario shows 64 MMT CO_2e of avoided emissions from the electricity grid.

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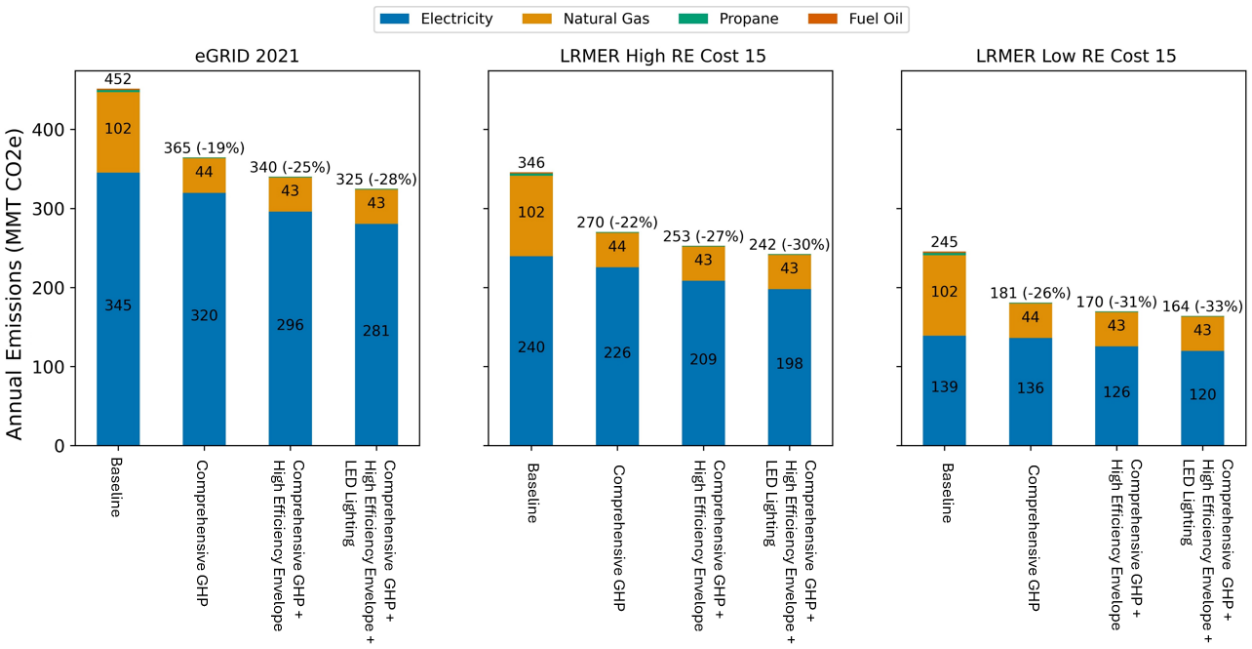

Figure 5. CO_2e comparison of the ComStock baseline, Comprehensive GHP scenario, Comprehensive GHP + High Efficiency Envelope scenario, and Comprehensive GHP + High Efficiency Envelope + LED Lighting scenario

Three electricity grid scenarios are presented: eGRID 2021, Cambium Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy (RE) Cost 15-Year, and Cambium LRMER Low RE Cost 15-Year.
Note: MMT stands for million metric tons. .

A comparison of the eGRID 2021 emissions results for the three Comprehensive GHP packages is summarized in Table 17:

Table 17. Emissions Savings Comparison Between Comprehensive GHP + High Efficiency Envelope + LED Lighting Package and the Other Two Comprehensive GHP Packages, Using eGRID 2021 Emissions Results

Compared to the *Comprehensive GHP* package, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates:	**Compared to the *Comprehensive GHP + High Efficiency Envelope* package**, the Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates:
11.8% stock **total emissions** savings across all fuels (40 MMT CO_2e)	**4.4%** stock **total emissions** savings across all fuels (15 MMT CO_2e)
13.2% stock **electricity emissions** savings (39 MMT CO_2e)	**5.1%** stock **electricity emissions** savings across all fuels (15 MMT CO_2e)
2.3% stock **natural gas emissions** savings (1 MMT CO_2e)	**No change in natural gas emissions savings**
No change in propane and fuel oil emissions savings	**No change in propane and fuel oil emissions savings**

Similar to the site energy results, we see that when the LED Lighting measure is added into the package, we see additional savings at the stock level for emissions. This is primarily due to the Lighting measure reducing electricity emissions. However, there are also cooling and fan savings

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that reduce electricity emissions. There are minimal changes to the emissions of the remaining fuels compared to the Comprehensive GHP + High Efficiency Envelope package.

5.5 Site Energy Savings Distributions

This section discusses site energy consumption for quality assurance/quality control purposes. 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, energy costs, or avoided emissions.

Figure 6 shows the percent savings distributions of the baseline ComStock models versus the Comprehensive GHP + High Efficiency Envelope + LED Lighting package by end use and fuel type for applicable models. In other words, each data point in the distribution represents the percent energy savings between a baseline ComStock model and the corresponding upgrade model with measures applied.

Natural gas heating and other fuel heating show nearly 100% savings in most buildings as a result of converting the space heating load to electricity. As mentioned previously, some buildings, such as warehouses and retail, maintain some gas-heated spaces after the GHPs are installed, which is why not all buildings show 100% savings for these end uses.

Electric heating savings are in the range of 50%–90% for most buildings. It is important to note that Figure 6 only shows buildings that started out with some amount of electric heating. Buildings that started with 100% natural gas heating would have an infinite increase in electric heating and are not shown in Figure 6. Therefore, the electric heating savings represent swapping out electric resistance heating with heat pumps that have a heating coefficient of performance of 3–5, combined with the envelope and lighting measures that further reduce HVAC loads. Some buildings show large negative electric heating savings. This represents buildings that started out with mostly gas heating but a small portion of electric resistance heating; they therefore show a large increase in electric heating when converting much of the heating load to electricity.

