ComStock Measure Documentation:

Geothermal Heat Pumps + High Efficiency Envelope 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
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

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 sub-hourly 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 sub-hourly 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 different savings 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 six measures—Central Hydronic Geothermal Heat Pump (GHP), Packaged GHP, Console GHP, Window Replacement, Exterior Wall Insulation, and Roof Insulation—which we will refer to collectively as the "Comprehensive GHP + High Efficiency Envelope" 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.

Table ES-1. Key Modeling Specifications

Package Title:	Comprehensive GHP + High Efficiency Envelope Package
Technology Description	This package replaces existing HVAC systems with one of three GHP-based systems, as well as upgrades wall insulation, roof insulation, and replaces windows in applicable models. It is a combination of six upgrades: Hydronic GHP, Packaged GHP, Console GHP, Wall Insulation, Roof Insulation, and New Windows. It is a combination of two existing measure packages: Comprehensive GHP and High Efficiency Envelope.
Performance Assumptions	Some key performance assumptions of each measure include: • <u>Packaged Water-to-Air GHP</u>: 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. • <u>Central Hydronic Water-to-Water GHP</u>: 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. • <u>Console Water-to-Air GHP</u>: 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. • <u>Window Replacement</u>: 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. • <u>Exterior Wall Insulation</u>: R-values of new wall insulation are determined by climate zone, ranging from R-13 in warmest climates to R-29 in coldest climates. • <u>Roof Insulation</u>: R-values of new roof insulation are determined by climate zone, ranging from R-21 in warmest climates to R-37 in coldest climates.
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. • <u>Packaged Water-to-Air GHP</u>: 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. • <u>Central Hydronic Water-to-Water GHP</u>: 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. • <u>Console Water-to-Air GHP</u>: 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. • <u>Window Replacement</u>: 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

Package Title:	Comprehensive GHP + High Efficiency Envelope Package
	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.
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 improvements. In summary, this package demonstrates that the number of boreholes is reduced by 21% and capacity of the geothermal heat pump is reduced by 18% (based on median) due to the addition of envelope measures.

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	877.8	1,524.1	57.6%	1,381.0	63.6%
Electricity	478.7	3,173.4	15.1%	2,781.7	17.2%
Other Fuel*	41.1	53.7	75.4%	52.7	78.0%
Total	1,397.6	4,751.2	29.4%	4,215.5	33.2%

*combination of Fuel Oil and Propane annual site energy results

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	55.8%	15.7	61.8%
Electricity	19.4	107.7	18.0%	94.0	20.6%
Fuel Oil	0.6	0.7	89.8%	0.6	93.1%
Propane	0.7	1.0	67.5%	1.0	68.3%
Total	30.4	126.8	24.0%	111.4	27.3%

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	58.6	101.8	57.6%	92.3	63.6%
Electricity	31.0	239.6	13.0%	212.2	14.6%
Fuel Oil	1.6	1.7	89.7%	1.7	93.1%
Propane	1.9	2.7	68.7%	2.7	69.4%
Total	93.1	345.9	26.9%	308.9	30.1%

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, and 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.

1.3 Summary

The building envelope can impact the performance and required capacity of HVAC equipment in a building. For this reason, this package pairs the GHP upgrades with envelope to understand the combined impacts of these measures. By comparing the standalone GHP upgrades with the Comprehensive GHP + High Efficiency Envelope package, we can analyze how much improving the envelope of a building can impact the performance and size requirements of the GHP system.

2 ComStock Baseline Approach

The following sections provide high-level summaries of the ComStock baseline approach for HVAC systems, windows, walls, and roofs. 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 land available for the ground heat exchanger.

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].

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

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.

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.

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.

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 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 6). 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 6. 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 7). Second, it finds all the constructions used by exterior walls in the model, clones them, adds a layer of insulation to the cloned 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 7. 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 8), 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 8. 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.

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 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 statistics from this implementation are shown in Table 9. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 9. 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 [12].

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 [13]. Residential prices are used because commercial prices are only available at the national resolution. Additionally, most commercial buildings using these fuels are assumed to be smaller buildings where a residential rate is likely realistic. For states where state-level pricing was available, these prices are used directly. For other states, Petroleum Administration for Defense District (PADD) average pricing is used. For states where PADD-level pricing is not available, national average pricing is used.

The primary resource for ComStock electric utility rates is the Utility Rate Database (URDB) [14], 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 [15]. 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.

3.8 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 [16], [17]. 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 [18]. Emissions due to on-site combustion of fossil fuels use the emissions factors shown in Table 10, which are from Table 7.1.2(1) of draft American National Standards Institute/Residential Energy Services Network/International Code Council 301 [19]. 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.

Table 10. 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

3.9 GHEDesigner Workflow

GHEDesigner is a software tool available as a Python package for designing ground heat exchangers used with GHP systems [20]. 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.

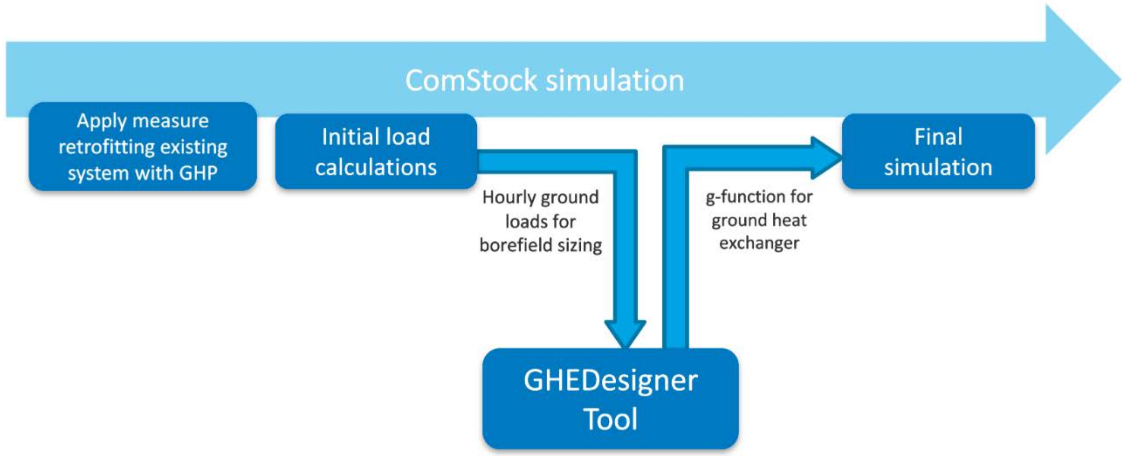

Figure 1. ComStock GHEDesigner workflow

All figures created by the authors, unless noted otherwise.

3.10 Limitations and Concerns

3.10.1 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.

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 [21].

3.10.2 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.

4 Output Variables

Table 11 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 11. 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.).

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).

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 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 package by upgrade combination. As a reminder, the wall, roof, and window measures were only applied if one of the three GHP measures was applicable. In a vast majority of cases, all three envelope measures were applied. The most common scenario was the Packaged GHP + Walls + Roof + Windows, making up 61.7% of floor area, followed by Hydronic GHP + Walls + Roof + Windows (11.7% of floor area) and Console GHP + Walls + Roof + Windows (10.8% of floor area). In less than 2% of floor area, only two of the envelope measures were applied. There are other upgrade combinations not shown in the figure; however, they make up less than 0.1% of floor area. 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.

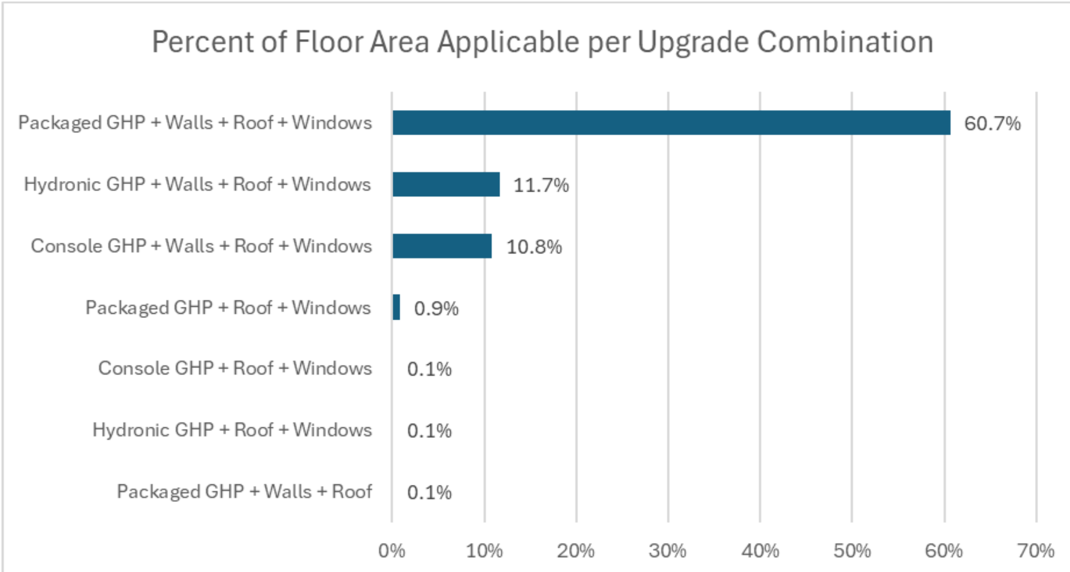

Figure 2. Applicability for the Comprehensive GHP + High Efficiency Envelope package by upgrade combination

5.2 Stock Energy Impacts

The Comprehensive GHP + High Efficiency Envelope package demonstrates 28.7% total site energy savings (1,398 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 12.

