ComStock Reference Documentation: 2025 Release 3

Andrew Parker, Henry Horsey, Matthew Dahlhausen,
Marlena Praprost, Christopher CaraDonna,
Amy Van Sant, Janghyun Kim, Lauren Klun,
Eric Ringold, Wenyi Kuang, and Landan Taylor

National Renewable Energy Laboratory

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Table of Contents

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

Executive Summary

The commercial building sector stock model, or ComStock™, is a highly granular, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual subhourly energy consumption of the commercial building stock across the United States. This document contains the methodology and assumptions behind ComStock and serves as a guide to its use.

Motivation: Why Do We Need a Commercial Building Stock Energy Model?
Across the United States, the number of decarbonization initiatives in cities, counties, and states continues to grow. The goals of these initiatives are often aspirational, targeting 100% renewable energy by a specific date for a specific geographic area. When considering the task of decarbonizing the energy system, electric grid supply-side generation technologies such as solar photovoltaics (PV) and wind are often the first technologies that come to mind. However, the energy system's demand side also offers significant decarbonization opportunities. In the United States, on-site fossil fuel combustion, primarily for space and water heating, accounts for 40% of on-site energy usage in commercial buildings (EIA). Even if a grid is converted to 100% renewable energy, more than half of on-site energy consumption remains to be decarbonized. A major effort is required to achieve clean energy goals on the demand side, and it falls on public sector staff, the engineering and policy consulting communities, and research organizations to ensure that these goals are realistic, equitable, and achievable.

Understanding how the commercial building stock uses energy is a first step toward meeting these goals. The U.S. commercial building stock consumes 11% of the natural gas and 34% of the electricity used in the country (EIA). This consumption, plus a smaller amount of other fuels, means that the commercial sector is responsible for 16% of U.S. CO_2 emissions associated with energy consumption (EIA).

To make informed decisions about emissions, it is necessary to understand when and where energy consumption is happening in more detail. The U.S. Energy Information Administration's (EIA) Commercial Building Energy Consumption Survey (CBECS) collects detailed information on energy consumption and building characteristics of the commercial sector. However, CBECS data are only provided at an annual timescale and at a census division spatial resolution. As the grid evolves, the timing of energy consumption is becoming more important in decision-making, and policies impacting energy consumption are increasingly being made at the state and city level. Decision makers need a tool to evaluate the impact of potential changes to their building stock, and need the results to be relevant to their local building stock and grid context.

Currently available energy analysis tools including energy audits and building energy models focus on individual buildings and a static power grid mix. However, the power grid mix continues to change as it incorporates wind, solar PV, batteries and electric vehicle charging. Advanced building controls and demand response programs make possible grid-interactive efficient buildings (GEB) that can achieve greater savings by responding to real-time changes in the power grid. Time becomes a vitally important factor when considering the changing energy supply and demand environment. The time of day or night when building energy efficiency measures provide energy savings needs to be identified and then correlated with the power grid mix. Do energy savings occur at night when wind is on the grid or during daytime PV production? These considerations are further impacted by the geographic location and local climate.

To meet clean energy goals and improve integration of the building stock with a changing power grid, a comprehensive analysis technique is required that can simultaneously analyze where, when, and how groups of buildings consume and could save energy. The ComStock analysis tool was developed by the National Renewable Energy Laboratory (NREL) with funding from the U.S. Department of Energy (DOE) to assist the professionals and researchers tasked with implementing these initiatives.

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Acknowledgements

ComStock owes its conceptual underpinnings to ResStock™, particularly to the work of ResStock's originators Craig Christensen, Scott Horowitz, and Eric Wilson of NREL. ComStock has been developed over many years, and has benefited from the leadership and guidance of many DOE staff, including Jason Hartke, Andrew Burr, Amy Jiron, Harry Bergmann, and Amir Roth. Additionally, ComStock has been improved upon through work for parties outside of DOE, most notably the Los Angeles Department of Water and Power, where support and feedback from Armen Saiyan has been instrumental in key improvements to the tool. Lastly, ComStock would not be possible without the EnergyPlus™ whole-building energy modeling tool and the OpenStudio® Software Development Kit, two pieces of software that are the result of many years of hard work by a large number of people at DOE, the national laboratories, and the private sector.

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List of Acronyms

AAMA American Architectural Manufacturers Association

AC air conditioner or air conditioning

ACC air-cooled chiller

ADA Americans with Disabilities Act

AER average emissions rate

AFUE annual fuel utilization efficiency

AHU air handling unit

AMI Advanced Metering Infrastructure

AMY actual meteorological year

ASHP air-source heat pump

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers

AWS Amazon Web Services

BA balancing authority

BAS building automation system

BEM building energy model

BPR base-to-peak ratio

BTU British thermal unit

CAEUS California End Use Survey

CAPFT capacity as a function of temperature

CBECS Commercial Buildings Energy Consumption Survey

CBSA Commercial Building Stock Assessment

CEC California Energy Commission

CEJST Climate and Economic Justice Screening Tool

CFL compact fluorescent light

cfm cubic feet per minute

CHW chilled water

CMU concrete masonry unit

COP coefficient of performance

CPUC California Public Utilities Commission

CU coefficient of utilization

CW condenser water

CZ climate zone

DCV demand control ventilation

DEER Database of Energy Efficiency Resources

DOAS dedicated outdoor air system

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DOE	U.S. Department of Energy
DST	daylight saving time
DX	direct expansion
EER	energy efficiency ratio
EFFFPLR	efficiency function of part load ratio
EIA	U.S. Energy Information Administration
EIR	energy input ratio
EIRFPLR	energy input ratio as a function of part load ratio
EIRFT	energy input ratio as a function of temperature
EJSCREEN	Environmental Justice Screening and Mapping Tool
EMS	energy management system
EPA	U.S. Environmental Protection Agency
EPD	equipment power density
ERV	energy recovery ventilator
EST	Eastern Standard Time
EUI	energy use intensity
EUL	effective useful life
EULP	end-use load profiles
FIPS	Federal Information Processing Standard
GGHC	Green Guide for Healthcare
gpm	gallons per minute
GSHP	ground-source heat pump
HID	high intensity discharge
HIFLD	Homeland Infrastructure Foundation-Level Data
HP	horse power
HSIP	Homeland Security Infrastructure Program
HSPF	heating seasonal performance factor
HVAC	heating, ventilating, and air conditioning
HW	hot water
IEAD	insulation entirely above deck
IEEE	Institute of Electrical and Electronics Engineers
ISO	independent system operator
IT	information technology
LBNL	Lawrence Berkeley National Laboratory
LDD	luminaire dirt depreciation
LED	light-emitting diode

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LFF	lighting loss factor
LLD	lamp lumen depreciation
LMC	lighting market characterization
LPD	lighting power density
LRMER	long-run marginal emission rate
LSM	lighting subcommittee model
NEEA	Northwest Energy Efficiency Alliance
NEMS	National Energy Modeling System
NFRC	National Fenestration Rating Council
NHGIS	National Historical Geographic Information System
NREL	National Renewable Energy Laboratory
OEDI	Open Energy Data Initiative
PADD	Petroleum Administration for Defense District
PFP	parallel fan-powered
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PLR	part load ratio
PPL	plug and process load
PNNL	Pacific Northwest National Laboratory
PSZ-AC	packaged single-zone air conditioner
PSZ-HP	packaged single-zone heat pump
PTAC	packaged terminal air conditioner
PTHP	packaged terminal heat pump
PVAV	packaged variable air volume
PPL	plug and process loads
PUMA	Public Use Microdata Area
RECS	Residential Energy Consumption Survey
ReEDS	Regional Energy Deployment System
RSDD	room surface dirt depreciation
RTO	regional transmission organization
RTU	rooftop unit
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SSL	solid state lighting
SWH	service water heating
TF	total lighting factor
TMY3	typical meteorological year

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Tstat	thermostat
UTC	Coordinated Universal Time
URDB	Utility Rate Database
VAV	variable air volume
VLT	visible light transmittance
VRF	variable refrigerant flow
WCC	water-cooled chiller
WSHP	water-source heat pump
WWR	window-to-wall ratio

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List of Figures

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This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

List of Tables

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

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1 Introduction

The commercial building sector stock model, or ComStock, is a highly granular, bottom-up model that uses multiple data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual subhourly energy consumption of the commercial building stock across the United States.

This document serves as a guide to and resource for the methodology and assumptions behind ComStock.

1.1 Overview and Primary Use Applications

ComStock answers two questions: **(1) How is energy used in the U.S. commercial building stock?** and **(2) What is the impact of energy-saving technologies?** Specifically, ComStock quantifies energy use across geographical locations, building types and end uses, and time of day. Additionally, it identifies the impact of efficiency measures: how much energy different efficiency measures save; where or in what use cases efficiency measures save energy; when or at what times of day savings occur; and which building stock segments have the biggest savings potential.

This type of analysis can be conducted using simple representation and fast execution or complex representation and slow execution modeling methods. Each methodology has benefits and trade-offs. The National Energy Modeling System (NEMS) used by the U.S. Energy Information Administration (EIA) is an example of a simple, fast method. NEMS models the entire U.S. energy system on the census region level, and its results for the building stock have very low granularity. Modeling each individual building within the building stock is an example of a complex, slow method. This approach offers a high granularity of results, but gives more detail than is needed and is highly impractical.

The ComStock methodology is positioned between these two extremes. It strikes a balance by presenting just enough information to answer its two driving questions. ComStock provides highly granular building stock data to capture the diversity within the building stock while maintaining a reasonable execution speed. Three advantages of this granular approach are: (1) hourly or subhourly detail; (2) modeling of controls, demand response, and measure interaction; and (3) the ability to post-process the data to extract as many insights as possible from the simulations.

Professionals and researchers have several pathways for using ComStock. They can use a web-based visualization platform to interact with the data set of annual and time series results, or they can use a simple spreadsheet-type analysis to interact with annual energy consumption results and aggregated time series load profiles. If users want to go deeper, they can even utilize the raw simulation results data set, which may require big-data skills and cloud or high-performance computing assets.

1.2 ComStock Calibration and Validation

As part of a three-year project, we compared the ComStock results to data from a wide range of sources. These data sources, as well as the comparison plots and accompanying discussion, are described in detail in that project's final report (Wilson et al.). Since the publication of that report, a few changes have been made to the ComStock modeling assumptions. The new assumptions are documented in this report, but an updated version of the detailed comparison has not yet been completed.

1.3 ComStock Data Access

Access to ComStock data sets is provided in multiple formats. The current state of data access changes periodically and is maintained at the National Renewable Energy Laboratory (NREL) End-Use Load Profiles for the U.S. Building Stock website.

1.4 Changes Since Last ComStock Release

The changes made during each ComStock release are documented in the GitHub repository release notes. The ComStock Reference Documentation (this PDF) is updated to reflect changes to the model, assumptions, data sources, etc. To understand the changes, compare the relevant sections of this version of the ComStock Reference Documentation with the previous version. *Note: This document is updated when possible; however, not all charts, graphs, or text may reflect the most recent data sets utilized (e.g., CBECs 2012 vs. CBECs 2018). The underlying methodology*

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remains the same. For the most current data, users should refer to the most recent GitHub repository and dataset releases, as discussed in Section 1.3.

2 ComStock Workflow

Accurately representing commercial building energy usage is complex because of how subsystems of a building interact with one another and with the surrounding environment. Every aspect of a commercial building can influence its energy consumption, so it is difficult to identify which aspects of a building are critical for a given energy-related metric and climate without simulation. To achieve its fundamental goal of representing the U.S. commercial building stock across all energy-related metrics, ComStock must capture the diversity and variability of the building stock. This requires a robust modeling and publishing workflow.