Cooling energy in applicable buildings decreased by an average of 55%–70% because of the replacement of existing air-cooled direct-expansion cooling systems with more efficient GHPs, combined with envelope and lighting improvements. The LED lighting reduces internal gains during summer, reducing cooling load. A small number of buildings experienced cooling penalties, which are mainly warehouses with very low cooling loads, making the percentage savings very sensitive to small changes in magnitude.

Interior lighting energy is reduced by 25%–55% as a result of upgrading all non-LED lighting in buildings. The percent savings varies by building because it is based on the existing lighting technology in the building. Buildings that started with Generation 1 lighting (incandescent bulbs, T12s) will show higher savings than buildings that started with Generation 3 lighting (compact fluorescent bulbs, T5s). The median building sees interior lighting savings of about 35%.

Pump energy increases by 10%–90% due to the added pumping needs of vertical GHP systems. Pumps represent a relatively small percentage of the overall stock energy (<2%), so the high percent savings can be misleading. Fan electricity saw savings in the top 75% of buildings, while 25% saw an increase in fan energy. Many of the buildings with very large changes in fan energy

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were found to be warehouses, which start out with low HVAC loads and therefore have sensitive percentage changes. In addition, the system replacement results in a variety of changes that can affect fan energy including lower supply temperatures, increase pumping energy, replacement and/or addition of fans. The median percent change in fan energy across the stock is around a 25% reduction.

The heat recovery end use showed nontrivial percentage changes in some buildings. However, this is solely based on the changes causing existing heat recovery systems to run for different amounts of time. The magnitude of this end use is negligible compared to total site energy.

Minimal or no differences are observed for service water heating systems, refrigeration, and interior equipment, as these systems are not directly impacted by the upgrade package. However, some buildings show minor changes due to subtle differences in zone air temperature that affect the operation of these systems.

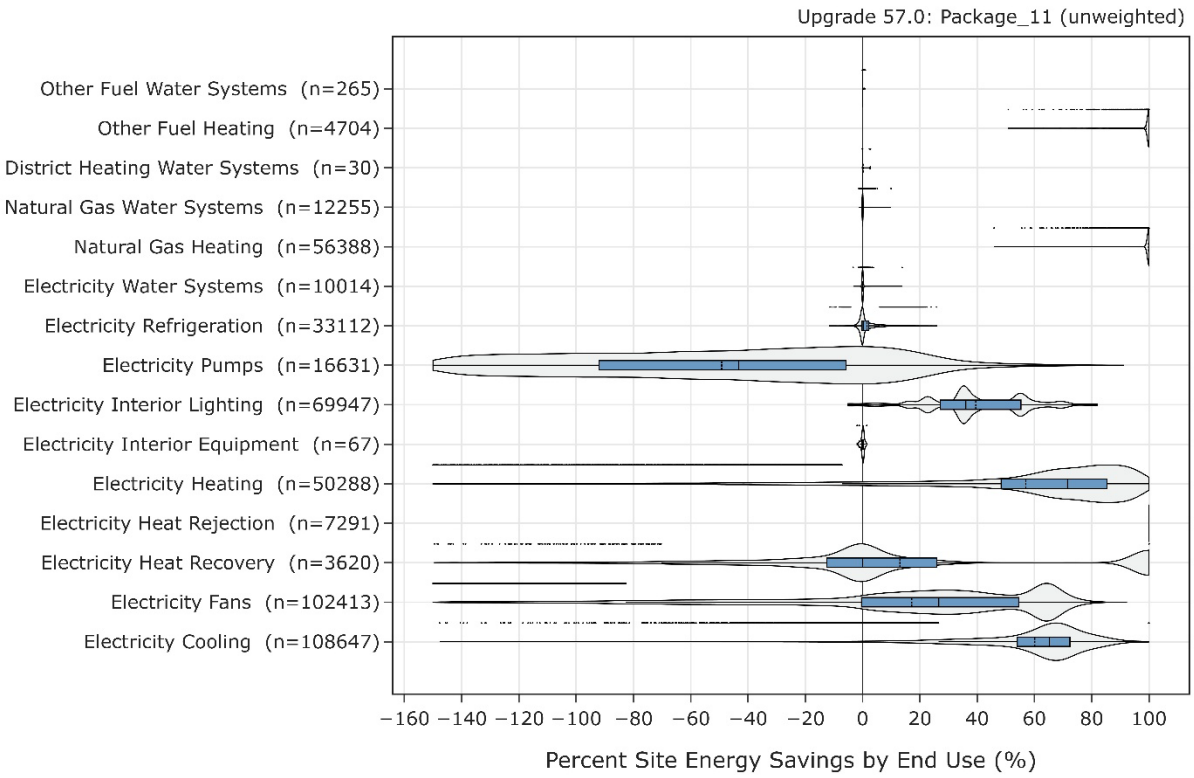

Figure 6. Percent site energy savings distribution for ComStock models with the Comprehensive GHP + High Efficiency Envelope + LED Lighting package applied by end use and fuel type

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 7 shows the percentage of total site energy savings by climate zone. A map of the ASHRAE climate zones is included in 0 [22]. There is a subtle trend of increased savings as we move from the hottest climate zone (1A – Hot Humid) to the coldest climate zone (8 – Subarctic). In warmer climate zones (1A through 3A), the median building sees site energy savings around 30%–35%, with the 75th percentile reaching over 40% site energy savings. In

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colder climate zones (5 through 7) we see median site energy savings up to 40% with the 75th percentile reaching 50% or more.

Some outliers across all climate zones show an increase in site energy with the package applied. Further investigation of these buildings revealed that large increases in fan and pump energy were the driving end uses behind the increased site energy consumption. In buildings with very low HVAC loads (such as warehouses), the percent savings is very sensitive to small changes in magnitude. When evaluating the magnitude of site energy increases, it is minimal for most of these buildings.