Table 12. Site Energy Savings from Comprehensive GHP + High Efficiency Envelope 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	877.7	1,524.1	57.6%	1,413.1	62.1%
Total electricity	478.2	3,172.9	15.1%	2,828.9	16.9%
Total heating	896.4	1,309.0	68.5%	1,192.0	75.2%
Gas heating	877.7	965.2	90.9%	909.8	96.5%
Electric heating	-22.4	260.1	-8.6%	240.1	-9.3%
Electric fans	142.8	568.5	25.1%	512.1	27.9%
Electric cooling	394.7	727.0	54.3%	655.5	60.2%
Electric interior lighting	0.0	440.4	0.0%	392.5	0.0%
Total	1,397.0	4,865.0	28.7%	4,295.0	32.5%

Throughout the subsequent results sections, the results of the Comprehensive GHP + High

Efficiency Envelope package will be compared to the baseline and the Comprehensive GHP package. A summary of these two 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.

The assumptions and applicability of the GHP measures in both packages are the same. With the application of envelope 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 stock energy consumption of the baseline and the two packages by fuel type and end use are illustrated in Figure 3.

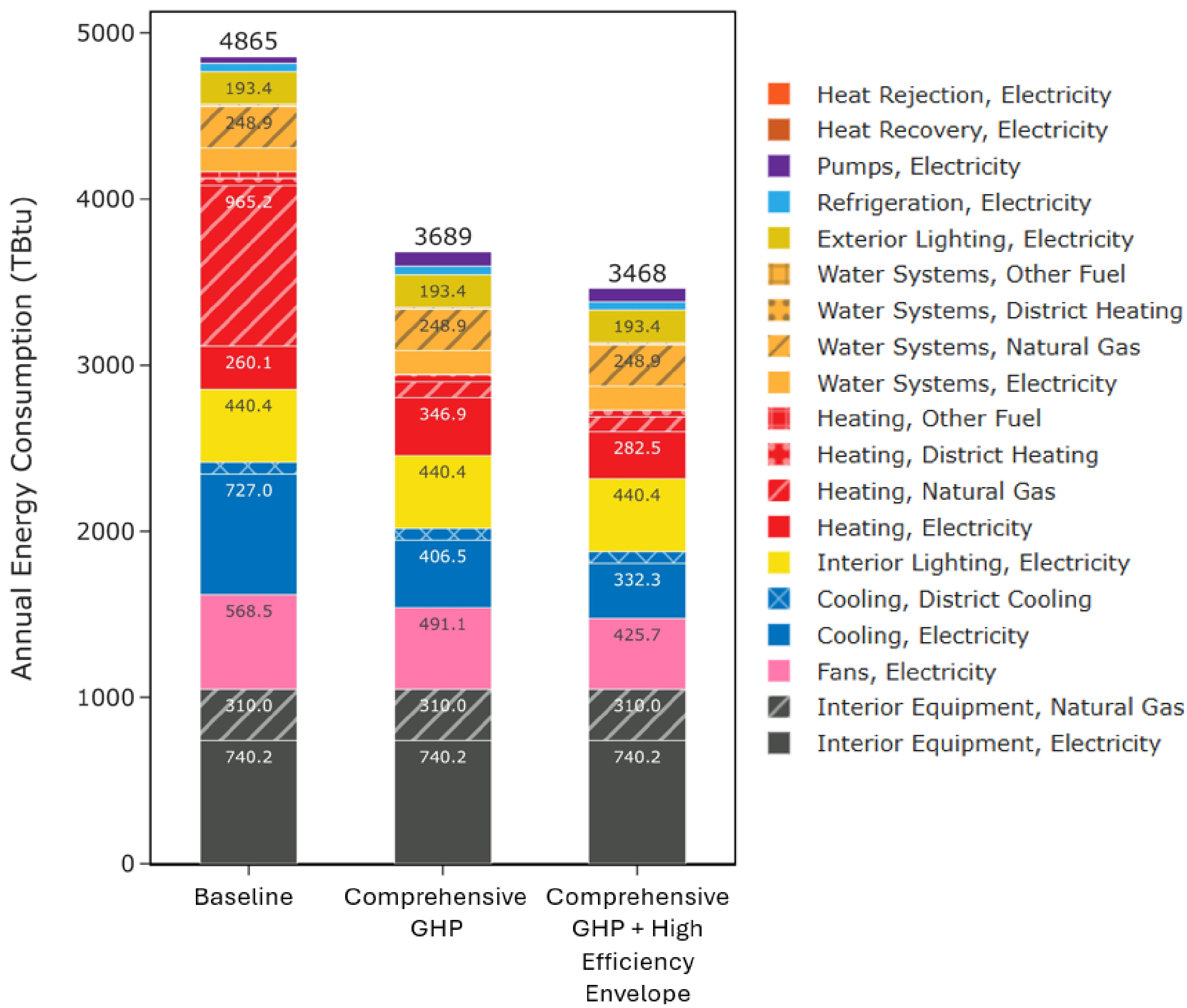

Figure 3. Comparison of annual site energy consumption between the ComStock baseline, the Comprehensive GHP scenario, and the Comprehensive GHP + High Efficiency Envelope scenario

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

Compared to the Comprehensive GHP package, the Comprehensive GHP + High Efficiency Envelope package shows an additional 4.5% (221 TBtu) total site energy savings. The additional savings are primarily attributed to electric heating, cooling, and fan energy. With improved wall and roof insulation and new windows, the buildings will maintain internal temperatures better and therefore reduce HVAC load. A comparison of the results for the two packages is summarized in Table 13:

Table 13. Energy Savings Comparison Between Comprehensive GHP + High Efficiency Envelope Package and Comprehensive GHP Package

Compared to the *Comprehensive GHP* package, the Comprehensive GHP + High Efficiency Envelope package demonstrates:
6.0% stock **site energy** savings (221.0 TBtu)
18.3% stock **cooling electricity** savings (74.2 TBtu)
13.3% stock **fan electricity** savings (65.4 TBtu)
18.6% stock **heating electricity** savings (64.4 TBtu)
8.9% stock **pump electricity** savings (7.8 TBtu)
8.2% stock **heating natural gas** savings (7.8 TBtu)

Compared to the baseline, this package reduces stock-level natural gas heating by 91%, which is expected because the implementation of the GHP measures converts nearly all natural gas or other fuel space heating to electricity in buildings for which the measures are applicable. There are a few exceptions to this, including some warehouse and retail buildings, in which parts of the building are served by gas unit heaters that are not replaced by GHPs. This is described in more detail in the documentation of the individual GHP measures (Central Hydronic GHP, Packaged GHP, Console GHP). The application of envelope measures in this package results in some additional gas heating savings in warehouse and retail models where parts of the building maintain natural gas heating.

In addition, 16% of the ComStock floor area is made up of HVAC systems that do not receive any of the three GHP measures, including district systems, direct evaporative coolers, and a few other less common system types. Therefore, this package does not convert 100% of the natural gas heating load in ComStock to electricity.

There is a 9% increase in site electric heating energy compared to the baseline, which is also expected when transitioning from gas heating to electric heating. The magnitude of the site's gas space heating savings (878 TBtu) is much larger than the magnitude of the site's electric space heating increase (22.4 TBtu). This is due to the same space heating load being met more efficiently with heat pumps (heating coefficient of performance typically between 3 and 5) relative to the existing gas or electric coils in ComStock (efficiency 0.8 for gas and 1 for electric). The envelope measures mitigate the increase in electric heating substantially – in the Comprehensive GHP scenario, electric heating increased by 33%, but in the Comprehensive GHP + High Efficiency Envelope scenario, electric heating only increased by 9%.

As a result, total site heating usage across all heating fuels decreases by 68% compared to the baseline, which contributes substantially to the total site energy savings of 29%. However, site energy savings is not a comprehensive assessment of other notable considerations such as source energy savings, energy costs, peak demand, or emissions.

The Comprehensive GHP + High Efficiency Envelope package also shows cooling savings of 54% compared to the baseline because of the higher efficiency of the various heat pump configurations compared with existing cooling systems. The fans end use shows 25% savings, which is a result of numerous operational changes across the three GHP configurations, including changes in supply temperatures, cooling load requirements, and airflow rates. The pump end use, while making up a small portion of the total stock energy, experienced a 107% increase compared to the baseline due to the pumping needs of the ground heat exchangers and condenser loops of the new GHP systems. When compared to the Comprehensive GHP package, all three of these end uses show improved stock-level impacts (higher savings for cooling and fans, lower penalty for pumps) when the GHP measures are combined with the high efficiency envelope measures.