At the heart of ComStock are the approximately 350,000 building energy models (BEMs) that collectively represent the commercial building stock in the United States (roughly 6 million buildings). These models do not represent specific individual buildings (for example, there is no ComStock model for the Empire State Building). Modeling individual buildings would be impractical given the difficulty of compiling accurate data on the U.S. building stock at a national scale. Identifying distributions of characteristics is a more tractable problem. For example, the EIA's Commercial Buildings Energy Consumption Survey (CBECS) (EIA) provides information on how many buildings by type have specific heating, ventilating, and air-conditioning (HVAC) system characteristics (e.g., an office building with a chiller). Combining this information with a building's size and when and where it was built has allowed the ComStock team to develop statistical distributions that determine the characteristics for each of the 350,000 models.

Creating and running the 350,000 BEMs that lie at the heart of ComStock—and then sharing the results—requires significant infrastructure. The workflow that defines, executes, and post-processes these BEMs is shown in Figure 1. The remainder of this section contains an abridged discussion of the elements of this workflow and their role in creating the ComStock BEMs and the results data set. Each aspect of the workflow is revisited in detail in Section 4 as modeling assumptions and algorithms are discussed.

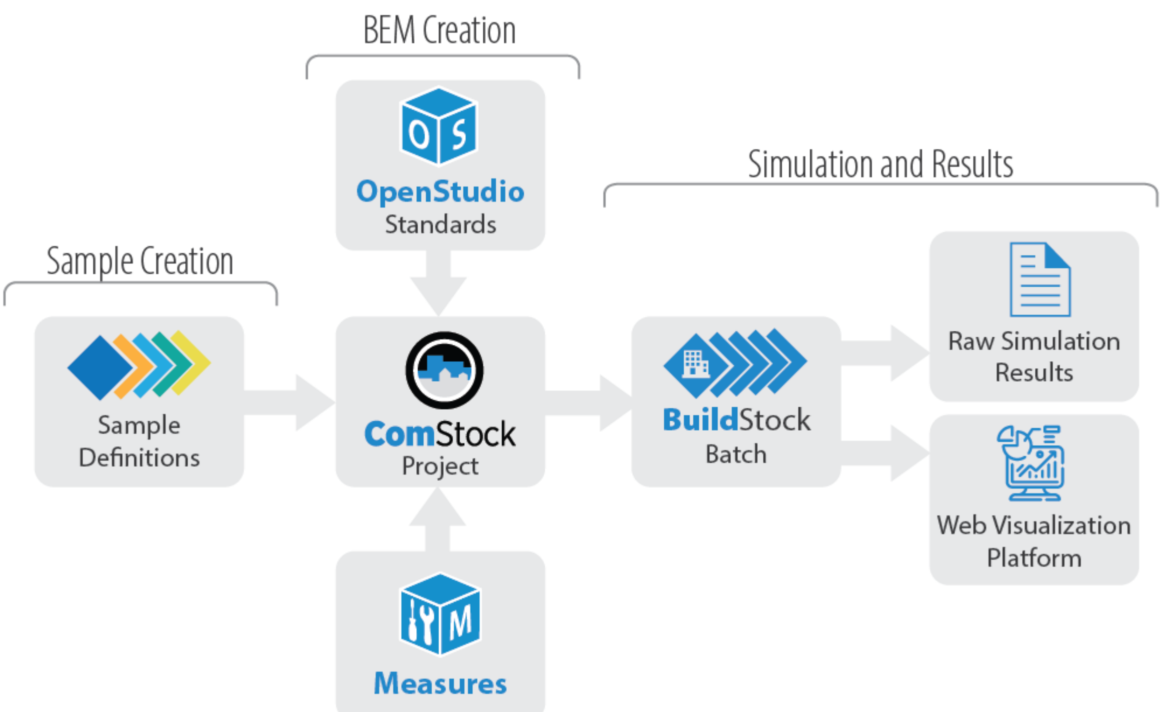

Figure 1. Flowchart of the ComStock workflow.

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ComStock accomplishes its goal of accurately representing the U.S. building stock through a three-part workflow process:

1. ComStock creates samples that represent the U.S. commercial building stock.
2. These samples are translated into BEMs and modified to represent either the baseline U.S. commercial building stock or an altered version thereof (i.e., modeling the impact of an efficiency or electrification measure).
3. The physics-based BEMs are evaluated through an energy simulation engine that uses high-performance computing to simulate each model. The resulting data are made available to a wide range of stakeholders.

2.1 ComStock Sample Definitions

ComStock uses a number of publicly and privately available databases that define what buildings exist, where they are located, when they were built, and with what characteristics they have. The characteristics include (but are not limited to) floor area, HVAC system type, and window type, as well as building-type-specific characteristics such as number of beds (for hospitals) or number of students (for educational institutions). When assembled, these data sets provide the basis for representing the U.S. commercial building stock.

The input data sets used to develop ComStock are often the result of extensive, highly capital-intensive data collection efforts. Some of the data sets purchased for this work are subject to data retention clauses that require deletion of the raw data after the contractual use has been completed. Given these contractual agreements, ComStock typically aggregates and joins with other data sets to generate distributional estimates of relationships between key characteristics. These input distributions are the first step in generating samples for ComStock.

Translating the input distributions into individual samples, or combinations of characteristics, requires a sampling process. Currently, ComStock assembles all input distributions as an n-dimensional joint probability distribution, which is then sampled using a space-filling sampling algorithm. The goal of the sampling algorithm is to minimize the largest void, or "gap," between individual samples.

Each sample generated by the sampling algorithm defines the input characteristics for a single BEM. This results in hundreds of thousands of BEMs (millions when alterations to the building stock are also considered). Each of these BEMs must be created through automated model-generation scripts (discussed in Section 2.3) and evaluated via a BEM physics engine (discussed in Section 2.5). Additionally, it is often necessary to consider the impact of alterations or retrofits to the building stock—the development and use of Measures are discussed in the following section (Section 2.2).

2.2 Measures for ComStock

A major advantage of physics-based models is their ability to change the inputs and evaluate the effect on the outputs. For ComStock, such changes are primarily evaluated using Energy Efficiency Measures or Electrification Measures. Although the word *measure* has a generally accepted meaning in the energy efficiency industry, when capitalized henceforth, *Measure* indicates a script that can be executed on the ComStock BEMs to alter the model inputs. A collection of Measures is a collection of scripts that allow various alterations—such as energy efficiency interventions, electrification interventions, or demand-response strategies/technologies—to be applied across the 350,000 BEMs that comprise a national run with ComStock. These automated alterations are a key aspect of ComStock's value proposition.

Throughout ComStock's development, various Measures have been developed for specific projects. These include Measures developed to support the Los Angeles 100% Renewable Energy Study (LA100), the Advanced Building Construction Typology Report, and, in ComStock's infancy, the Electrification Futures Study. Currently, the ComStock team is developing a more robust and generalized set of Measures that will be published. These Measures are still in development, but at minimum will include efficiency and electrification Measures.

A key element of Measures is the interconnected nature of the intervention and the BEM representation of building systems and technologies. As an example, when modeling an intervention that adds an economizer to all rooftop

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units without an economizer, the modeling workflow relies on (a) the Measure identifying which rooftop units already have an economizer, and (b) the Measure updating the BEMs that do not have an economizer.

In the case of a Measure that electrifies forklifts in warehouses, however, two issues arise. First, none of ComStock's sample definition characteristics provide information on which warehouses (or other building types) this measure is applicable to, or to what degree. Second, there is no disambiguation of forklift load vs. other internal load in ComStock. As such, any Measure that attempts to implement this intervention has to rely on scaled measurement and verification or market research studies. In both cases, the estimates may be accurate, but it is difficult to tie the impact to any fundamental characteristic of the model and represent the variability of the impact across buildings. Although this does not invalidate the value of such a measure, it is important to differentiate measures that fit into ComStock's sample definitions and OpenStudio-Standards' workflow from those that are "bolted on" post-hoc.

2.3 OpenStudio-Standards

OpenStudio-Standards is an open-source modeling library that defines the detailed inputs of a BEM based on simple input values. It contains the software needed to add all building systems for each vintage of every building type. This software is primarily based on the building energy code at the time of construction/retrofit. It contains the software code needed to add all building systems for each vintage of every building type, primarily based on building energy code followed by the building at time of construction/retrofit. This capability is paired with a set of space types that represent the loads of a specific building type to allow for complete model definition.

OpenStudio-Standards was originally developed to help automate the process of creating energy code baseline BEMs. This allowed for more consistent creation of baseline models for efficiency incentive programs. Throughout the development and calibration of ComStock, these code-minimum assumptions have been altered to better reflect the building performance seen in measured data sources. In some cases, this has resulted in components being defined on a non-code basis (e.g., LEDs), whereas in other cases, calibration has resulted in alterations to the nominal assumptions in code-minimum definitions. These alterations are discussed in detail in the relevant subsections of Section 4.

OpenStudio-Standards was not originally developed for ComStock and is used for many other purposes. The standards represent the collaborative work of many researchers at Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory.

2.4 ComStock Project

A ComStock project includes a baseline building stock definition and a selection of Measures. For example, a ComStock project that analyzes the building envelope savings potential for the state of Colorado would include all building samples in Colorado and Measures that capture several efficiency levels for walls, roofs, and windows. The results of this project would identify the energy impacts of bringing Colorado commercial building envelopes up to code and/or above code.

Results for a ComStock project are relative to a fixed point in the lifespan of the building stock. For example, ComStock currently represents the building stock as it looked in 2018. Results assume overnight adoption of changes to the building stock. In reality, large-scale changes to the building stock take many years, and the building stock evolves during that process. If either the baseline building stock characteristics or the measures being considered change significantly, careful consideration of the applicability of results is needed. In many cases, the changes in the point in time and the measures being considered will not significantly change the results. However, in some cases, a rapidly evolving understanding of technology performance and saturation, or increasingly refined questions, will trigger the need for updated or refined analyses. For example, state-of-the-art air-source heat pump characteristics may change rapidly, making results from a ComStock project using older technology assumptions obsolete.

2.5 BuildStockBatch

BuildStockBatch is a software library that executes ComStock and ResStock projects. ResStock is a residential building sector model and shares many workflow components with ComStock. BuildStockBatch is typically used by NREL researchers on NREL's high-performance computing system, Eagle. However, the ResStock team has developed and demonstrated an Amazon Web Services (AWS)-based workflow that can be used by entities without

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access to the U.S. Department of Energy's (DOE's) high-performance computing system. BuildStockBatch can run up to tens of millions of simulations for a given ComStock (or ResStock) project. Although the number of simulations in these projects can vary greatly, BuildStockBatch scales by distributing simulations across a number of servers. The number of servers increases in proportion to the number of simulations, ranging from a few servers to hundreds of servers. After each server completes its requested simulations, it pushes the results to a remote file-system-based database.

Currently, BuildStockBatch utilizes an Eagle high-performance computing workflow for ComStock. In the future, ComStock expects to provide a proof-of-concept BuildStockBatch implementation that uses AWS to execute a ComStock simulation. It is not yet clear whether funding will be allocated to support this workflow's use by third-party users, but the AWS-enabled code base will be publicly available when developed.