In addition, with GHP systems, unless the building is rejecting and extracting the exact same amount of heat to and from the ground over the course of the year, the system could end up with an imbalanced load. This imbalanced load can result in increased pumping energy to maintain temperatures within the desired range on the heat pump condenser loop. Compressor heat can also exacerbate imbalanced loads. In climates with a more balanced heating and cooling load, the ground temperatures remain more stable through the year, and over the course of many years of operation. Despite cold climates experiencing more significant air temperature swings throughout the year, the ground temperature stays relatively stable, resulting in consistent and efficient performance of GHPs year-round. For this reason, combined with the envelope improvements, we see higher site energy savings as we move to colder climates.

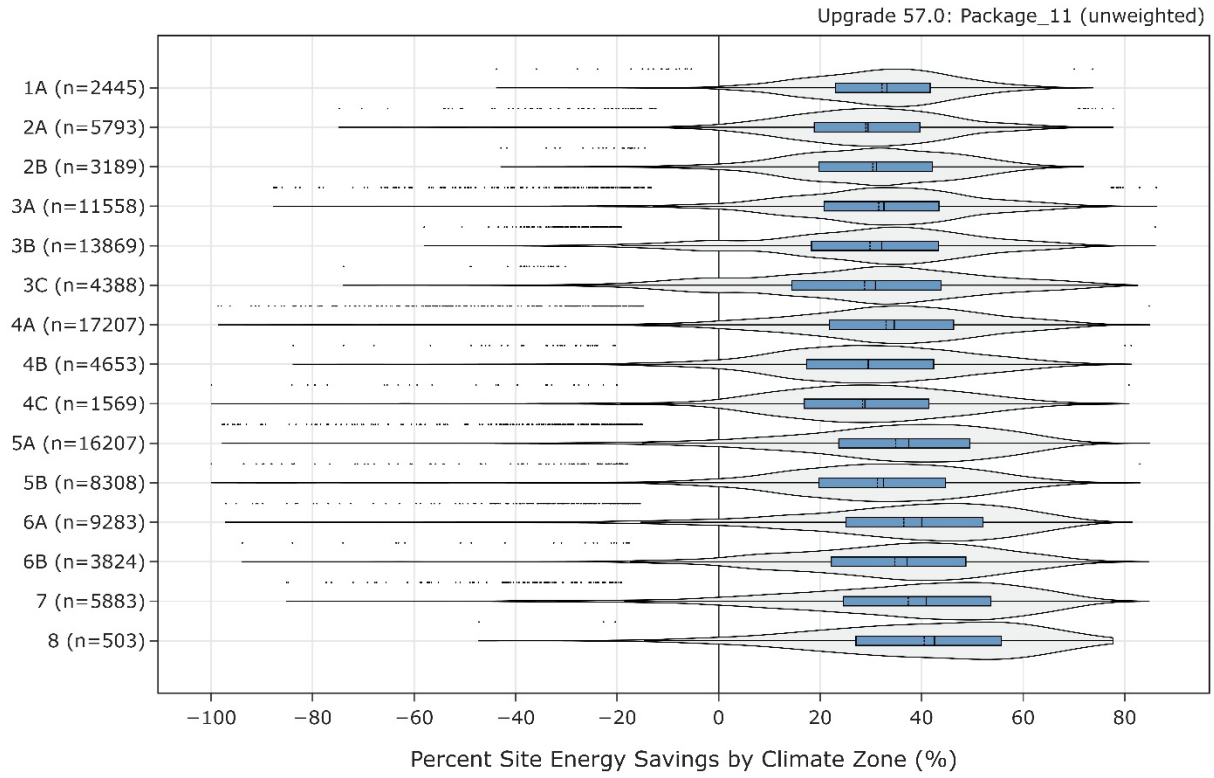

Figure 7. Percent site energy savings by climate zone between the baseline and Comprehensive GHP + High Efficiency Envelope + LED Lighting scenario

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5.6 Utility Bill Savings Distributions

When evaluating utility bills savings distributions, there is a slight correlation between total utility bills savings and climate zone (Figure 8). A map of the ASHRAE climate zones is included in 0 [22]. In warmer climate zones, the median utility bill savings reach 30%–35%, whereas in the colder climate zones, the median is closer to 20%–25%. This is due to cold climates having higher heating loads. This package converts much of the natural gas heating load to electricity (which costs more than natural gas in most locations), therefore the utility bills in colder climates are impacted more significantly. However, the efficiency improvements from the envelope and lighting measures and GHPs offset the utility bill costs, therefore all climates see net positive savings in utility bills in the top 75% of buildings.

There are some buildings in the bottom 25% in each climate zone that see negative utility bill savings (i.e., an increase in bills). These are primarily buildings that didn't originally have cooling, or buildings in locations where electricity is much more expensive than natural gas. In addition, these once again tend to be buildings with low loads/bills, where the percent change is sensitive to any change in magnitude.