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 package resulted in $29–$32 billion nationally of utility bills savings (22%–26% reduction) depending on the electricity rate used (Figure 4).

Natural gas bills are reduced by $9 billion (53%) because of fuel switching much of the space heating 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 package, the electricity bills showed a $18–$21 billion decrease in electricity bills nationally depending on the rate chosen.

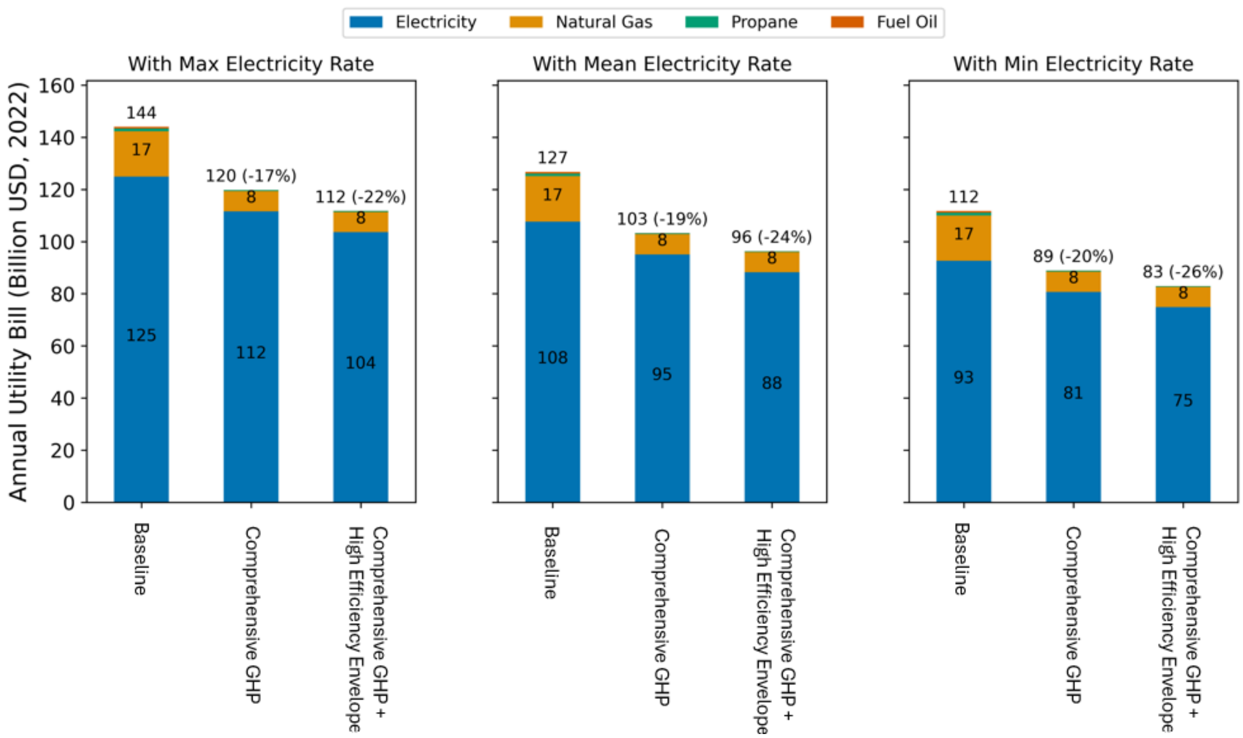

Figure 4. National annual utility bills comparison of the ComStock baseline, Comprehensive GHP scenario, and Comprehensive GHP + High Efficiency Envelope scenario using maximum, mean, and minimum electricity rates

Compared to the Comprehensive GHP package, the Comprehensive GHP + High Efficiency Envelope package shows no notable change in natural gas bills. However, the addition of the envelope measures to the GHP scenario adds $6–$8 billion of additional electricity bill savings nationally. This is due to the lower electric heating, cooling, and fan requirements of buildings with an improved building envelope. A comparison of the utility bill results for the Comprehensive GHP + High Efficiency Envelope versus the Comprehensive GHP package is summarized in Table 14:

Table 14. Utility Bill Savings Comparison Between Comprehensive GHP + High Efficiency Envelope Package and Comprehensive GHP Package, Using the Mean Electricity Rate

Compared to the *Comprehensive GHP* package, the Comprehensive GHP + High Efficiency Envelope package demonstrates:
6.8% total utility bill savings across all fuels ($7 billion USD nationally)
7.4% electricity utility bill savings ($7 billion USD nationally)
No change in natural gas utility bill savings
No change in propane and fuel oil utility bill savings

5.4 Stock Carbon Emissions Equivalent Impact

ComStock simulation results show avoided emissions across all three electricity grid scenarios and all on-site combustion fuel types (Figure 5). When combining all fuel types, the Comprehensive GHP + High Efficiency Envelope package resulted in 75 to 112 million metric tons (MMT) of carbon emissions equivalent (CO_2e) avoided (25%–31% 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 to a high efficiency ground-coupled electric system. 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 package, the LRMER Low RE Cost and High RE Cost scenario show a 13 MMT CO_2e and 31 MMT CO_2e decrease in electricity emissions, respectively. The eGRID scenario shows 49 MMT CO_2e of avoided emissions from the electricity grid.

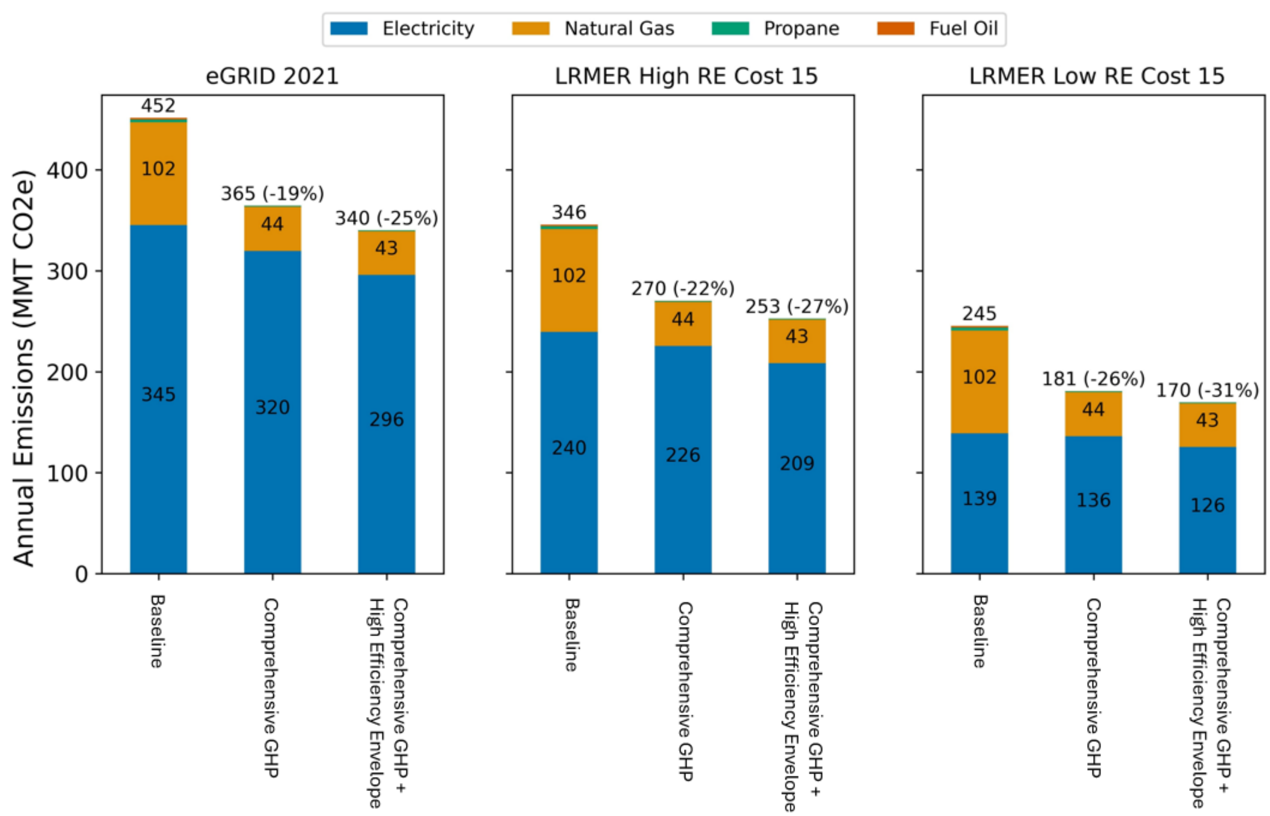

Figure 5. CO_2e comparison of the ComStock baseline, Comprehensive GHP scenario, and Comprehensive GHP + High Efficiency Envelope scenario

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..