2.6 Raw Simulation Results

The simulation results from national ComStock releases are transferred to an AWS bucket provided by the Open Energy Data Initiative (OEDI) Data Lake partnership with AWS. This bucket contains several versions of the raw results. It contains the OpenStudio BEMs (.osm files) used to represent each sampled building. It also provides each building sample's simulated energy consumption results on a 15-minute basis, per end use, per Measure upgrade. These files are stored such that they can be queried using AWS's Athena service. Finally, the annualized results are provided on a baseline/upgrade basis, where each Measure upgrade defined in the ComStock project has its own annualized result file.

2.7 Web-Based Visualization Platform

ComStock and ResStock utilize a shared platform for data visualization. In most cases, users are looking for the sum or average load profile of all buildings of a given type in a given geographic area. These are referred to as "aggregate" load profiles. The visualization platform, which can be found at comstock.nrel.gov, provides users with an interface to interact with both annualized and 15-minute-interval data segmented by geography and building characteristic. As previously discussed, ComStock does not providet results that represent specific buildings, but rather aims to represent the distribution and variability of the building stock across the United States. Users who interact with comstock.nrel.gov generally have a more consistent and beneficial experience than those who interact with individual sample results. The results are available for several weather years and several different geographic resolutions. It is important to note that, at present, the more refined the geographic resolution, the less confidence should be placed in the results. This is because fewer samples will have been generated to approximate the relevant stock.

3 Building Characteristic Sampling

There are three steps to creating the sample of buildings modeled by ComStock. The first step creates estimates of the sizes, ages, types, and locations of the buildings that exist throughout the United States. The second step is characteristic estimation, which is detailed in Section 4. This step defines the additional characteristics of buildings that determine energy consumption and performance. These characteristics are mostly derived from different data sources than those used in the stock estimation step, although they often depend on stock estimation parameters such as building type or age. The third step is sampling the multidimensional probability space to generate a collection of input parameters, or samples. The final samples give an accurate estimation of the commercial building stock at large while not attempting to model any individual building exactly. Stock estimation and sampling are described further in this section, but the majority of the characteristics are discussed in Section 4.

3.1 Stock Estimation

Any estimate of the energy consumption of the U.S. commercial building stock relies heavily on an estimate of how much floor area of each type of building exists in each part of the country. As shown by CBECS (EIA) and others, energy consumption of commercial buildings predominantly scales with floor area, not with building count. An accurate estimate of building floor area is therefore a critical input into any stock modeling tool focused on energy or energy-related metrics.

A secondary issue is the type of building associated with each floor area. Although accurately estimating the total floor area of commercial buildings is necessary, it is not sufficient, as building type also has an impact on energy use intensity (EUI), measured in units of energy use per square foot per year. As an example, a large office with a data center would be expected to have a dramatically higher electric load per square foot than an unconditioned warehouse.

The goal of the stock estimation process is to identify the type, floor area, and location of buildings across the United States. This task is complicated by a number of factors, including data sources that are inconsistent across the United States. However, floor area estimation is central to ensuring that ComStock is accurate for its intended use cases. ComStock takes a three step approach towards achieving an accurate estimate. To begin, national data sources are assembled to present overlapping (and often conflicting) reports of the U.S. commercial building stock. Second, the buildings reported by the various data sources are assigned a consistent set of type descriptors—e.g., large office or secondary school. Finally, the various data sets are amalgamated to create a final, consistent data set that is used in the sampling process.

3.1.1 Data Sources

ComStock's stock estimation is assembled using several data sources. The primary data sources are CoStar, a commercial building real estate intelligence broker, and Homeland Infrastructure Foundation-Level Data (HIFLD), a Department of Homeland Security database that provides cross-agency information on critical infrastructure assets across the United States. Both of these data sets, due to their business-/mission-driven use cases, tend to have very high accuracy for the buildings they represent. However, the major downside of both data sources is that the buildings they do not collect data on are not represented in any manner. While this is challenging, it is easier to adjust/correct for this sparsity than to use other data sets in which buildings are incorrectly and inconsistently represented.

CoStar is a "leading provider of commercial real estate data and marketplace listing platforms. Its data offerings contain in-depth analytical information on over five million commercial real estate properties related to various subsections, including office, retail, multifamily, healthcare, industrial, self-storage, and data centers" (CoStar). CoStar's data is driven by commercial leases and commercial sales data, and is updated with millions of dollars' worth of research per year. CoStar's data set is not always complete, both in terms of geography and building type. For example, building types that are rarely bought and sold, such as schools and major hospital complexes, are less likely to be represented in CoStar's database.

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HIFLD is a set of data tables assembled by the U.S. Department of Homeland Security to support critical infrastructure awareness, disaster recovery, and various other uses. Their databases include information on critical infrastructure facilities such as refineries and military bases, but also include information on schools (which are often used as disaster assistance centers) and hospitals. This is particularly useful, as these are two of the key building types that are less likely to be represented in CoStar. Although the schools data set provided by HIFLD always provides information on the number of students enrolled in a given school (which is used as a proxy to determine the floor area of the school when not otherwise available), the hospital table fails to report the number of beds in a given hospital (which is likewise used to scale floor area) in approximately half the states in the United States. In these cases, data from states that do report this information is generalized and used to infer the floor area in states without data.

Although both of these data sets provide excellent coverage of buildings they consider, they do not provide full and complete coverage of commercial buildings across the United States. Of particular note, using these two data sources results in an estimate of U.S. commercial buildings that differs from that published by CBECS. The ComStock team, after significant discussion, has decided to treat the CBECS estimate of the floor area of each building type as a truth data set. Following the sampling of the CoStar and HIFLD data sets, the CBECS estimates are used to "true up" the numbers on a national basis. As a result, ComStock's floor area estimates match CBECS' by building type on a national basis. Although other truth data sources were considered, CBECS' centrality to all commercial energy use estimation made it the obvious and consistent choice for estimating the U.S. commercial building stock's energy use.

3.1.2 Building Type Assignments

Building type definitions frequently do not match across data sources. This is particularly noticeable in the case of CoStar, CBECS, and DOE prototype buildings data sources. The DOE prototype building models, discussed further in Section 4.1.2, defines specific combinations of space types as "building types," which are then used by ComStock. The building types represented by the DOE prototype building models were decided on during the development of their precursors, the DOE reference building models (Deru et al.). As such, "translating" building types across data sources introduces a layer of complexity.

ComStock maps the building type definitions from each data source to a specific building type from the DOE prototype buildings to maximize consistency. While these mappings are imperfect, they represent the best efforts of the ComStock team to capture the unique energy-related characteristics of different building types within the modeling framework created and used by DOE over the last 15 years. Table 1 shows the mapping from the CoStar building types and HIFLD tables to the DOE prototype buildings, and from the DOE prototype buildings to CBECS' Principal Building Activity Plus.

It is important to note that only one of either the CoStar or HIFLD data is used to represent each type of DOE prototype building—that is, no building type is pulled from both data sets. This ensures that any errors that exist in either data set are independently corrected by the CBECS normalization. According to CBECS' estimation, the amalgamation of these three data sets accounts for 63% of the energy use and 63% of the floor area of commercial buildings in the United States. The remaining 37% of energy use not represented is due to several CBECS building types that are not included in ComStock yet such as mixed-use office and religious worship. Figure 2 shows the building types not represented in the ComStock model, on a CBECS Principal Building Activity Plus basis, and their relative contribution to the commercial building energy use in the United States. As can be seen in the figure, mixed-use offices represent the largest un-modeled building classification by energy use, followed by recreation, other, religious worship, nursing home/assisted living, and social/meeting buildings. Although these building types all consume energy, the ComStock team does not have sufficient information to make a reasonable estimate of their energy use, either annually or on a time-series basis, using the approach discussed in Section 4.1.7.

DOE prototype building type is used to represent a significant amount of the U.S. building stock but is also not used in many cases due to concerns regarding its accurate representation of specific building sub-types. The following list discusses each building type, and what buildings it does and does not represent, as understood by ComStock's developers.

Table 1. Building Type Mapping Across Data Sources

CoStar Building Type	HIFLD Table	DOE Prototype and ComStock Building Type	CBECS Principle Building Activity Plus
Retail: Bar	Not applicable	Full service restaurant	Restaurant/cafeteria
Retail: Restaurant			Bar/pub/lounge
Not applicable	Healthcare: Hospitals	Hospital	Hospital/inpatient health
Hospitality: Hotel	Not applicable	Large hotel	Hotel
Hospitality: Hotel casino			
Office: Industrial live/work unit		Office	Administrative/professional office
Office: Office live/work unit			Bank/other financial
Office: Office/residential			Government office
Retail: Bank			Medical office (non-diagnostic)
Flex			Other office
Office: Service			
Health care: Rehabilitation center		Outpatient	Medical office (diagnostic)
Health care: Skilled nursing facility			
Office: Medical			Clinic/other outpatient health
Health care			
Not applicable	Education: Public schools	Primary/secondary school	Elementary/middle school
	Education: Private schools		High school
Retail: Fast food	Not applicable	Quick service restaurant	Fast food
General retail: Fast rood			
Retail: Department store		Retail	Retail store
Retail: Freestanding			
Retail: Garden center			Other retail
General retail: Freestanding			
Hospitality: Motel		Small hotel	Motel or inn
Hospitality			
Flex: Showroom		Strip mall	Strip shopping mall
Retail: Storefront			
Retail: Storefront retail/office			
Retail: Storefront retail/residential			
Specialty: Post office			
Retail			
General retail			
Flex: Light distribution		Warehouse	Distribution/shipping center
Flex: Light manufacturing			
Industrial: Distribution			
Industrial: Service			Nonrefrigerated warehouse
Industrial: Showroom			
Industrial: Truck terminal			
Industrial: Warehouse			Self-storage
Specialty: Airplane hangar			
Specialty: Self-storage			
Retail: Supermarket		Grocery	Grocery store

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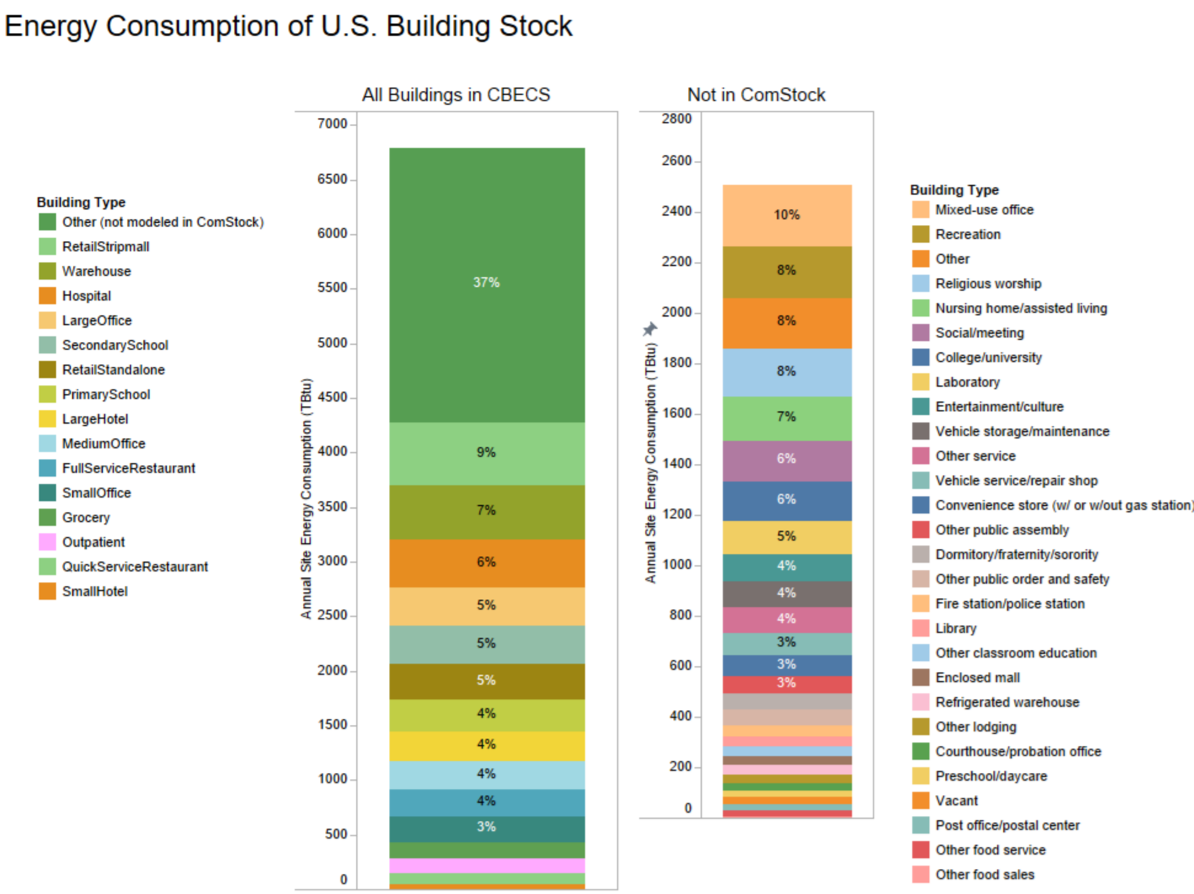

Figure 2. CBECS Principal Buildings Activity Plus building types not covered by ComStock on an energy use basis.