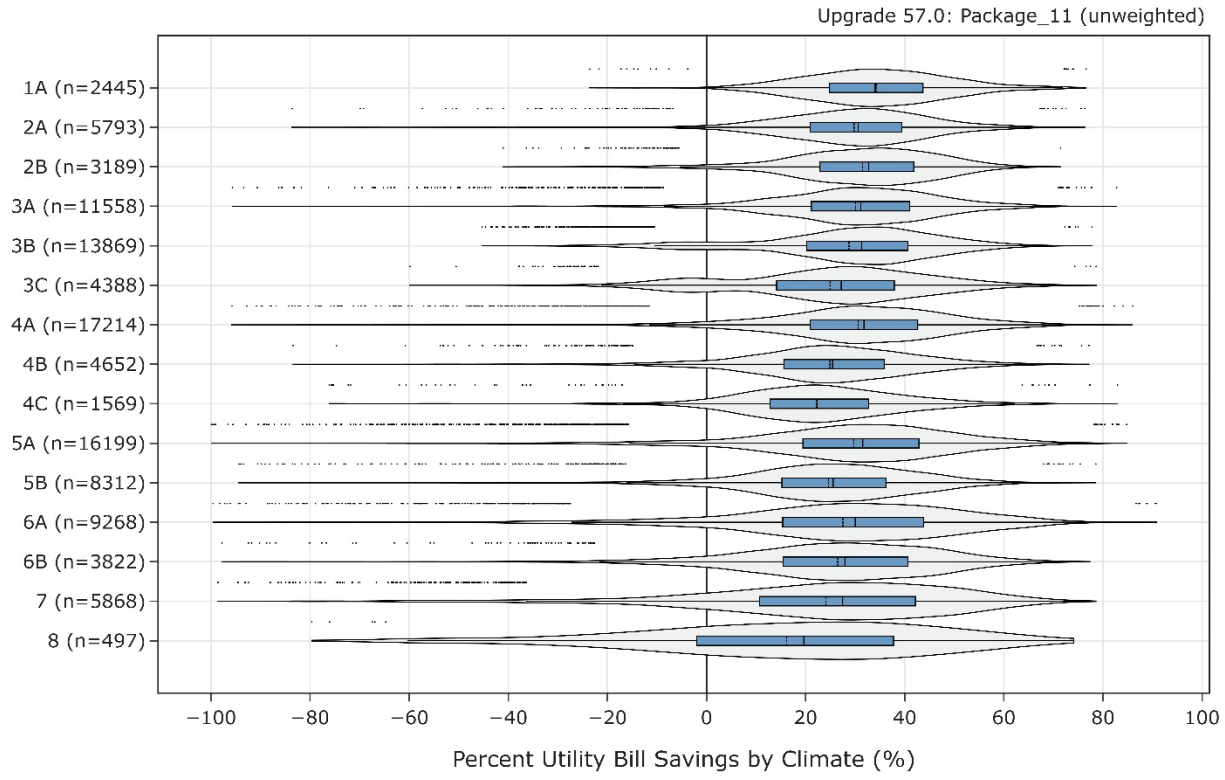

Figure 8. Percentage utility bills savings distribution for ComStock models with the Comprehensive GHP + High Efficiency Envelope + LED Lighting scenario applied by climate zone

When evaluating utility bill savings by fuel type (Figure 9), we see that natural gas, fuel oil, and propane bills show the highest reduction in bills, with the top 75% of buildings saving over 50%. Electricity bill savings are in the 10%–40% range for the middle 50% of buildings. Some buildings do show negative electricity bill savings, meaning the new electric heating load was not offset by the efficiency improvements of the GHP, envelope, or lighting measures.

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The total utility bill when using the mean electricity rate for each building saw 20%–40% savings for the middle 50% of buildings. Some buildings saw total bill savings above 50%, while others saw an increase in their total utility bill as a result of converting to electric heating.

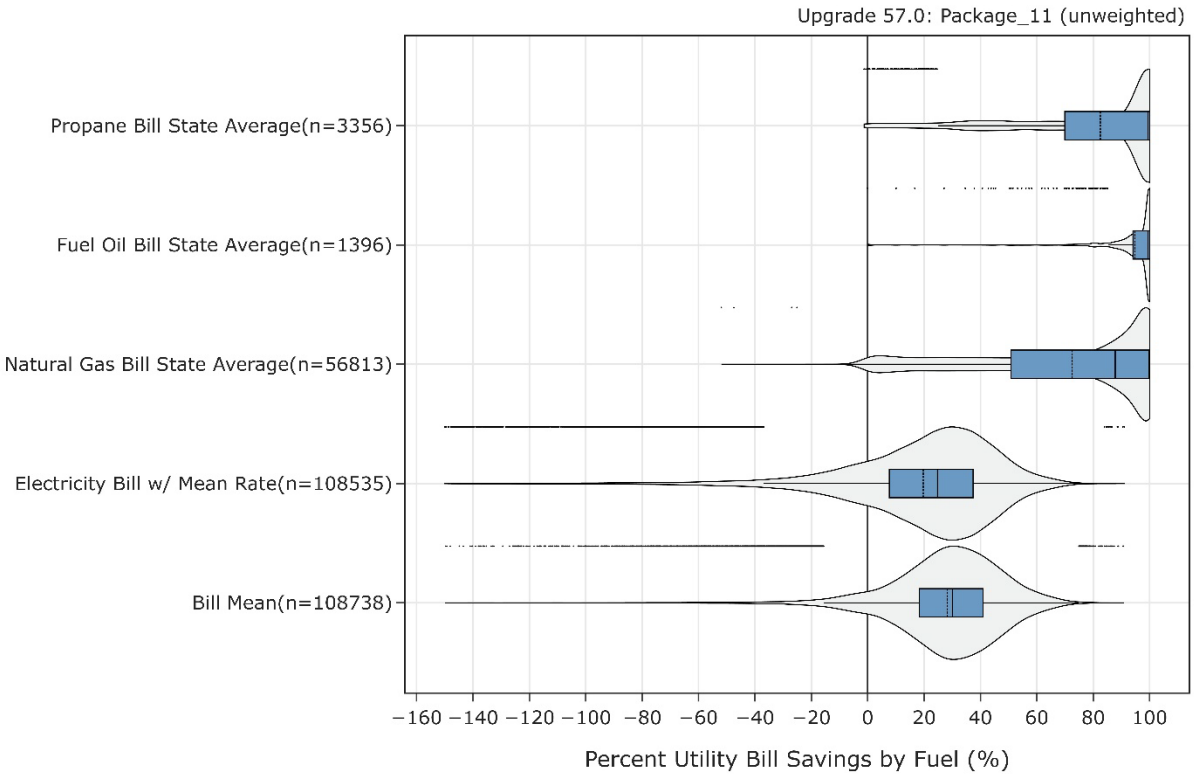

Figure 9. Percentage utility bills savings distribution for ComStock models with the Comprehensive GHP + High Efficiency Envelope + LED Lighting package applied by fuel type

5.7 Peak Impacts

Figure 10 shows the impact of the Comprehensive GHP + High Efficiency Envelope + LED Lighting package on seasonal peak hours, compared to the Baseline and the other Comprehensive GHP packages. Compared to the baseline, summer and shoulder peak times have minimal change, with the median moving earlier in the day by a fraction of an hour. Compared to the Comprehensive GHP + High Efficiency Envelope package, there is effectively no change in summer and shoulder peak times.