Compared to the Comprehensive GHP package, the Comprehensive GHP + High Efficiency Envelope package demonstrates additional reductions in electricity, natural gas, and total emissions. This is due to the envelope measures reducing space heating and cooling loads in buildings. A comparison of the eGRID 2021 emissions results for the Comprehensive GHP + High Efficiency Envelope versus the Comprehensive GHP package is summarized in Table 15:

Table 15. Emissions Savings Comparison Between Comprehensive GHP + High Efficiency Envelope Package and Comprehensive GHP Package, Using eGRID 2021 Emissions Results

Compared to the *Comprehensive GHP* package, the Comprehensive GHP + High Efficiency Envelope package demonstrates:
6.8% stock **total emissions** savings across all fuels (25 MMT CO_2e)
7.5% stock **electricity emissions** savings (24 MMT CO_2e)
2.3% stock **natural gas emissions** savings (1 MMT CO_2e)
No change in propane and fuel oil emissions savings

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 cost savings, or avoided emissions.

Figure 6 shows the percent savings distributions of the baseline ComStock models versus the Comprehensive GHP + High Efficiency Envelope 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 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 50%–70% in most buildings because of the replacement of existing air-cooled direct-expansion cooling systems with a more efficient ground-coupled system, combined with several envelope improvements. 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.

Pump energy increased by 10%–90% due to the added pumping demands 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 75% of buildings, while 25% saw an increase in fan energy. Many of the buildings with very large changes in fan energy were found to be warehouses, which start out with low HVAC loads and therefore percentage calculations are sensitive to small energy use 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 25% savings.

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 minimal compared to total site energy.

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

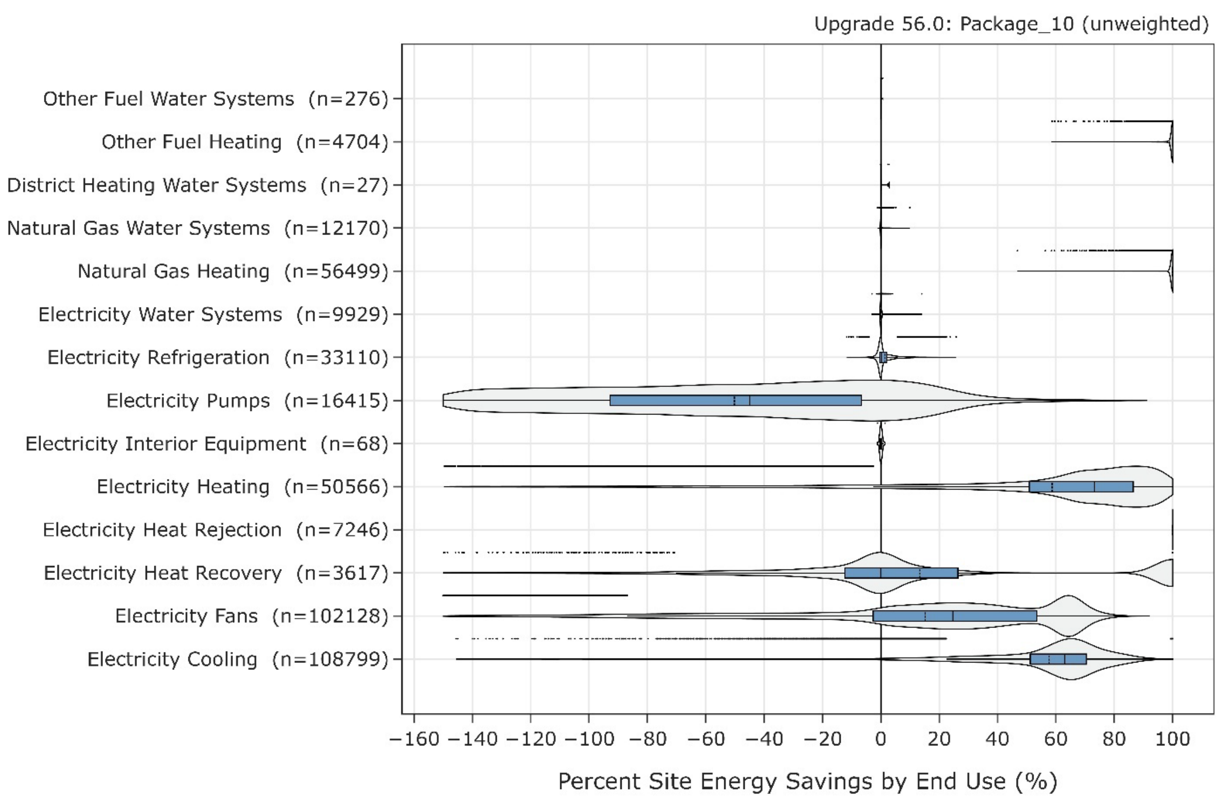

Figure 6. Percent site energy savings distribution for ComStock models with the Comprehensive GHP + High Efficiency Envelope package applied by end use and fuel type

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 warmest climate zones (1 through 3), the median building shows site energy savings around 25%–30%, with the 75th percentile reaching around 40% site energy savings. In colder climate zones (5 through 7) we see median site energy savings up to 35%–40% with the 75th percentile reaching 50% or more. This trend indicates that heating energy savings for this package is outpacing cooling energy savings, which is why the colder climates with heating dominated load see higher savings.

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. 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 for 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. Since cooling loads are present during most parts of the year in commercial buildings, cold climates tend to exhibit more balanced load profiles. GHPs can be more advantageous in climates with more balanced heating and cooling loads because of the long-term ground temperature implications on the ground heat exchange size.

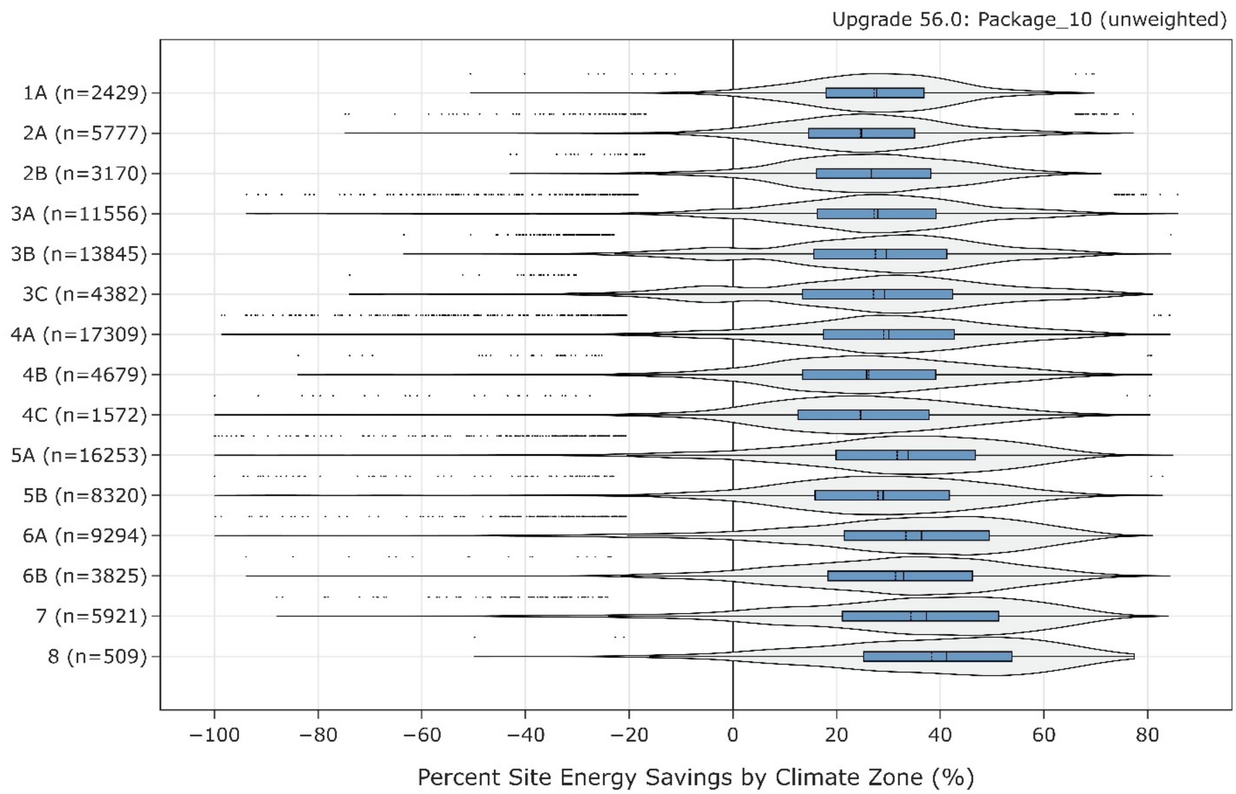

Figure 7. Percent site energy savings by climate zone between the baseline and Comprehensive GHP + High Efficiency Envelope scenario

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%, whereas in the colder climate zones, the median is closer to 20%. This is due to colder climates having higher heating loads. This package converts much of the natural gas heating load to electricity (which costs more than natural gas in many locations), therefore the utility bills in colder climates show lower savings. However, the efficiency improvements from the envelope measures and GHPs offset the utility bill costs, therefore all climates see net positive savings in utility bills in the median building.

There are some buildings in the bottom 25th percentile in each climate zone that see negative utility bill savings (i.e., an increase in bills). This could be buildings that didn't originally have cooling, or buildings in locations where electricity is much more expensive than natural gas, among other reasons.