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Full Service Restaurant Both sit-down restaurants and bars are included in this category, as both typically require significant cooking and sanitation equipment for their operation.

Grocery Store Grocery stores, also commonly referred to as supermarkets, are buildings whose primary purpose is the sale of food and dry goods rather than general merchandise. This category includes facilities that feature extensive refrigerated and frozen storage, fresh produce, and prepared foods, typically supported by substantial lighting, heating, ventilation, and refrigeration equipment loads. Convenience stores, small specialty food shops, and general merchandise retailers that include grocery sections are not represented by this category.

Hospital Hospitals, wherever possible, are disambiguated from outpatient clinics through the existence of around-the-clock medical facilities. This is not possible in many states, in which case the differentiation is based on available CoStar data.

Large Hotel Large hotels are differentiated from small hotels on the basis of conference or casino spaces. Hotels that have major facilities for conferences, events, or gambling are classified as large hotels.

Offices Offices are divided up into three subsets: small, medium, and large. Each type of office is based on the thresholds used by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Appendix G (ASHRAE), which include both size and number of stories. In the case of large offices, there are additional probability distributions that determine what percent (if any) of the office is a data center.

Outpatient Outpatient facilities, as represented in ComStock, include non-hospital medical centers, rehabilitation centers, and medical offices.

Primary School The primary school type is used to represent all schools that do not include secondary or post-secondary education, i.e., grades 9 and beyond. Schools that provide education for pre-secondary to post-secondary students (e.g., grades 5–12) are classified as secondary schools. This grouping means that any daycare facilities classified as schools by HIFLD are included as primary schools, unless the facilities also support secondary students.

Quick Service Restaurant Quick service restaurants consist entirely of fast food restaurants.

Retail This category predominantly features large national retailers, excluding grocery stores. This includes big box stores, garden centers, department stores, and any other freestanding retailers that do not include a significant grocery section.

Secondary School Secondary schools incorporate all schools that offer instruction to pupils in grades 9–12. No post-secondary institutions (e.g., community colleges and universities) are represented by ComStock unless they fall into another building type defined herein.

Small Hotel Small hotels encompass all hotels that do not have significant spaces for conferences, meetings, or gambling.

Strip Mall Strip malls encompass all multi-tenant retail buildings, as well as single-tenant buildings that are not classified as large retailers, such as post offices, showrooms, etc. These buildings have additional probability distributions that determine how much of the building floor area (if any) is a restaurant. This is critically important, as restaurants have a far higher EUI and as a result can cause strip malls to have far higher energy uses than would otherwise be expected in a stand alone retail building.

Warehouse Warehouses are perhaps the most differentiated building type in the commercial building stock. They are represented in ComStock as a conjunction of office spaces and high-bay spaces. This building type is used to model distribution centers, light manufacturing, and some showroom and truck terminal spaces, as well as airplane hangars, service depots, and self-storage centers. The spaces encompass a large number of functions; however, it is difficult to differentiate these spaces when examining national databases of building stock characteristics. This makes further disambiguation of these buildings impossible without additional data sources.

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3.1.3 Data Amalgamation for Sampling

The data from CoStar and HIFLD were converted from individual building data points to probability distributions for geographic areas due to data retention clauses.

The ComStock team tagged all individual buildings with a climate zone and a county to convert the county-level locations of buildings within the United States into a probability distribution. From this data, one distribution was created: the likelihood of a building in the United States being located in a given climate zone. In this distribution, there is a much higher likelihood of being located in a heavily populated climate zone (like 4A, which includes much of NJ, DC, MD, DE, VA, etc.) than a sparsely populated climate zone (like 8, which includes only part of AK). Next, for each climate zone, another distribution was created: the likelihood of a building being located in each county within that climate zone. In these distributions, there is a much higher likelihood of being located in a heavily populated county than a sparsely populated county. These two sets of distributions allow any ComStock sample to be assigned a climate zone and a county prior to any additional characteristics being calculated.

The next characteristic to be described as a probability distribution was the building type. Based on the combined CoStar and HIFLD data sets, the likelihood of a building being of a specific building type was calculated for each county in the United States. In some cases, the county in question had an insufficient number of buildings in CoStar and HIFLD to create a realistic distribution. In these cases, the county was instead assigned a distribution of building types based on all the buildings in the state. This is not frequently required for building type, but is more common for floor area, vintage, and number of stories (discussed next).

Probability distributions for three additional characteristics were created using the HIFLD and CoStar data sets: floor area, vintage, and number of stories. CoStar's database has excellent coverage of floor area of a building as a function of county and building type, good coverage of vintage (the year the building was constructed), and reasonable coverage of the number of stories. HIFLD, on the other hand, has good information on vintage, but not on floor area or the number of stories. For floor area, inferences were based on the number of students enrolled (for schools) and the number of beds (for hospitals). Where information on the number of beds was missing, the aggregate distribution for the United States was used to infer the floor area. The number of stories was estimated based on the inferred floor area for each hospital/school. These estimates, as well as the estimates provided by the CoStar data, were used to create distributions for each building type's characteristics on a county basis. There were several cases in which one or more characteristics could not be accurately estimated for a building type/county pair. In these cases, the aforementioned approach of using the state-level distribution was employed.

The approach employed is mathematically accurate. However, the downside to using building count when creating probability distributions is that a high sample count is required to ensure that less common but highly impactful buildings, such as buildings over one million square feet, are well represented. For example, if a county contains 100 retail stores with a floor area of 1,000 square feet each (for a total of 100,000 square feet) and one retail store (perhaps a mall) of one million square feet, the large retail store would be expected to use roughly ten times (1,000,000 square feet/ 100,000 square feet) the energy of all of the smaller retail stores put together. With the current count-based approach, around 100 samples would need to be generated from this distribution to ensure that the one million square foot retail store was represented in the model. Although the impacts of this are minimal at a higher geographic level, it is a known weakness of the current approach.

3.2 Characteristic Estimation

The variability of the commercial building stock begins with building type and location, but extends to include a variety of additional factors. These include schedule diversity, installed equipment type, age of installed equipment, and building code. Each of the characteristics associated with these categories are discussed at length in Section 4, and overviews of each are provided below.

Schedule diversity is a key source of variability in the U.S. commercial building stock. Some buildings operate on a 24/7 basis, but the percentage varies drastically by building type—i.e., there are very few primary schools throughout the United States that are "on" 24 hours per day, let alone 365 days per year. There is also monthly/seasonal variability in a few building types, most notably schools and hotels. Although many of the buildings have lower occupant- or schedule-driven loads during various periods, some do not (e.g., schools that offer summer school). The nuances of this variability are represented in the schedule-driven characteristic distributions.

Equipment characteristics can make a significant difference in the energy consumption of a building through differences in efficiency, fuel type, and the presence or absence of certain types of equipment. ComStock represents this variability by accounting for the fuel type variability within a given state. This allows ComStock to calculate the likelihood of various heating, ventilating, and air-conditioning (HVAC) system types as a function of building type and fuel type. As part of this calculation, systems that do not provide cooling are considered, particularly in the case of warehouses. The fuel type distribution is also used as an input to the selection of water heating equipment.

The third major category of variability is equipment vintage. In most cases, this category is driven by the age of the building. Equipment within a building is generally updated and replaced over time for reasons such as remodeling or equipment failure. As discussed in Section 4.1.5, there is a great degree of variability in equipment lifespans, which leads to variability in the current equipment installed in buildings of a given year of construction. The age of the equipment (or, put another way, the year of manufacture/sale of the equipment) plays a large part in a buildings' efficiency. In some cases, such as buildings built within the last 5–10 years, it is unlikely that many of the building systems have been replaced. The equipment distribution, which is conditioned on the building's year of construction, reflects these nuances.

Finally, building energy codes have an impact on the efficiency of components installed within a building. Building energy codes set the minimum efficiency levels for various building components, but code adoption is not uniform across the United States. As discussed in Section 4.1.4, the building code in force at the time of replacement/installation of a building component is a key driver of its efficiency.

3.3 Publication of Building Characteristic Probability Distributions

Some of the distributions described above cannot be published for contractual agreement reasons, but certain distributions can be published. The ComStock team has generated tab-separated values (tsv) files containing probabilities and dependencies. See Table 2 for the full list of building characteristic probability distributions. More detail on each building characteristic is provided later in this report.