The median winter peak time moved earlier in the day by less than an hour compared to the baseline. Compared to the Comprehensive GHP + High Efficiency Envelope package, the winter peak hour moved very slightly earlier in the day. However, it is fair to say that the addition of the lighting measure does not have any substantial impact on the daily timing of seasonal peaks.

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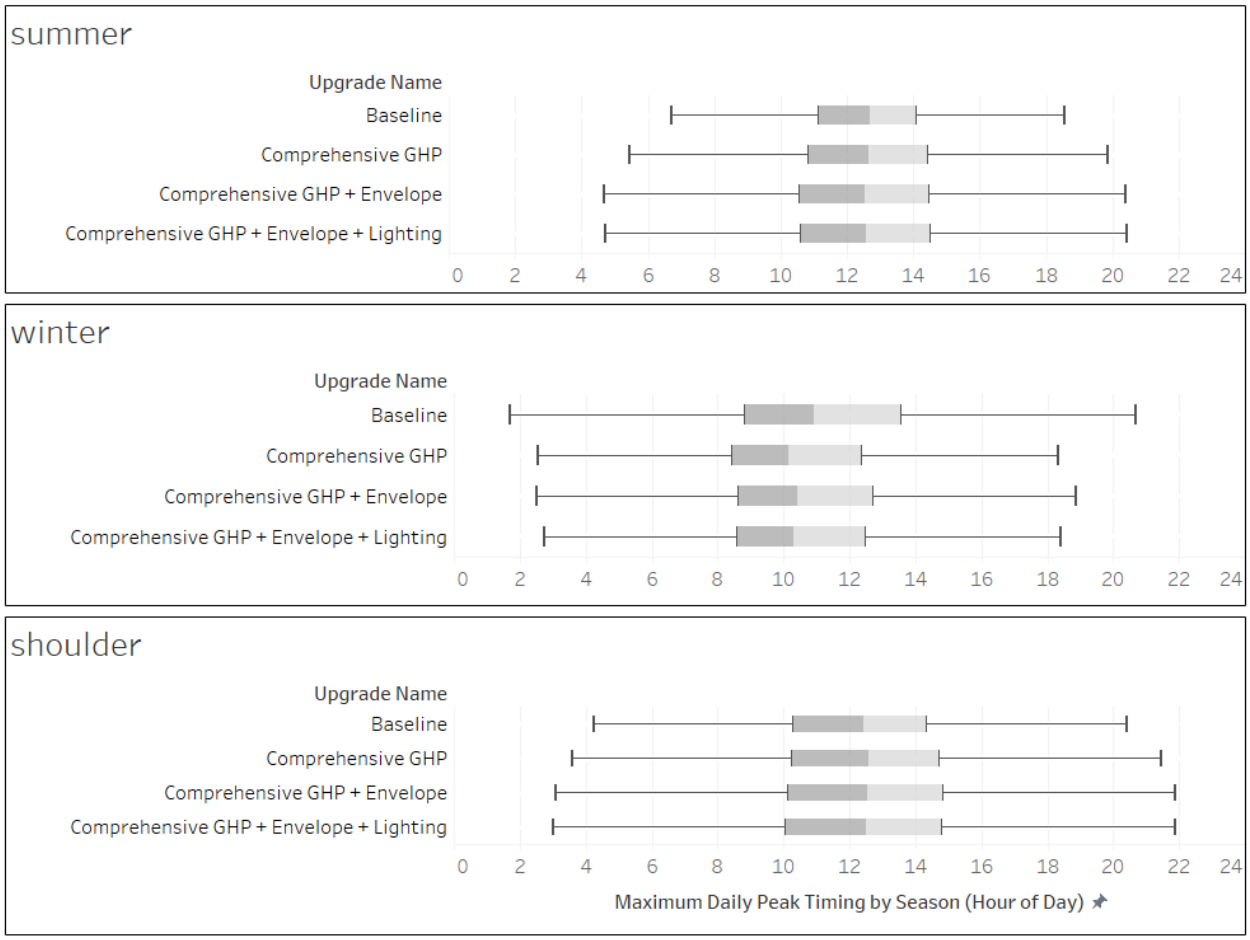

Figure 10. Maximum daily peak timing by season between the baseline, Comprehensive GHP scenario, Comprehensive GHP + High Efficiency Envelope scenario, and Comprehensive GHP + High Efficiency Envelope + LED Lighting scenario

Figure 11 shows the impact of the Comprehensive GHP packages on seasonal peak intensity for the median building. In all climate zones and seasons, the peak intensity is reduced further and further as more efficiency measures are added. The Comprehensive GHP + High Efficiency Envelope + LED Lighting package demonstrates the lowest peak intensity of the four scenarios shown for all climate zones and seasons. This indicates that the envelope and lighting measures are lowering the HVAC loads during critical hours of the day throughout the year.