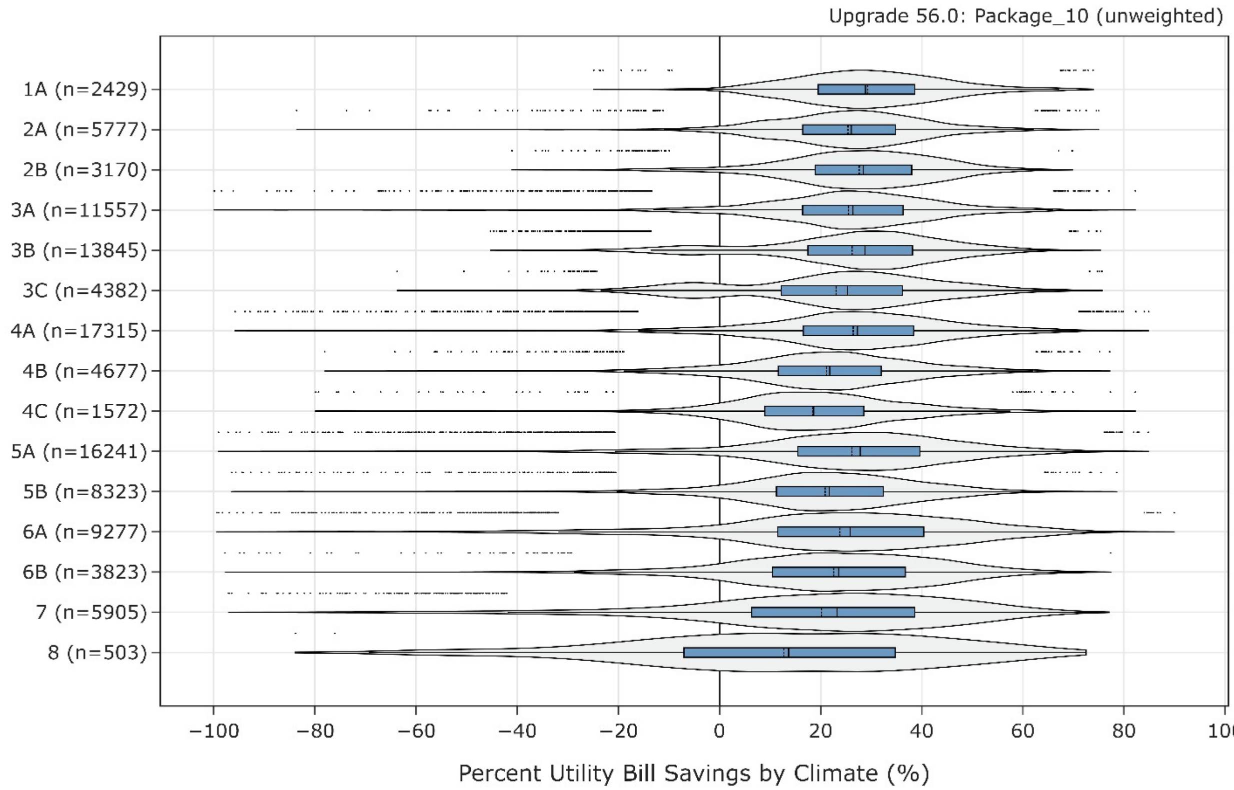

Figure 8. Percentage utility bills savings distribution for ComStock models with the Comprehensive GHP + High Efficiency Envelope scenario applied by climate zone

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 most buildings saving over 50% on these bills. Electricity bill savings are in the 0–30% 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 or envelope measures.

The total utility bill when using the mean electricity rate for each building saw 15%–40% savings in 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. Utility bill impacts of converting from natural gas to electricity will vary by building because of the regional differences in the prices of natural gas versus electricity.

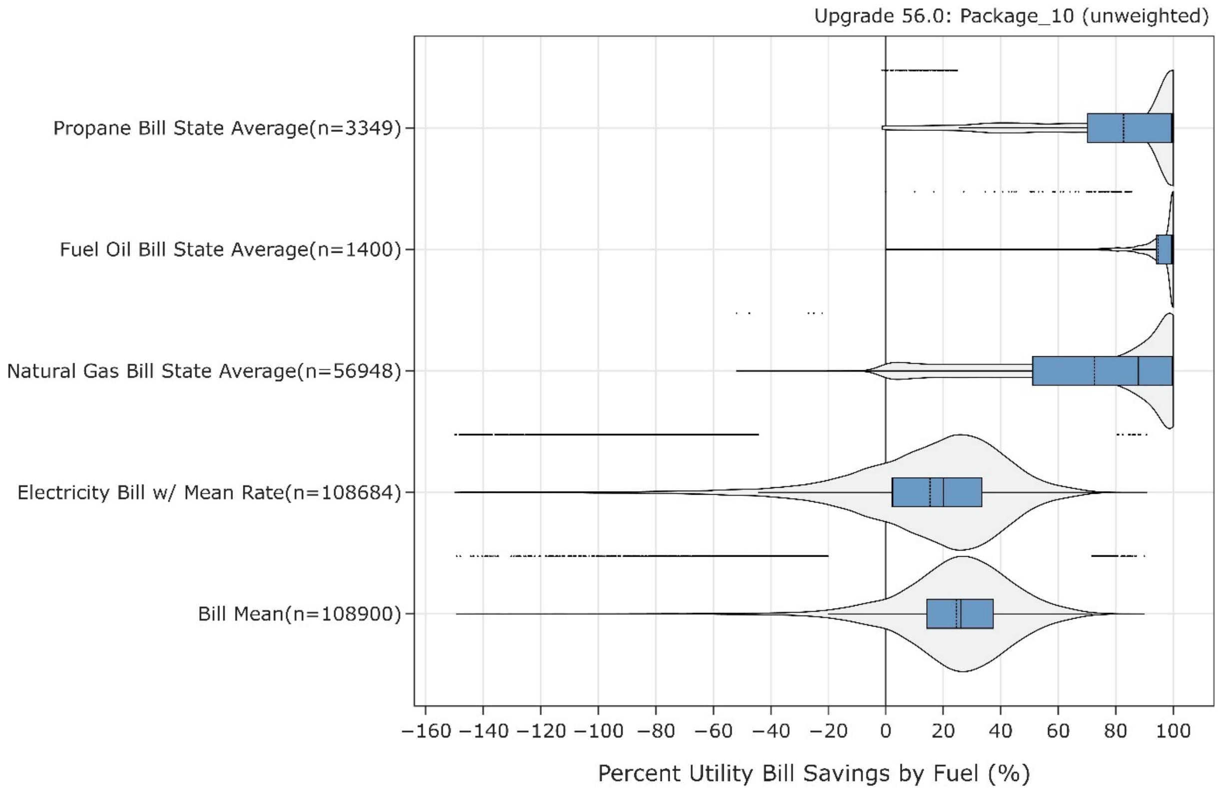

Figure 9. Percentage utility bills savings distribution for ComStock models with the Comprehensive GHP + High Efficiency Envelope package applied by fuel type

5.7 Peak Impacts

Figure 10 shows the impact of the Comprehensive GHP + High Efficiency Envelope package on seasonal peak hours, compared to both the Baseline and the Comprehensive GHP package. The summer peak moves slightly earlier in the day, compared to both the Baseline and Comprehensive GHP package. The envelope improvements in this package help the building maintain temperature better, therefore the cooling-driven summer peak is moved slightly earlier in the day, before the hottest temperatures occur.

In the Comprehensive GHP package, the winter peak is shifted earlier in the day by nearly an hour as morning electric heating now has more influence on peak load in winter. The combined impact of morning warmup during the time of day that is often the coldest can exacerbate this morning peak. This is one of the concerns with mass adoption of electric heating, as it becomes harder to offset morning loads with renewable sources like solar. However, when the envelope measures are added, the winter peak moves later in the day, closer to the winter peak of the Baseline. This is beneficial for grid planning, as the later winter peaks align better with solar generation profiles.

The shoulder peak times remain relatively unchanged in the Baseline and both Comprehensive GHP packages. The distribution of peak times becomes slightly wider in the upgrade scenarios, but the median peak time remains nearly the same in all scenarios.