Table 2. Building Characteristic Distributions Included in the ComStock Sampling Process, Including Probabilistic Dependencies and Descriptions

Building Characteristic	Description	Data Source	Conditional On
Simulation Year	Year used in simulations		
Climate Zone	Climate zone as defined by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 169–2006	CoStar	
County	County FIPS code (includes state specification)	CoStar	Climate Zone
State	State FIPS code	CoStar	County
Building Type	Primary building type of model	CoStar	County
Building Rentable Area	Building total floor area	CoStar	County, Building Type
Census Region	Census region	CoStar	State
Year of Construction	Year in which the building was constructed	CoStar	County, Building Type, Simulation Year
Year of Construction Bin	Year bin in which the building was constructed	CPUC DEER EULs	Year of Construction
Energy Code in Force When Constructed	Energy code applicable to building when constructed	State Code Adoption History	State, Year of Construction Bin
Building Subtype	If applicable, subtype of primary building type	NREL analysis of strip malls	Building Type
Ownership Status	Ownership and occupant status of the building	CBECS 2012	Building Type

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Building Characteristic	Description	Data Source	Conditional On
Party Responsible for Purchase Authority	Entity responsible for purchasing decisions	CBECS 2012	Ownership Status
Party Responsible for Operation	Entity responsible for operation of the building	CBECS 2012	Ownership Status
Number of Stories	Number of stories above grade	CoStar	County, Building Type
Window-to-Wall Ratio	Window-to-wall ratio	NFRC Commercial Fenestration Market Study	Building Type, Building Rentable Area, Energy Code in Force When Constructed
Building Shape	Building shape designation	CBECS 2012	Building Type
Aspect Ratio	Aspect ratio of building	CBECS 2012	Building Shape
Building Rotation	Rotation of building relative to North	CBECS 2012	
Space Heating Fuel	Principal heating fuel for the building	CBECS 2012 Plus ResStock Residential Heating Fuel by County	Building Type, County
Water Heating Fuel	Heating fuel for service water heating	CBECS 2012	Space Heating Fuel, Building Type
HVAC System Type	Primary building HVAC system type	CBECS	Building Type, Space Heating Fuel, Census Region
HVAC Nighttime Variability	HVAC nighttime ventilation operation	NREL end-use data analysis	HVAC System Type, Building Type
Weekday Operation Start Time	Building weekday operation start time	NREL/Lawrence Berkeley National Laboratory (LBNL) AMI analysis	Building Type
Weekend Operation Start Time	Building weekend operation start time	NREL/LBNL AMI analysis	Building Type
Weekday Operational Duration	Building weekday operation duration	NREL/LBNL AMI analysis	Building Type, Weekday Operation Start Time
Weekend Operational Duration	Building weekend operation duration	NREL/LBNL AMI analysis	Building Type, Weekend Operation Start Time
Thermostat Set point for Heating	Heating set point during occupied hours	NREL Tstat data analysis	Building Type
Thermostat Setback for Heating	Heating setback during unoccupied hours	NREL Tstat data analysis	Building Type
Thermostat Set point for Cooling	Cooling set point during occupied hours	NREL Tstat data analysis	Building Type
Thermostat Setback for Cooling	Cooling setback during unoccupied hours	NREL Tstat data analysis	Building Type
Wall Construction Type	Building wall construction type	LightBox	Climate Zone, Number of Stories
Lighting Technology Size Bin	Building size classification for lighting technology type		Building Rentable Area
Plug Load Base-to-Peak Ratio type	Methodology for variability of plug load amplitude	NREL end-use data analysis	Building Type
Plug Load Weekday Base-to-Peak Ratio	Ratio between nominal and maximum weekday plug Load levels	NREL end-use data analysis	Building Type, Plug Load Base-to-Peak Ratio Type
Plug Load Weekend Base-to-Peak Ratio	Ratio between nominal and maximum weekend plug Load levels	NREL end-use data analysis	Building Type, Plug Load Base-to-Peak Ratio Type
Lighting Base-to-Peak Ratio Type	Methodology for variability of lighting load amplitude	NREL end-use data analysis	Building Type
Lighting Weekday Base-to-Peak Ratio	Ratio between nominal and maximum weekday lighting load levels	NREL end-use data analysis	Building Type, Lighting Base-to-Peak Ratio Type

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Building Characteristic	Description	Data Source	Conditional On
Lighting Weekend Base-to-Peak Ratio	Ratio between nominal and maximum weekend lighting load levels	NREL end-use data analysis	Building Type, lighting Base-to-Peak Ratio Type
Code Compliance for Building Construction	Building energy code compliance when first constructed	Assumption	State
Code Compliance for Interior Lighting	Building energy code compliance for latest interior lighting replacement	Assumption	State
Code Compliance for Walls	Building energy code compliance for latest walls replacement	Assumption	State
Code Compliance for Service Water Heating	Building energy code compliance for latest service water heating replacement	Assumption	State
Code Compliance for Roof	Building energy code compliance for latest roof replacement	Assumption	State
Code Compliance for Exterior Lighting	Building energy code compliance for latest exterior lighting replacement	Assumption	State
Code Compliance for Interior Equipment	Building energy code compliance for latest interior equipment replacement	Assumption	State
Code Compliance for Windows	Building energy code compliance for latest window replacement	Assumption	State
Code Compliance for HVAC	Building energy code compliance for latest HVAC replacement	Assumption	State
Last Replacement Year for Interior Lighting	Year of most recent replacement of the interior lighting system	CPUC DEER EULs	Simulation Year, Year of Construction
Last Replacement Year for HVAC	Year of most recent replacement of the HVAC system	CPUC DEER EULs	Simulation Year, Year of Construction
Last Replacement Year for Service Water Heating	Year of most recent replacement of the service water heating system	CPUC DEER EULs	Simulation Year, Year of Construction
Last Replacement Year for Walls	Year of most recent replacement of the wall	CPUC DEER EULs	Simulation Year, Year of Construction
Last Replacement Year for Windows	Year of most recent replacement of the windows	CPUC DEER EULs	Simulation Year, Year of Construction
Last Replacement Year for Roof	Year of most recent replacement of the roof	CPUC DEER EULs	Simulation Year, Year of Construction
Last Replacement Year for Exterior Lighting	Year of most recent replacement of the exterior lighting system	CPUC DEER EULs	Simulation Year, Year of Construction
Last Replacement year for Interior Equipment	Year of most recent replacement of the interior equipment system	CPUC DEER EULs	Simulation Year, Year of Construction
Code in Force for Replacement of Interior Lighting	Energy code in force at time of last interior lighting renovation	State Code Adoption History	State, Last Replacement Year for Interior Lighting
Code in Force for Replacement of Windows	Energy code in force at time of last window renovation	State Code Adoption History	State, Last Replacement Year for Windows
Code in Force for Replacement of Roof	Energy code in force at time of last roof renovation	State Code Adoption History	State, Last Replacement Year for Roof

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Building Characteristic	**Description**	**Data Source**	**Conditional On**
Code in Force for Replacement of HVAC	Energy code in force at time of last HVAC renovation	State Code Adoption History	State, Last Replacement Year for HVAC
Code in Force for Replacement of Walls	Energy code in force at time of last walls renovation	State Code Adoption History	State, Last Replacement Year for Walls
Code in Force for Replacement of Service Water Heating	Energy code in force at time of last service water heating renovation	State Code Adoption History	State, Last Replacement Year for Service Water Heating
Code in Force for Replacement of Interior Equipment	Energy code in force at time of last interior equipment renovation	State Code Adoption History	State, Last Replacement year for Interior Equipment
Code in Force for Replacement of Exterior Lighting	Energy code in force at time of last exterior lighting renovation	State Code Adoption History	State, Last Replacement Year for Exterior Lighting
Energy Code Followed for Building Construction	Energy code followed when building was constructed	State Code Adoption History Plus Year Built and Turnover	Energy Code in Force when Constructed, Code Compliance for Building Construction
Energy Code Followed for Replacement of Interior Lighting	Energy code followed when current interior lighting system installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of Interior Lighting, Code Compliance for Interior Lighting
Energy Code Followed for Replacement of Service Water Heating	Energy code followed when current service water heating system installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of Service Water Heating, Code Compliance for Service Water Heating
Energy Code Followed for Replacement of Windows	Energy code followed when current windows were installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of Windows, Code Compliance for Windows
Energy Code Followed for Replacement of Roof	Energy code followed when current roof was installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of Roof, Code Compliance for Roof
Energy Code Followed for Replacement of Interior Equipment	Energy code followed when current interior equipment installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of Interior Equipment, Code Compliance for Interior Equipment
Energy Code Followed for Replacement of HVAC	Energy code followed when current HVAC system installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of HVAC, Code Compliance for HVAC
Energy Code Followed for Replacement of Walls	Energy code followed when current walls were installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of Walls, Code Compliance for Walls
Energy Code Followed for Replacement of Exterior Lighting	Energy code followed when current exterior lighting system installed	State Code Adoption History Plus Year Built and Turnover	Code in Force for Replacement of Exterior Lighting, Code Compliance for Exterior Lighting
Lighting Technology Generation	Generation of lighting technology used in building	Lighting Market Characterization	Code in Force for Replacement of Interior Lighting, Last Replacement Year for Interior Lighting
Window Technology Type	Window technology type used in the building	NFRC Commercial Fenestration Market Study	Energy Code Followed for Replacement of Windows, Climate Zone
Economizer Drybulb Limit Fault	Presence of economizer drybulb limit control fault	Studies of HVAC equipment fault prevalence	HVAC System Type, Energy code followed when current HVAC system installed, Climate Zone

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Building Characteristic	Description	Data Source	Conditional On
Economizer Damper Stuck Fault	Presence of economizer damper stuck fault	Studies of HVAC equipment fault prevalence	HVAC System Type
Includes Refrigeration	Presence of commercial refrigeration including walk-in coolers or refrigerated display cases	Assumption	Building Type
Refrigeration Technology Level	Efficiency level of the commercial refrigeration equipment	Historical DOE shipment reports for commercial refrigeration equipment	Includes Refrigeration, Last Replacement Year for Refrigeration, Size Bin
Last Replacement Year for Refrigeration	Year of most recent replacement of the refrigeration equipment	DOE EULs	Year of Construction, Size Bin, Simulation Year

3.4 Sampling Methodology

3.4.1 Overview

ComStock's new segment allocation sampling methodology uses a two-step process to create the national dataset. This new approach improves upon previous methods by enhancing accuracy, particularly for rural and less densely populated areas, while also reducing computational costs. This section provides a detailed description of the processes involved in generating sampled models from defined sample segments and allocating the sampled models using the previously described stock data.

The first step in the segment allocation sampling process is creating a set of representative models, referred to as "sampled models." These models are selected using a combination of expert judgment and data-driven techniques to ensure they represent the diversity and variability of U.S. commercial buildings covered by ComStock. The sampled models capture a wide range of characteristics, such as building type, size, vintage, and energy system configurations. This step ensures that all major aspects of the covered U.S. commercial building stock are available in the dataset across geographic regions.

In the second step, the "stock truth data" estimate, which provides estimates of the types, sizes, and vintages of buildings by location, is used to allocate the sampled models to specific geographic regions. The stock truth data estimates what buildings of what type, size, and vintage are located where, based on the results of Section 3.1.3. This allocation is performed quasirandomly to match each sampled model to areas where it is most relevant. The result is a statistical representation of the entire commercial building stock across the United States.

This two-step process is a significant change to the prior ComStock sampling process, with significant benefits in accurate representation of small or rural areas. In addition, this approach significantly decreases the computational expense of creating ComStock datasets, helping offset the increasing size of ComStock datasets across releases. However, the method introduces challenges for projects that require highly resolved weather data alignment with external sources, such as those involving nodal demand and renewable energy resource modeling. Please refer to the Implications section for discussion of the implications of the sampling approach used.

3.4.2 Method

Step 1: Generation of Sampled Model Specification

ComStock's commercial building energy models, discussed in detail in Section 4, are specified through a collection of input arguments; for example, building type, energy code of heating, ventilating, and air conditioning (HVAC) equipment, weekend start time, location, and economizer fault status. These are five examples of ~100 input arguments used in ComStock's building energy modeling workflow. The full factorial combination of each supported input of every attribute is dozens of orders of magnitude too large to feasibly model. Therefore, a smaller subset of possible combinations of inputs must be selected for use in ComStock.

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Some ComStock inputs, such as building type or size, are obvious and significant drivers of the energy consumption of a building. While an input such as weekend start time is impactful in the weekend load shape of the building, this input is far less impactful than if the building is 10,000 vs 100,000 square feet (ft^2). Likewise, ComStock models not only the building stock as it exists today (the baseline), but also the impacts of different potential technical equipment or system upgrades and/or retrofits on the building stock. The upgrades are often highly reliant on the HVAC system already in place in the building, as many options for retrofitting buildings are highly dependent on the manner of and equipment associated with space conditioning equipment distribution throughout a building. Likewise, the building energy code is a significant driver of the energy efficiency of all building components and depends on the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) climate zone. These considerations formed the basis for selecting segmentation variables. These variables define the new sample space for generating the sampled models.