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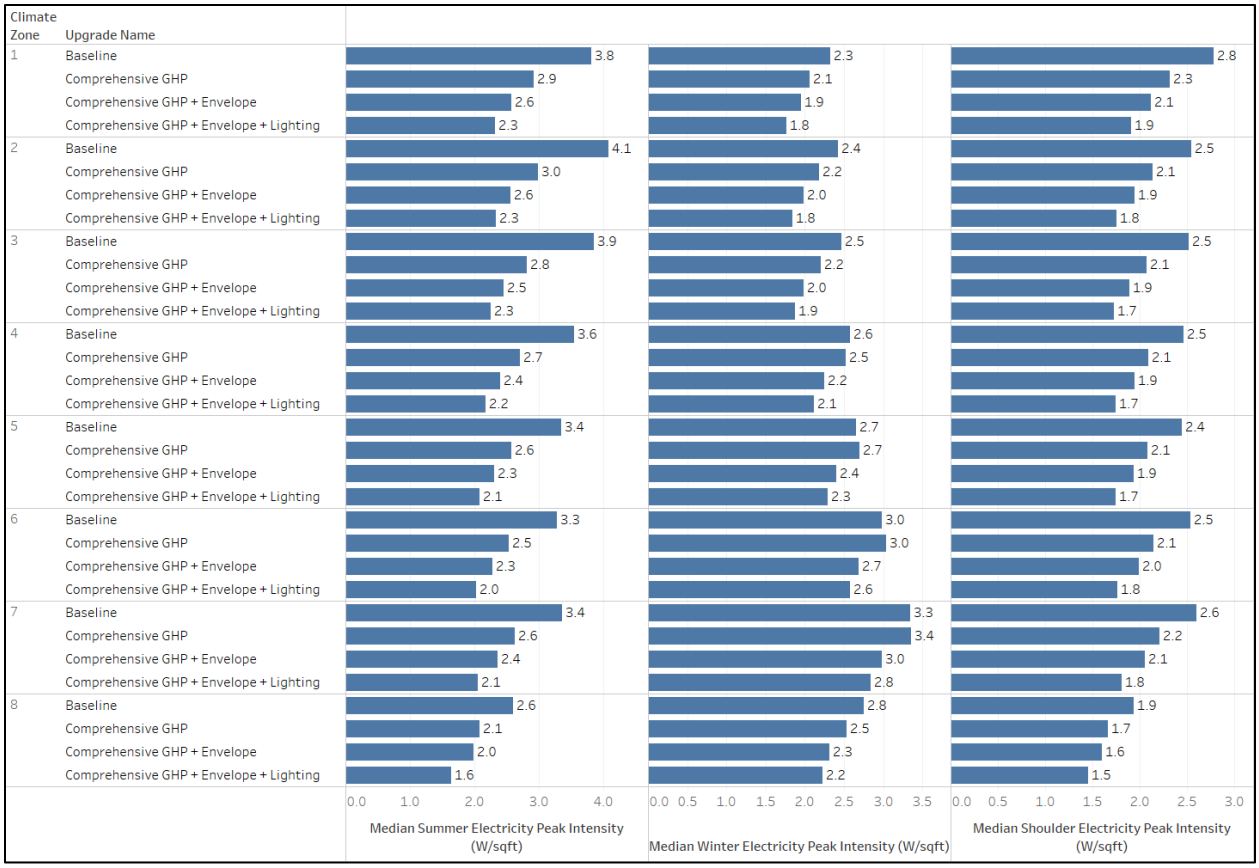

Figure 11. Maximum daily peak intensity by season between the baseline, Comprehensive GHP, Comprehensive GHP + High Efficiency Envelope, and Comprehensive GHP + High Efficiency Envelope + LED Lighting scenario

5.8 Sizing Analysis

During each building simulation, the GHEDesigner tool is used to automatically size the ground heat exchanger used in the model based on the annual load of the building. This process is explained in more detail in Section 3.10 as well as the individual measure documentation. When the envelope and lighting measures are combined with the GHP measures, the annual load of a building is reduced due to the efficiency improvements. Therefore, there is an opportunity to reduce the size of the required ground heat exchanger loop for the building. The heat pump unit itself is also resized in the measure after the envelope measures are applied, so it could also be possible to reduce the required capacity of the heat pump. This section compares several ground heat exchanger outputs for the Comprehensive GHP package, Comprehensive GHP + High Efficiency Envelope package, and Comprehensive GHP + High Efficiency Envelope + LED Lighting package. This gives insight into how much the envelope improvements and LED lighting can help reduce ground heat exchanger size, heat pump size, and hence drilling time and cost, for a building installing GHPs.

5.8.1 Ground Heat Exchanger Sizing

Figure 12 shows the borehole count, borehole depth, and total length of the ground heat exchanger for the three Comprehensive GHP packages. Because commercial buildings have such

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a wide range of size and load, the borehole count is normalized by building floor area (number of boreholes per thousand feet of floor area). The total ground heat exchanger loop length is calculated by multiplying the number of boreholes by the borehole depth, resulting in a rough approximation for the total length of drilling that would be required for the system.

When comparing the three packages, the borehole count, borehole depth, and total ground heat exchanger length get progressively smaller as more efficiency measures are added to the package. While the impact on the median building is rather minimum in all three cases, we see more substantial impacts on the more extreme ends of the box-and-whisker plot. In general, it appears that the envelope measures have a higher impact on the ground heat exchanger sizing than the lighting measure. This makes intuitive sense because the envelope measures primarily impact the HVAC end uses, while the lighting measure mainly impacts the lighting end use, with residual effects on HVAC end uses. Still, it is clear from the results of this package that combining GHPs with envelope and lighting improvements has a variety of positive impacts on the savings potential for a building, whether that be energy, emissions, utility bills, or installation and drilling costs.