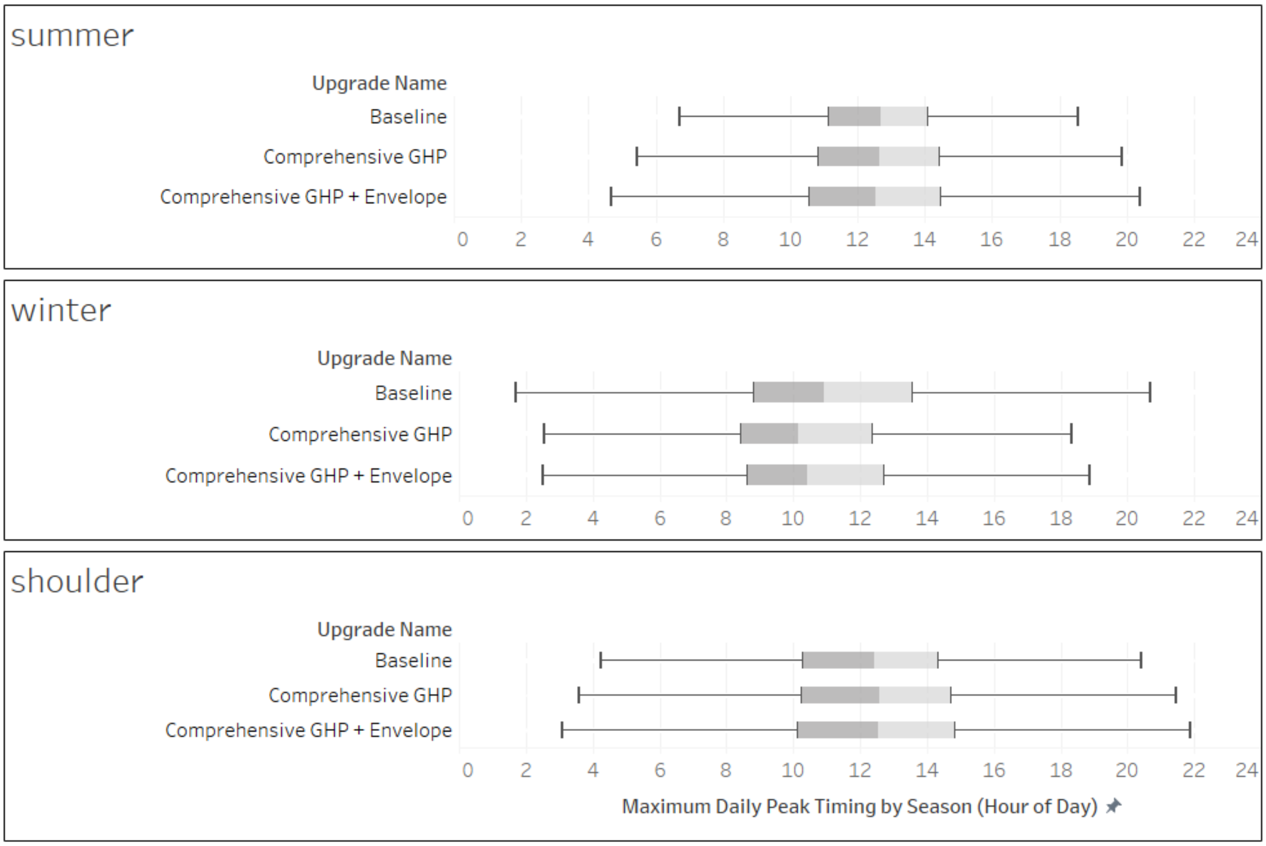

Figure 10. Maximum daily peak timing by season between the baseline, Comprehensive GHP scenario, and Comprehensive GHP + High Efficiency Envelope scenario

Figure 11 shows the impact of the Comprehensive GHP packages on seasonal peak intensity for the median building. For the Comprehensive GHP + High Efficiency Envelope package, summer, winter, and shoulder peak intensities are reduced across all climate zones. In all seasons and climate zones, the peak intensity for this package is lower than that of the Comprehensive GHP scenario, indicating that the envelope measures are helping reduce HVAC loads at critical hours of the day.

In the coldest climates, the winter peak intensity for the Comprehensive GHP scenario is the same or higher than the baseline, which is due to fuel switching of the heating load. However, with the envelope measures applied, the Comprehensive GHP + High Efficiency Envelope package shows winter peak intensity reductions for all climate zones. This is insightful for grid and utility planners and other stakeholders who may have concerns over winter peak spikes due to mass conversion to electric heating systems. However, the results of this scenario show that when paired with envelope improvements, we can mitigate the winter peak impacts of heat pumps and see peak reductions throughout the year in all climates in the U.S.

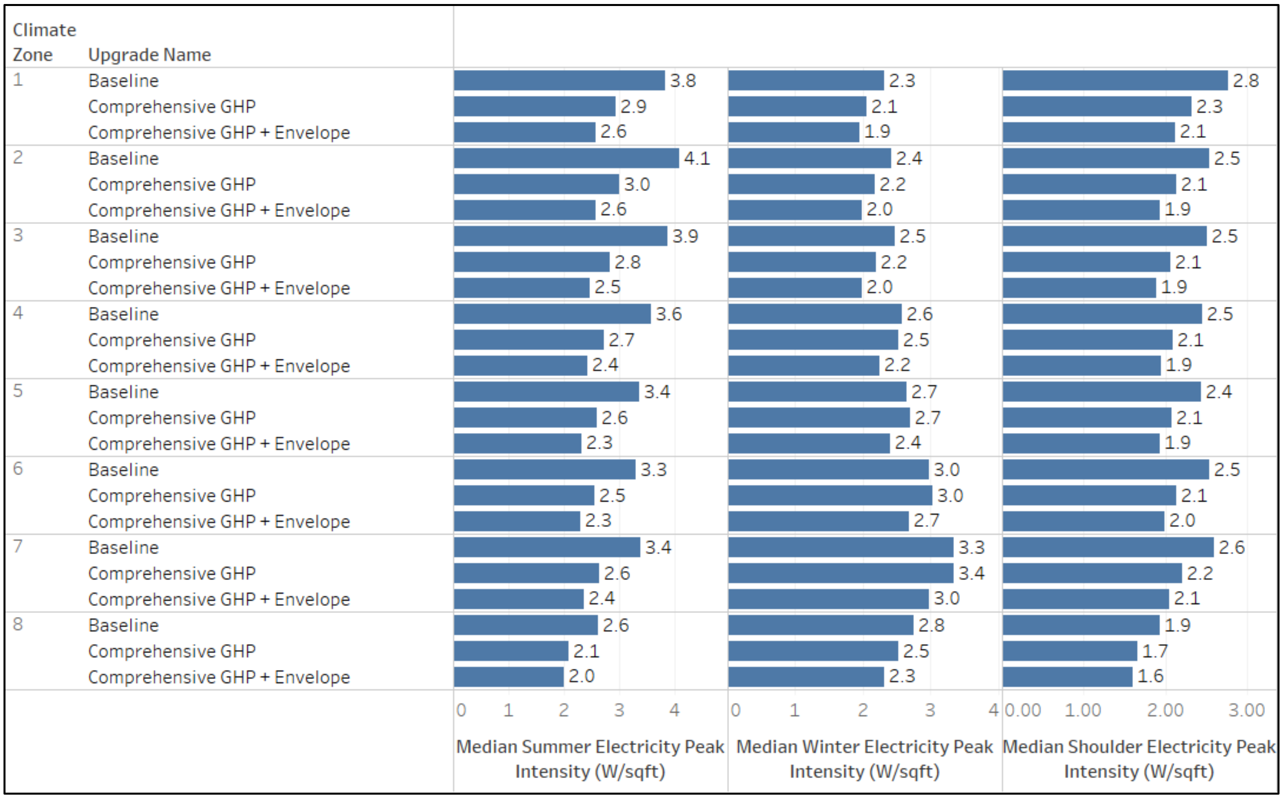

Figure 11. Maximum daily peak intensity by season between the baseline, Comprehensive GHP, and Comprehensive GHP + High Efficiency Envelope scenario

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 3.9 as well as the individual measure documentation. When the envelope measures are combined with the GHP measures, the annual load of a building is reduced due to the efficiency improvements of added insulation and new windows. Therefore, there is 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 GHP and ground heat exchanger outputs for the Comprehensive GHP package and Comprehensive GHP + High Efficiency Envelope package. This gives insight into how much the envelope improvements 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 Comprehensive GHP package and Comprehensive GHP + High Efficiency Envelope package. Because commercial buildings have such 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 Comprehensive GHP package and Comprehensive GHP + High Efficiency Envelope package, the median normalized borehole count is reduced by 0.3 boreholes per thousand feet of floor area (21% reduction) with the addition of the envelope measures. However, at the upper end of the box and whisker, we see the upper quartile is reduced by 1.1 boreholes per thousand feet (19% reduction), and the upper whisker is reduced by 2.6 boreholes per thousand feet (19% reduction).

The number of boreholes is not the only factor; the average borehole depth is also reduced because of the envelope improvements. The median is reduced by 2 feet, the lower quartile by 3.7 feet, and the lower whisker by 8.3 feet. The upper bound for borehole depth is fixed around 443 feet, which is due to practical constraints and limitations set in GHEDesigner.

By multiplying the borehole count (non-normalized) by the borehole depth, we can approximate the total ground heat exchanger loop length. We see that the median building can save nearly 11,000 feet (23.4% reduction) of drilling by implementing envelope measures combined with their GHP, saving drilling time, cost, and resources. Buildings at the upper whisker (likely large buildings with substantial loads) can reduce the size of the ground heat exchanger loop by 73,000 feet (17.5% reduction) by improving their envelope.

Based on these findings, we can expect about 15-25% reduction in the number of boreholes and total length of the ground heat exchanger loop when combining the GHP measures with the high efficiency envelope upgrades. Of course, each individual building’s results will vary based on climate zone, building type, building loads, etc. This will be explored in subsequent plots.