The five variables selected as segmentation variables serve as fixed boundaries for ComStock results. Any combination of segmentation variables not modeled in the sampled models will not be represented in the published dataset, and every building in the truth dataset with a specific combination of segmentation variables is represented only by sampled models with matching segmentation variables. After significant consideration, we selected the following inputs as segmentation variables for the purpose of creating sampled models, in no particular order:

- **Building type.** The building type in ComStock specifies the proportion of various spaces within the building and all associated loads. In addition, it is the primary dependency for many distributions defining the operational schedule of a building. In practice, when a user filters ComStock results by geography, the building type is often the first variable used to segment (i.e., group) the results for further analysis.

- **Heating fuel type.** The heating fuel type is important, particularly in colder climates, for accurately representing the use of secondary energy sources. For instance, in a region without widespread access to a natural gas distribution system, heating will have to be supplied either through electricity or delivered fuel such as fuel oil. This variable is fairly responsive to location; for example, New England has significantly increased rates of fuel oil as the heating fuel than the rest of the country.

- **HVAC system type.** As discussed earlier, the location and capacity of equipment, piping, and ducting is all largely dependent on the HVAC system type predominantly associated with a building. While two different HVAC systems may have roughly similar efficiencies in providing ventilation and space conditioning, the availability of existing duct, piping, and equipment infrastructure largely constrains the potential retrofits for that building. For instance, a large hotel that uses packaged terminal air conditioners (PTACs) for guest rooms likely does not have the physical space required to retrofit with a variable air volume (VAV) system, making any potential upgrade to a VAV system infeasible. The complexity of applicability logic for HVAC-related upgrade measures is significant and frequently a variable used in analyses of ComStock data results.

- **Building size bin.** Commercial buildings in the United States range from under 200 ft^2 (in the case of a roadside coffee shop) to over 5 million ft^2. In the United States, most of the energy used in commercial buildings between 1,000 and 1 million ft^2. However, analysis of CBECS data demonstrates that the HVAC system type is strongly tied to the square footage of the building. While the distribution of HVAC system types for buildings of 10,000 and 25,000 ft^2 may not be significantly different, the same cannot be said of buildings of 10,000 and 200,000 ft^2. In many building types, the impacts of these differences are significant. Put differently, although buildings of twice or half the size may have comparable attribute distributions, buildings with two orders of magnitude square footage difference often do not. To address this issue, the ComStock team created square footage bins that group together building square footages with generally consistent HVAC system types as reported via interpretation of CBECS data. These bins are documented in the building type size bin distribution.

- **Sampling region.** Sampling regions are collections of counties grouped together to serve ComStock's need for a geographic segmentation variable. A building's efficiency assumptions in ComStock are determined by using the combination of ASHRAE 90.1 code in force at the time of building construction and climate zone. While these assumptions are implemented through OpenStudio Standards and not directly in ComStock's sampling, there is a 1:1 relationship between the ComStock-sampled value and the energy modeling implementation.

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For example, a state with a history of rapid statewide 90.1 code adoption will have a very different distribution of building efficiencies (and in some cases even equipment such as economizers) than states with no code requirements. Likewise, buildings in colder climates require significantly increased insulation in comparison to buildings in, say, San Diego. ComStock currently implements code requirements on a state basis using data collected through the Building Code Assistance Project (BCAP) and ASHRAE 169-2006 climate zone definitions. For more information, refer to Section 4.1.1 and Section 4.1.4. To account for the combination of building codes and climate zones, we grouped counties across the United States together by using their state code adoption history and climate zone. We grouped counties with seven or fewer cumulative incremental code cycle adoption differences (as reported by BCAP) together, as well as counties with the same ASHRAE 169.1-2006 climate zones. Incremental code cycle adoption differences measure the number of code differences between states for each BCAP reporting cycle (i.e., 90.1 2007 and 90.1 2004 would have a difference of 1, whereas 90.1 2004 and 90.1 2013 would have a difference of 4). In California, we only grouped California Energy Commission (CEC) climate zones with sufficiently similar heating degree days/cooling degree days distributions and low numbers of buildings together, specifically 1 and 2, 4 and 5, 6 and 7, 11 and 12, and 14 and 15. Table 3 shows the mapping of CEC climate zone to ComStock sampling region. Finally, we made manual adjustments to remove any resulting regions with a low count of commercial buildings by joining them with their most equivalent regions covering significant numbers of commercial buildings. The resulting 62 sampling regions are shown in Figure 3. Note that the only noncontinuous regions are the cyan region across Kansas and Missouri, the fuchsia region in New York State, the yellow region in New Hampshire and Rhode Island, the deep green region in New Jersey and Pennsylvania, the royal blue region in West Virginia, the tan region in Michigan and Wisconsin, and the teal region in Colorado. Alaska and Hawaii, not shown, are each a single sampling region.

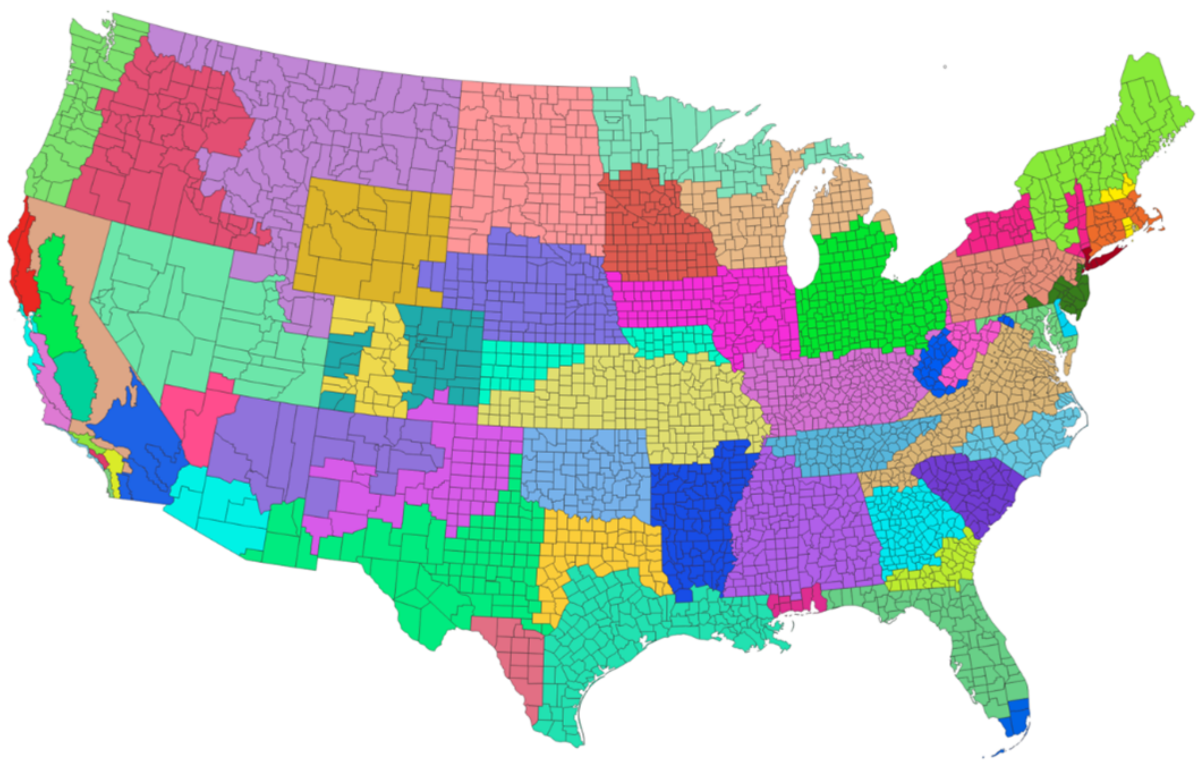

Figure 3. Map of sampling regions used by ComStock.

Figure 4 shows the segment selection process based on segmentation variables. We selected combinations of the segmentation variables to be included in the sampled models and grouped the stock truth data by the segmentation variables. In addition, we summed and ordered the square footage associated with each combination. We then calculated the cumulative percent square footage covered by the combinations, and selected the combinations contributing to 99% of total square footage preferentially by square footage represented. Finally, if any combinations of building type, heating fuel type, building size bin, and sampling region (i.e., all segmentation variables except HVAC system

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Table 3. Mapping of CEC climate zones to ComStock sampling regions.

CEC Climate Zone	Sampling Region
1	100
2	100
3	101
4	102
5	102
6	103
7	103
8	104
9	105
10	106
11	107
12	107
13	108
14	109
15	109
16	110

type) are not included in the selected segments, then the combination is added back into the selected segments with the highest square footage HVAC system type for that collection of segmentation variables. This process ensures that most buildings in the stock truth data estimate are represented and ensures that uncommon fuel types or building types in a region are still represented, albeit with less HVAC system type diversity.

The set of selected segments in the standard dataset release 2024 Release 2 is 12,835. Each of these buckets is allotted 12 samples. Each of these 12 samples is randomly sampled using the network of tsv files representing the balance of ComStock building characteristic distributions described in Table 2, with the five segmentation variables associated with the specific segment held constant. In this way, there are precisely 12 modeled samples per selected segment, with the exception that there are some model failures during simulation that result in one or two of the models not being included within a selected segment. Simultaneously, the distributions of nonsegmentation variables are adequately represented across the modeled samples. We used a pseudorandom sampling methodology when sampling the nonsegmentation variables.

The result of this process is the complete modeled samples set (154,020 models) commonly referred to as the "buildstock.csv" (the filename historically associated with this file). The process by which the variables in this file are converted into energy models and simulated is discussed in Section 4. The simulation results of this file are then inputted into the next step of the sampling process.

Step 2: Allocation of Sampled Models

The modeled sample set obtained from the first step contains well over an order of magnitude fewer building energy models than there are actual buildings in the United States covered by ComStock (154,000 vs 6 million). Section 3.1.2 details which building types in the commercial building stock ComStock currently covers. To best represent the covered commercial building stock, each of the buildings in the stock truth data needs to be assigned one (or more) building energy model results from the modeled sample set. This process, the allocation of sampled models to the stock truth data, takes place in postprocessing, following the generation of the building energy models and calculation of their annual and time series results.