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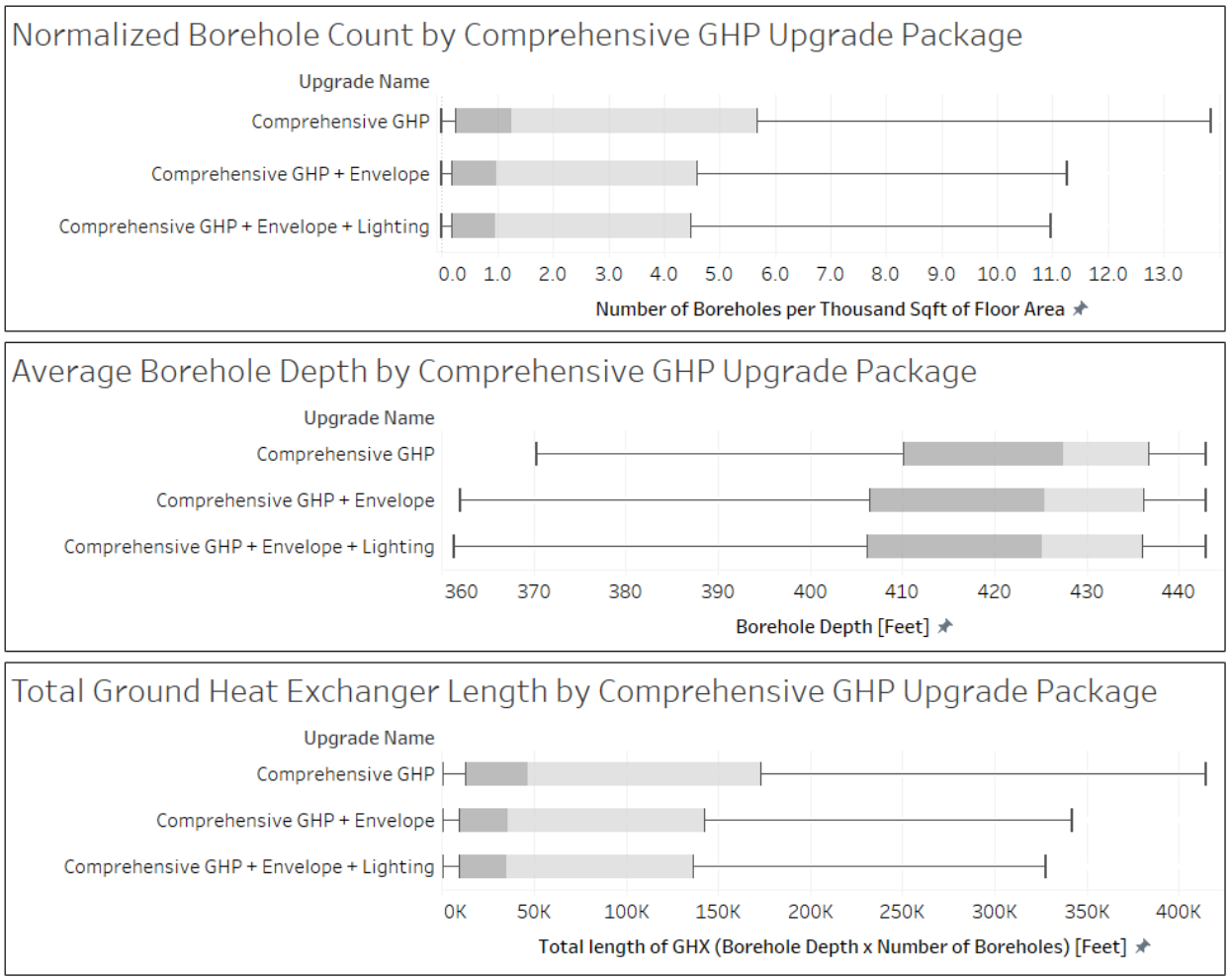

Figure 12. Ground heat exchanger sizing comparison of Comprehensive GHP, Comprehensive GHP + High Efficiency Envelope, and Comprehensive GHP + High Efficiency Envelope + LED Lighting package

5.8.2 Geothermal Heat Pump Sizing

In addition to recalculating the ground heat exchanger size, the envelope measures can also impact the capacity of the required geothermal heat pump unit. In the GHP packages, the envelope measures are applied before any heat pump sizing occurs, therefore the GHP capacities consider the impacts of the envelope improvements. As such, the GHP capacities in most buildings can be reduced because the envelope measures reduce the heating and cooling requirements.

Figure 13 shows the water-to-air GHP heating and cooling capacities for the two packages. Note that only water-to-air GHPs (modeled in the packaged GHP and console GHP measures) are represented in this plot. As explained in the Comprehensive GHP + High Efficiency Envelope measure documentation, the heat pump capacities are reduced by over 15% for much of the building stock when envelope measures are combined with GHPs. However, when adding the LED Lighting measure to this package, we see relatively minimal impact to the heating and cooling capacities across this board. Because the LED Lighting measure almost exclusively

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impacts the lighting end use, the heat pump capacity for most buildings is not reduced substantially. The more efficient lights give off less heat and therefore have some minimal impacts on a building's heating and cooling load, but we are not seeing notable savings in heat pump capacity with this upgrade included in the package.

Compared to the Comprehensive GHP + High Efficiency Envelope package, we see some heat pump capacity reductions at the upper whisker (20 kW or 1.6% for heating and 86 kW or 1.8%). The buildings at this end of the distribution are large buildings with significant loads/capacities to begin with. In general, we can say that the envelope measures have much more impact on the heat pump capacities than the lighting measure, which is expected.

The results for the water-to-water GHPs are not included at this time, as the output variables required for this analysis are not yet included in the dataset.