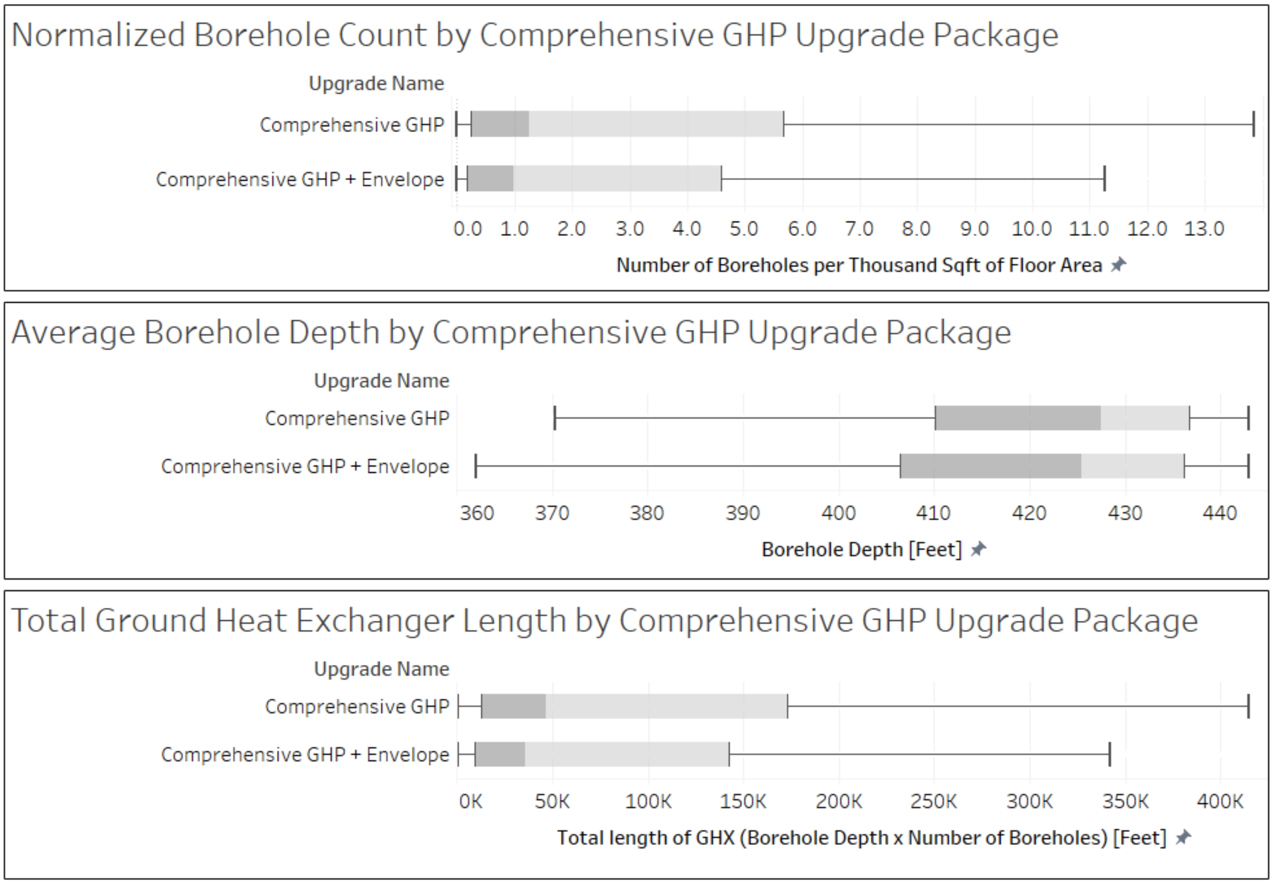

Figure 12. Ground heat exchanger sizing comparison of Comprehensive GHP package and Comprehensive GHP +High Efficiency Envelope package

The sizing of the ground heat exchanger by GHEDesigner is a complex calculation that is dependent on the annual building load, but it also considers the long-term ground temperature stability over many years of operation. Therefore, the normalized borehole count can vary greatly from building to building. Figure 13 shows the normalized borehole count by building type. As shown, the building type, and thus the energy intensity of the building, contributes heavily to the size of the ground heat exchanger. High energy intensity buildings like hospitals and restaurants are going to require far more boreholes per square foot of floor area compared to warehouses. For all building types, the addition of the envelope measures reduces the normalized borehole count.

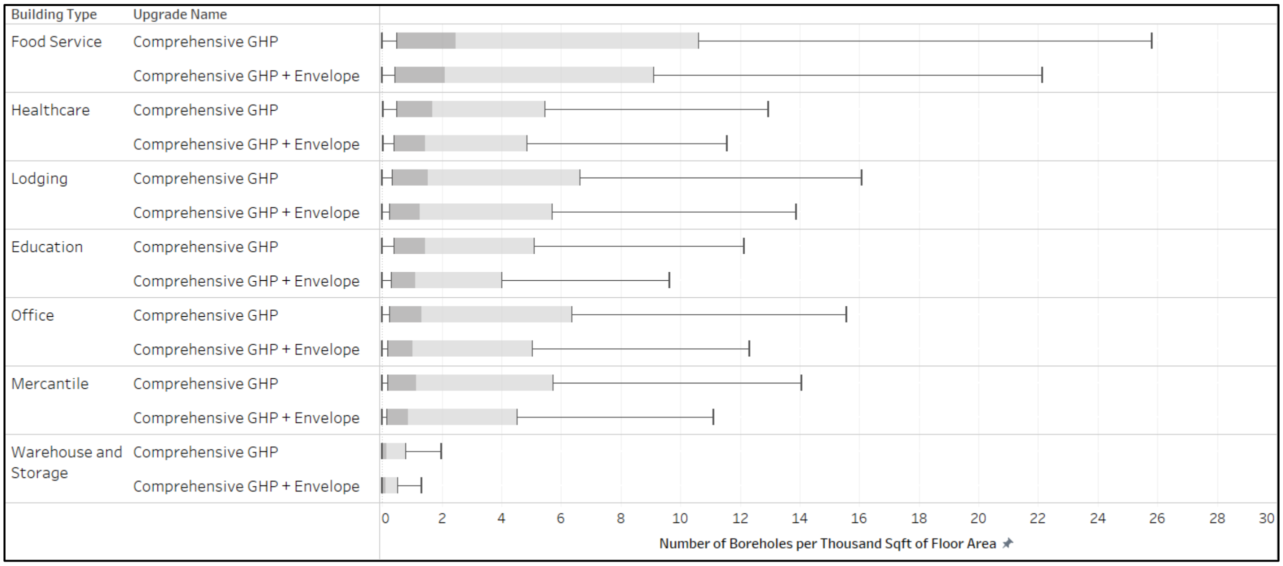

Figure 13. Normalized borehole count by building type for the Comprehensive GHP package and Comprehensive GHP + High Efficiency Envelope package

Similarly, climate zones also have a big impact on ground heat exchanger size. GHEDesigner sizes the ground heat exchanger such that the ground temperature remains stable within certain bounds over the assumed 20-year lifespan of the system. If a building is rejecting far more heat to the ground than it is extracting, or vice versa, the ground heat exchanger will need to be larger to prevent the ground temperature from shifting over time. We can see this illustrated in Figure 14, in which the moderate climates (with a more even balance of heating and cooling load throughout the year) result in the lowest borehole count. In climates 3 through 5 for the Comprehensive GHP scenario, the median building requires 0.7-1.3 boreholes per thousand square feet of floor area.

The hot climates, which reject heat to the ground for much of the year, show larger ground heat exchanger requirements (median of 6 boreholes per thousand square feet in climate zone 1 for the Comprehensive GHP scenario). The cold climates, especially Subarctic climate zone 8, show much larger ground heat exchanger requirements than the other climate zones (median of 44 boreholes per thousand square feet for Comprehensive GHP scenario). Buildings in this climate are using heating energy for much of the year and extracting a lot of heat from the ground, which is already 50°F–55°F (10°C–13°C) to begin with. For this reason, a building in climate zone 8 may require a much larger ground heat exchanger than an identical building in a moderate climate.

However, GHPs are still advantageous in cold climates due to their relatively stable source temperatures, resulting in consistent performance year-round. In all climate zones, we can see that the addition of the envelope measures reduces the required ground heat exchanger size. This effect is especially pronounced in the coldest climates, where the package with envelope measures has a substantial impact (in climate zone 8, the median building's ground heat exchanger is reduced by 15.8 boreholes per thousand square feet).