The allocation process begins by importing the stock truth data estimate. Each row of this dataset is a representative building in the United States based on the estimation and analysis process discussed earlier in this document. Although each of these buildings has an estimated square footage, building type, year of construction, and number of stories, many other key aspects of the building such as HVAC system are difficult to estimate without high-fidelity data. As a result, the allocation process attempts to more properly represent the uncertainty in these unknown variables through allocating multiple results from the modeled sample set. This data science technique, referred to as

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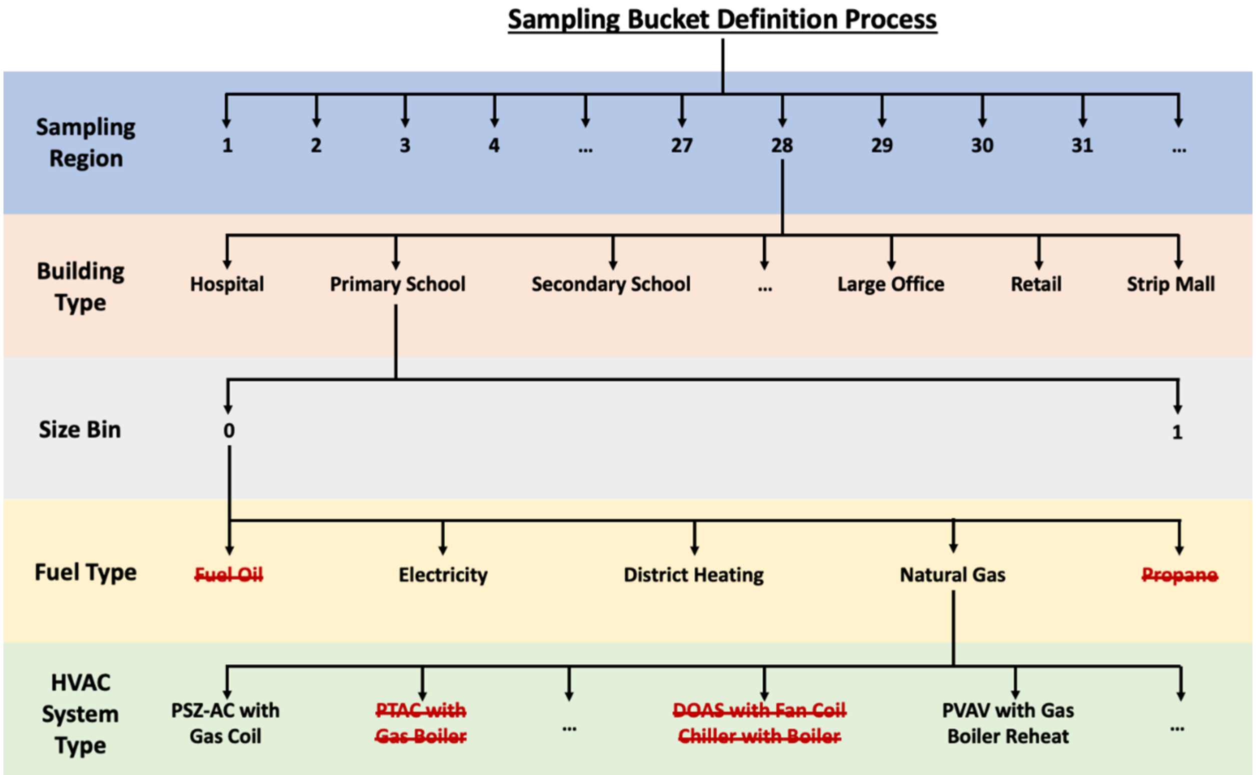

Figure 4. Diagram of segment selection based on segmentation variables, such as sampling region, building type, size bin, fuel type, and HVAC system type.

bootstrapping , helps ensure that when examining areas with fewer buildings, the uncertainty of both baseline energy use and upgrade savings is more accurately represented. ComStock currently uses a bootstrapping value of 3. Each of the rows in the stock truth data is duplicated three times and assigned an initial weight of 0.33, indicating that each row represents one-third of a real building believed to exist per the stock truth estimate.

Although initial weights have been assigned, directly allocating the modeled sample set to the stock truth data is not yet possible. This inability is because the segmentation-based approach used to generate the modeled sample set does not create a number of HVAC system type or fuel type models proportionate to the HVAC system type or fuel type probability distributions. Instead, we selected the key combinations of the primary variables as segments and assigned a number of samples. This approach results in a substantially improved representation of the variability of buildings within most segments but does not reproduce the HVAC system type or fuel type probabilities at the modeled sample set level. Therefore, to enable direct allocation from the modeled samples set to the truth data, both fuel type and HVAC system type must be sampled onto the bootstrapped truth data so that these distributions are accurately represented in the allocated dataset.

Three additions to the stock truth data are required prior to the allocation step:

- Introduce a new size bin variable which bins the square footage of each building by building type to align with the size bin primary variable used in the segment definition.
- Sample fuel type distributions, which depend on county and building type, first onto the bootstrapped stock truth data. Because each row already specifies a location at the census-tract level and a building type sampling, this distribution is easy.
- Sample the HVAC system type onto the updated bootstrapped stock truth data (as it depends on building type, census division, and fuel type), resulting in a bootstrapped stock truth data file that enables direct mapping to segments as defined in the modeled sample set.

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Now that the primary variables used to define segments in the modeled sample set results align with the variables in the bootstrapped stock truth data, building energy modeling results from the modeled sample set can be allocated directly onto the bootstrapped truth data. This process is done iteratively for each segment. For each row in the segment's bootstrapped stock truth data, a model from the matching modeled sample segment is drawn at random with replacement. Given that the square footage of the modeled sample and stock truth data will likely not match, the weight of that row in the stock truth data will be adjusted to correct (e.g., if a 5,000-ft^2-modeled sample was selected for a row with an estimated true square footage of 10,000 ft^2, the weight for that row would be doubled, from 0.33 to 0.66. This process results in the weighted square footage per building in the stock truth dataset perfectly matching the initial stock truth data.

For rows in the bootstrapped stock truth data that do not have a matching modeled sample segment (due to a very low probability combination of primary variables), the HVAC system type constraint is released for segment allocation and the row is then sampled at random from all modeled sample segments with equivalent sampling region, building type, size bin, and fuel type. This process results in slight deviations in the HVAC system type distributions, but only for system types with low probability for a specific fuel in a given census division.

Now that the modeled sample set has been allocated to the bootstrapped stock truth data, we applied the final CBECS normalization. The total weighted allocated square footage is divided by the total reported CBECS square footage by building type. The resulting factor is multiplied with the weights for each row by building type in the allocated bootstrapped stock truth data, ensuring that ComStock's national stock-level square footage by building type matches what is reported in CBECS 2018.

At this point, the weighted allocated bootstrapped stock truth data is persisted. This file, referred to in code as the foreign key table or "fkt," can be aggregated and/or filtered to whatever geography is of interest and the associated modeled sample set IDs and weights used to calculate the ComStock representation for that geography. Currently, the results are aggregated and reported at the census Public Use Microdata Area, county, state, and national level.

3.4.3 Implications of Sampling Approach for Users

The segment allocation sampling process described earlier has several benefits. However, there are important limitations and one notable regression to consider from the previous implementation regarding weather representation. The benefits will be described first, followed by the limitations, and finally the regression.

Benefits

The segment allocation sampling approach achieves a significant increase in the representation of covered commercial buildings in areas where said buildings are relatively uncommon or not dense (e.g., rural or sparsely populated areas). In the previous approach, multiple building types in rural areas would often not get randomly sampled and therefore not be modeled in ComStock, even though they were known to exist in the sampling space. Now, if these buildings are included in the stock truth data, they are represented in the ComStock results. This improved representation also applies to segments with relatively low counts, such as large office buildings. This improvement takes a significant step forward in addressing issues regarding low sample counts.

The next benefit is highly explicit mapping of ComStock results to the census-tract level. Although, as previously discussed in Section 3.1.3, the stock truth data are estimates, the ComStock results at a census-tract level now represent the best-available information in the public ComStock dataset. This information enables cities and other geospatial entities that are defined as aggregations of census tracts to be more accurately assessed with the segment allocation sampling approach. Additionally, the new methodology allows for more streamlined and reliable analyses for sparsely populated counties. Historically, the ability of ComStock to represent these counties required significant additional work for the user, generally requiring manual joining of an assessor's database and ComStock results from additional geographic regions.

A key additional change (which may be considered a benefit or limitation depending on viewpoint) is the bootstrapping approach used in the allocation step, particularly as it applies to upgrade calculations. Previously, a single sampled building energy model in a county might account for 10 similar archetypical buildings. In this case, if that building was randomly sampled with a PTAC HVAC system, then very few if any HVAC upgrade measures would be applicable for this building. Although this is reasonable if that single sample is one of 20 that are being analyzed, in aggregate this was often not the case. In the case of lower count building type and size combinations, we frequently observed the limitations of this approach. Now, instead of a single sample being allocated to each building, three samples are allocated (with replacement, as discussed previously). This change better reflects that ComStock cannot be certain which HVAC system type a building has (or for example when the lighting was last upgraded). As such, the upgrade savings estimates at a low sample count more accurately build in the propensity of ComStock's TSV structure to upgrade analyses. Although this ability can increase the complexity of interpreting results on a line-by-line basis, it can also significantly increase the likelihood of ComStock estimates in a smaller sample count to accurately reflect our best knowledge.

Limitations

Although the improvements discussed earlier are significant, there is an ever-increasing risk of ComStock's results being interpreted as more accurate than we believe them to be. The aggressive allocation to our stock truth estimate brings significant benefits, but the data lack information on many aspects of commercial buildings that determine their energy usage or saving potential to individual measures. While bootstrapping and a preference for aggregate result representations aim to address this limitation, ComStock cannot know the type of lights in a given building , the performance of key HVAC equipment, or the schedules of different equipment within the building, among many other factors. Despite the increased geographic granularity, our understanding of many key energy characteristics of buildings remains largely unchanged from the previous sampling methodology. We encourage interpreting the results as such. Increased granularity of what buildings of what type and size are where should not be interpreted to variables beyond that list.

Regressions

A key regression from the previous sampling approach is that the allocation process will select sampled models from within appropriate segments (including sampling region) for assignment without consideration for weather. This means that a building modeled using 2018 weather from Houston may be used throughout the Gulf Coast, within the bounds set by the sampling region. Sampling regions help to ensure that the ASHRAE 169.1 2006 climate zone is the same in almost all cases within a sampling region and state code adoption is likewise generally similar. This sampling approach, however, is a significant change from the previous one. The key negative implications of this change are that local coincident peaks across the stock within a small geography will have unaligned weather files, which may result in incorrect assessments of coincident peak time and magnitude. Likewise, upgrade analyses that are highly sensitive to coincident peak reduction may suffer, although the implications here are more uncertain at this time. The principal use case we identified that is significantly negatively impacted by this is grid-aligned modeling efforts at subnodal or subfeeder/circuit levels. As a result , the ComStock portfolio is working to provide alternate paths forward for this use case and will publish and validate methodologies on the ComStock documentation website.

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4 ComStock Building Models

ComStock uses about 30 high-level, whole-building characteristics to describe each building, as discussed in Section 3.4.3. However, whole-building energy models, such as the EnergyPlus® model used by ComStock, typically require thousands of inputs to describe a building for simulation. The purpose of the subsequent sections is to describe the assumptions, conventions, and data sources used to transform the high-level descriptions into inputs with the level of detail needed by EnergyPlus. Although the software used to implement this transformation is critical to the workflow, the focus is on the model inputs, not on the software workflow.

One question that often arises is why more of the input assumptions documented in this section are not incorporated directly into the sampling framework described in Section 3.4.3. This is an especially common question for those familiar with ResStock™ (Wilson et al.), the residential building stock modeling tool that ComStock is based on. After all, ResStock uses more than 100 building characteristics to describe residential dwelling units, which are arguably less complex than commercial buildings. There are two main drivers behind the decision to limit the number of building characteristics: (1) handling complexity and (2) data availability for commercial buildings.

From a complexity standpoint, there is significantly more diversity among commercial buildings than among residential buildings. At one extreme, there are buildings like large hospitals, which may be several hundred thousand square feet, encompass spaces ranging from operating rooms to cafeterias, and be served by a complex array of HVAC systems. At the other extreme, there are buildings like small standalone retail stores, which may consist of just one retail space, a small storage room, and a restroom. Accounting for the diversity in lighting power density for each space type across all commercial building types in ComStock would alone require more than 100 building characteristics, many of which would not be applicable for certain building types. Multiply this by the number of characteristics that vary between building types, and the number of building characteristics required quickly becomes untenable.