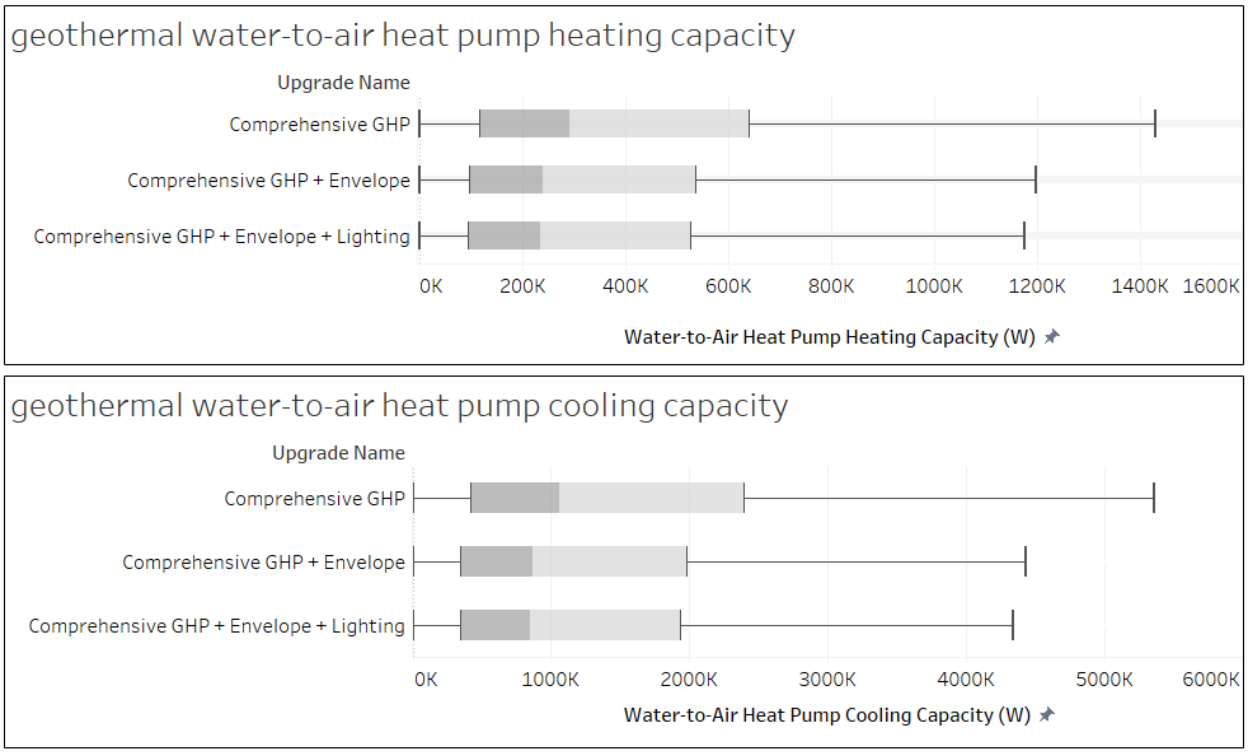

Figure 13. Water-to-air GHP heating and cooling capacities for Comprehensive GHP, Comprehensive GHP + High Efficiency Envelope, and Comprehensive GHP + High Efficiency Envelope + LED Lighting package

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Appendix. Additional Figures

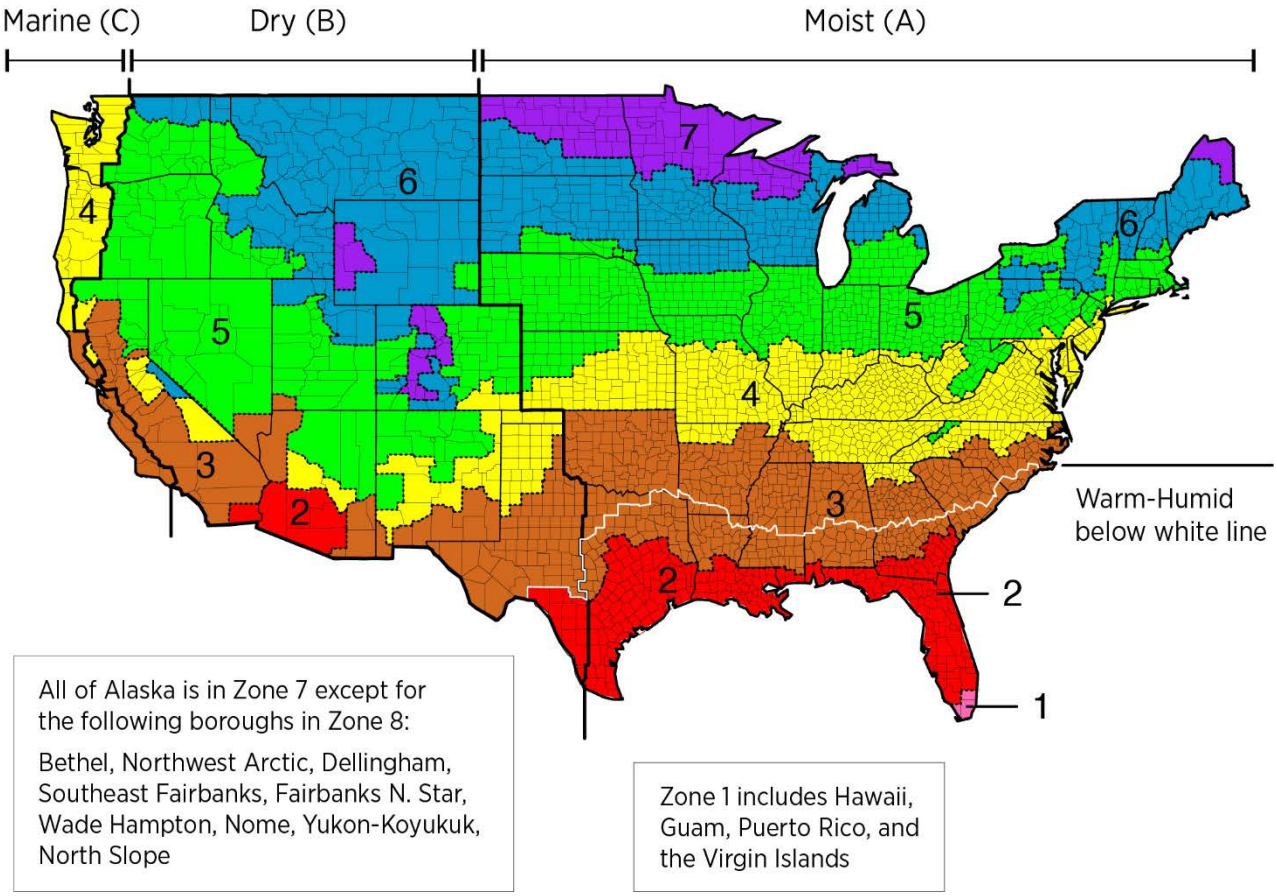

Figure A-1. Map of ASHRAE Climate Zones [22]

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