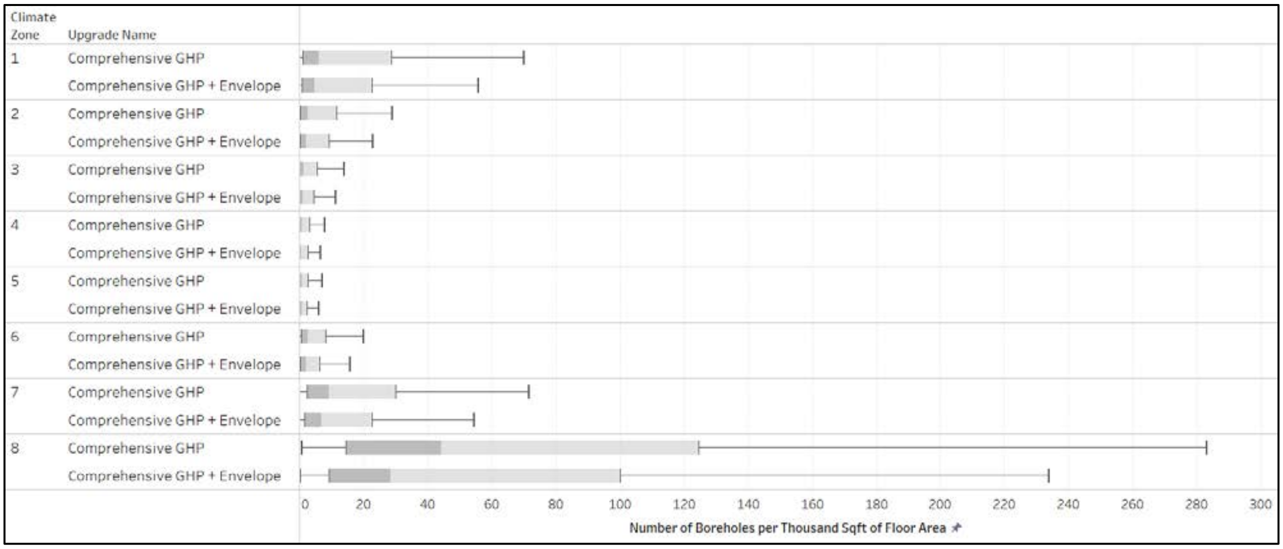

Figure 14. Normalized borehole count by climate zone for the Comprehensive GHP package and Comprehensive GHP + High Efficiency Envelope package

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 GHP unit. In the GHP packages, the envelope measures are applied before any heat pump sizing occurs, therefore the GHP capacities take into account 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 15 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. The median heating capacity is reduced by about 55 kW (17.9%) when the envelope measures are added. In the upper quartile, this heating capacity reduction is 113 kW (16.5%), while the upper whisker is reduced by 250 kW (16.4%).

The median cooling capacity is reduced by about 208 kW (18.8%) when the envelope measures are added. In the upper quartile, this cooling capacity reduction is 467 kW (18.1%), while the upper whisker is reduced by 1.1 MW (18.3%). At the lower quartile, the cooling capacity is reduced by 70 kW (16.5%). Note that most buildings in the stock are cooling-dominated, therefore the cooling capacities are generally much larger than the heating capacities. This means that the cooling capacities are what will drive the size of the heat pump. Across most of the stock, we can assume that the envelope measures will reduce the required heat pump capacity by at least 15%–18%, which can result in substantial capital cost savings.

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.

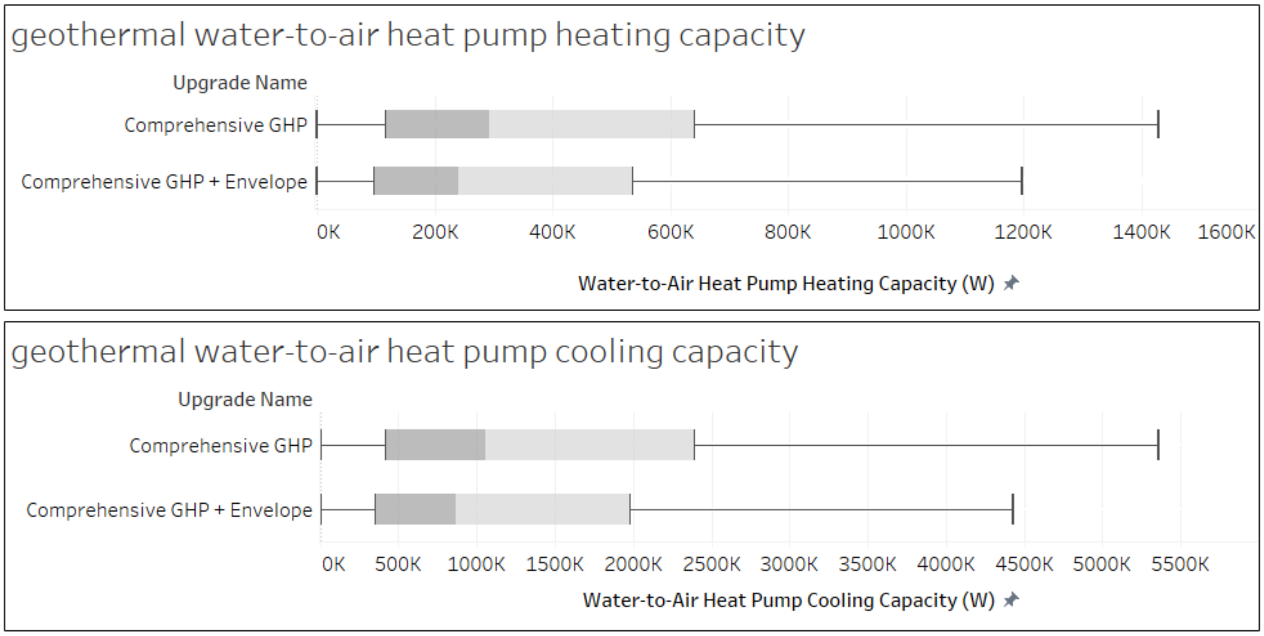

Figure 15. Water-to-air GHP heating and cooling capacities for Comprehensive GHP package and Comprehensive GHP + High Efficiency Envelope package

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Appendix. Additional Figures

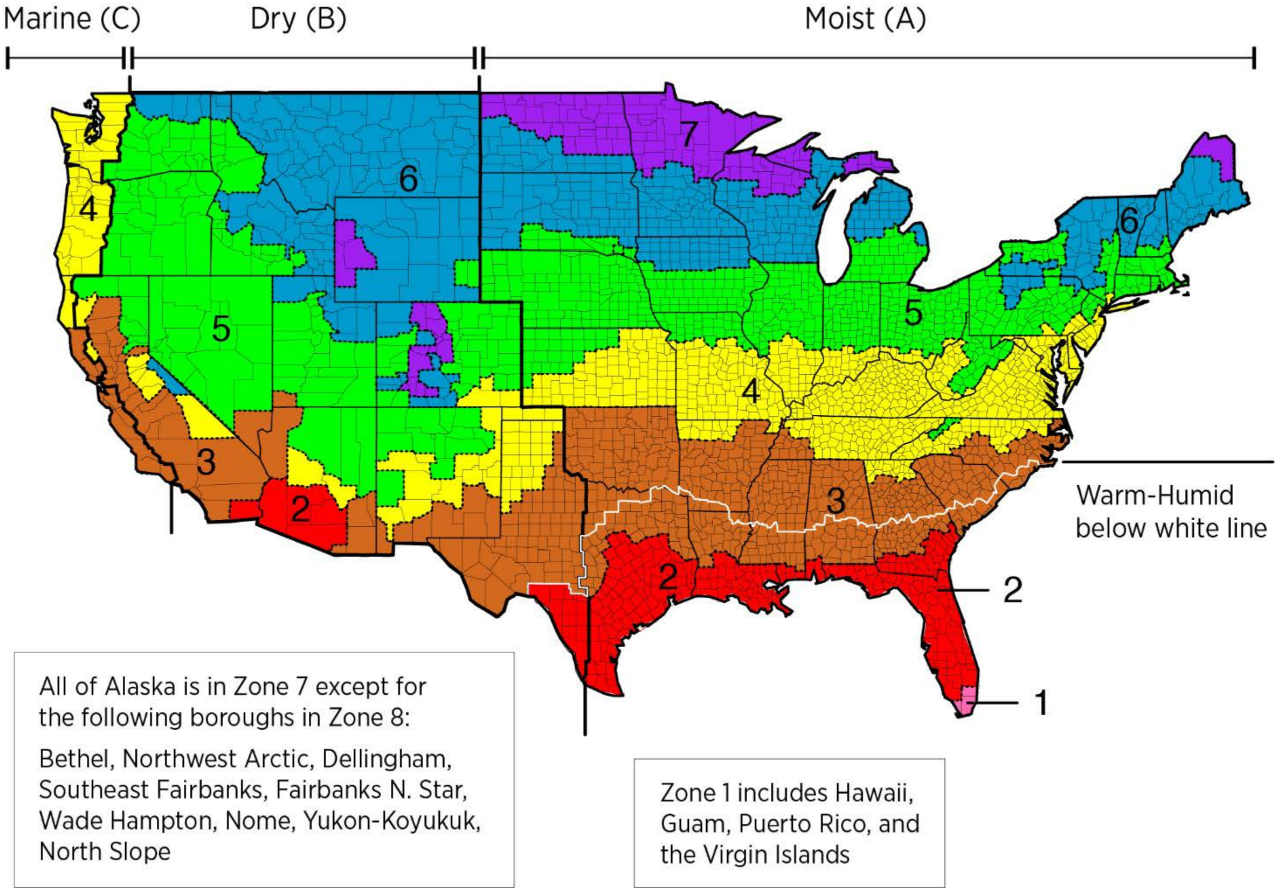

Figure A-1. Map of ASHRAE Climate Zones [22]