From a data availability standpoint, there is simply much less information available for commercial buildings than there is for residential buildings. This means that modeling the commercial building stock requires more assumptions than modeling the residential building stock. Compounding this lack of data is the fact that most commercial building data sources handle complexity by focusing on a single building type (e.g., offices), providing information only at the whole-building level, or providing percentages of floor area associated with a given characteristic. Rather than making engineering estimates to generate probability distributions for every building characteristic, we have chosen to make point estimates for certain parameters. Proponents of stochastic modeling may disagree with this approach, but we believe it is warranted, given the model complexity that is avoided.

The end result is that many of the intra-building characteristics of commercial buildings must be inferred from whole-building characteristics. Rather than adding these to the input layer, they are set in the process that expands these whole-building characteristics into energy model inputs.

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4.1 Location, Type, Age, Space Programming, Energy Code, and Change Over Time

4.1.1 Location

ComStock has four levels of location granularity for its building models: ASHRAE Standard 169 - 2006 climate zone, census division, state, and county. During sampling, each model is first assigned a climate zone, then a county, then a state and census division. The climate zone and county probability distributions come from the CoStar and HIFLD data provided by the Homeland Security Infrastructure Program (HSIP) on a building count basis. The state and census division are assigned using a lookup table that is based on the model's sampled county. The location metadata impacts numerous characteristics in the model, such as weather file, building type, building geometry characteristics (e.g., number of stories and rentable area), and energy code applicability. Table 4 shows the number of models used in each census division.

Additional location metadata is joined to the *buildstock.csv* for use in parsing ComStock results. This includes data such as Public Use Microdata Area (PUMA), Building America climate zone, independent system operator (ISO) region, and ReEDS balancing area. This location metadata is joined on the census tract level. Census tracts are assigned to the *buildstock.csv* using the CoStar and HSIP data. These location fields also include building cluster ID and name. Developed by DOE and NREL, these 88 geographic clusters allow for localized building stock analyses and are the basis for the U.S. Building Stock Segmentation Series. For more details about these clusters and their development, reference the Building Stock Segmentation Cluster Development technical report.

Table 4. Distribution of ComStock Models in Each Census Division

Census Division	Count	Percentage
East North Central	54122	15.46%
East South Central	19882	5.68%
Mid-Atlantic	44976	12.85%
Mountain	24258	6.93%
New England	16791	4.80%
Pacific	54799	15.66%
South Atlantic	72616	20.75%
West North Central	20910	5.97%
West South Central	41646	11.90%

4.1.2 Building Type

The building types used by ComStock were originally defined by the DOE reference buildings, which were extended to create the prototype buildings. These building type definitions represent buildings by drawing on the applicable building code sets. Both the reference buildings and the prototype buildings have historically been used by building code organizations, include the ASHRAE 90.1 committee, to understand the potential impact of various code updates on newly constructed buildings.

Each building type is predominantly defined by a space type breakdown. For a given square footage of a ComStock building type, the fraction of the square footage of space type A (open office) vs. B (closed office) will remain the same as what they are in the DOE prototype models with two exceptions. Although these definitions are useful in the analysis of energy codes, there are several cases where they fail to provide the variability required for ComStock to provide a useful representation of the U.S. commercial building stock. There are two building types are currently represented with additional variability in space programming - large office and strip malls.

Large Offices Currently, large offices have variable data-center loads in ComStock. This aligns with study data obtained through the End-Use Load Profiles (EULP) project that was used to calibrate ComStock. This results in a higher degree of EUI variability within the large office building type than would be expected with only a change in space programming, given the high energy intensity of the data center space type.

Strip Malls Strip malls often contain one or more restaurants. Strip malls with restaurants often have significantly higher EUIs than restaurant-free strip malls, which are the only kind represented by the reference and prototype models. To address the significant lack of diversity and variability in strip mall EUIs, the End-Use Load Profiles project added a variable restaurant component to strip mall models in ComStock. This results in a more realistic distribution of loads by end use across the strip mall segment.

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4.1.3 Vintage

Vintage, as previously discussed in the sampling section 3.2, is a key component of ascertaining the age and associated efficiency of building components. Vintage is determined based on information from either CoStar or HIFLD. However, in many cases, the vintage must be inferred due to a lack of available data on a county or state basis. When there is insufficient data on a county basis, state data are used, and in the few cases (typically in relation to hospitals) where state data are unavailable, national data are used.

Commercial buildings are complex in that each subsystem of the building—except perhaps walls—is expected to be replaced or updated at least once during the life of the building, without the building being reconstructed from the ground up. As such, it is critical to understand the year in which a building was first constructed in order to estimate the age (and the associated minimum energy code) as a function of the vintage. The latest year of intervention is calculated for each building component as a function of the vintage, and each of these are passed to an energy code lookup to determine which, if any, energy codes were in force.

Finally, it is important to note that vintage is especially important for recent construction. Buildings built within the last decade are unlikely to have significantly different or updated systems compared to those used at the time of construction. As a result, these buildings are a unique stock segment and have potential for cost-effective impact in the commercial building stock.

4.1.4 Energy Code

Energy Code Adoption

Some states have a statewide code, while others have codes that are determined at the city or county level. For ComStock, the adoption of an energy code is assumed to be a function of year and state. For states with no statewide code, ComStock selects the code covering the biggest cities in the state. Where a state code was not a derivative of the ASHRAE 90.1 series of codes, the most similar versions of ASHRAE 90.1 were used for that state. The exception to this is California, where the Title 24 series of codes, as represented in DEER (CPUC), was used because this series of codes was known to be significantly different from ASHRAE 90.1. Most of the information used to develop the code adoption history was taken from the Building Codes Assistance Project (Building Codes Assistance Project). Much of the building stock was constructed before energy codes were widespread. For this time period, the "energy code" is described as either "DOE Ref Pre-1980," whose assumptions are drawn from Deru et al., or "DOE Ref 1980-2004," whose assumptions are a combination of ASHRAE 90.1-1989 and Deru et al. Details on the specific assumptions for each energy code are described in more detail throughout this document. The code adoption history assumptions are shown in Figure 5.

Energy Code Compliance

For this discussion, energy code compliance is defined as the extent to which a building constructed to comply with a certain energy code meets the requirements of that code. For example, a building built to comply with ASHRAE 90.1-2010 may meet all envelope requirements but fail to meet some HVAC control requirements. Unfortunately, there is little information available on commercial energy code compliance at a national level, and the information that does exist is not detailed. The status of this information is described in a detailed report (EIA) generated for EIA's NEMS modeling effort. What we do know, both from this information and anecdotally, is that commercial energy compliance is imperfect. Some buildings and building systems exceed code, and others lag behind. Because of the data limitations, we assume that all building systems meet the requirements of the energy code that was in force in their location when the building was originally constructed and as the building systems were replaced over time. As data on major building systems become available we hope to move away from this code-compliance-based framework toward a model driven by distributions of known building characteristics.

4.1.5 Building System Turnover and Effective Useful Life

We assume that all major building systems are installed when the building is constructed, and that they are replaced periodically over the lifespan of the building. Replacements may be made because of equipment failure, building remodeling, energy efficiency upgrades, etc. To model the turnover of building systems, it is necessary to understand how often these building systems are replaced, which determines how long they last in the building stock. The metric commonly used by the energy efficiency community to describe the lifespan of a measure is effective useful life (EUL). The California Public Utilities Commission defines EUL as "an estimate of the median number of years that

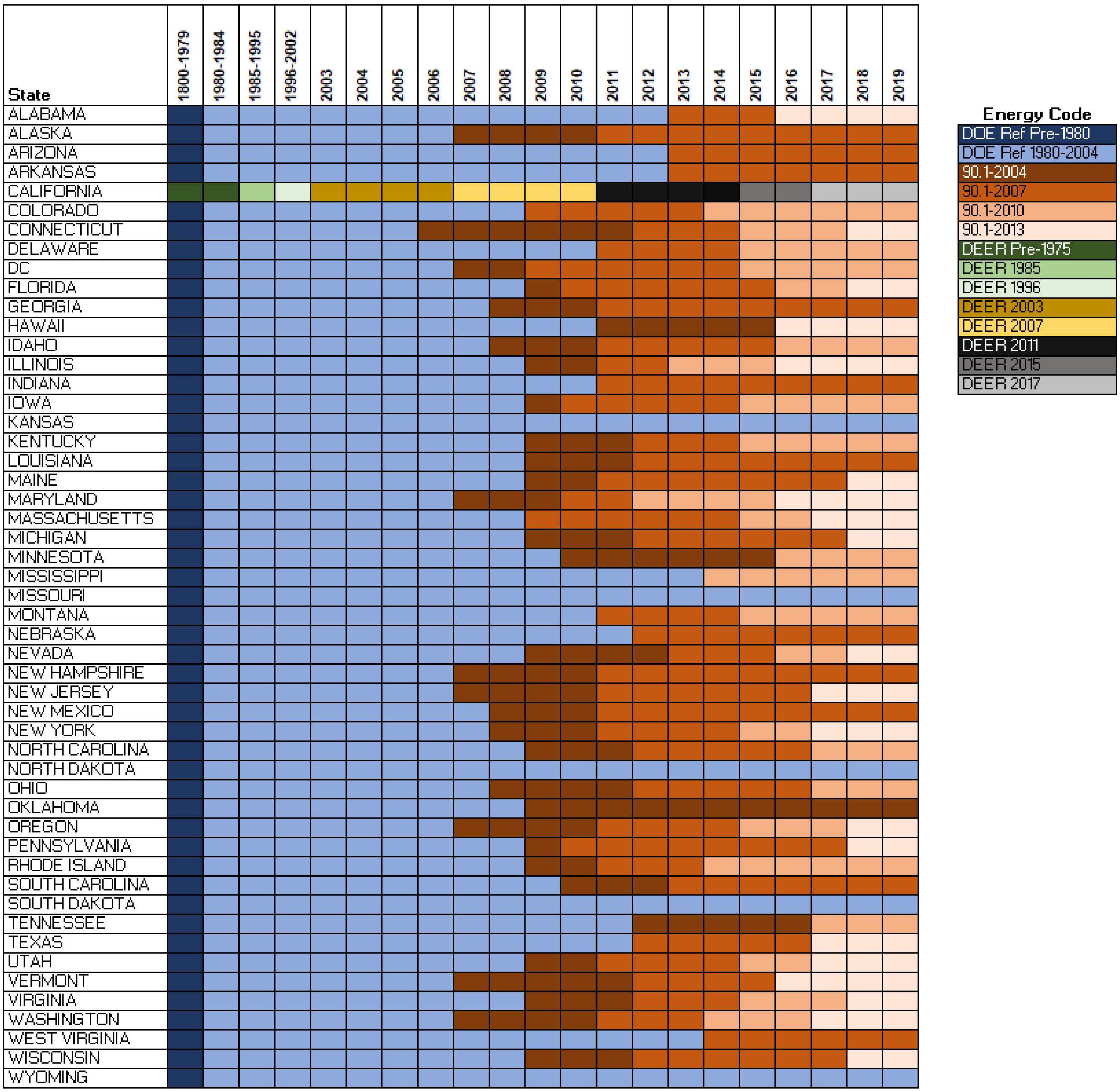

Figure 5. Adoption of energy codes by state over time.

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Table 5. Effective Useful Life of Major Commercial Building Systems

Major Building System	EUL (Years)	Notes
Envelope—Wall Insulation	200	This value was based on engineering judgment. DEER EULs are capped at 20 years, per CPUC policy. NEMS does not appear to model wall turnover separate from whole-building replacement.
Envelope—Roof Insulation	200	This value was based on engineering judgment. DEER EULs are capped at 20 years, per CPUC policy. NEMS does not appear to model roof turnover separate from whole-building replacement.
Envelope—Windows	70	Based on a reliability analysis of windows from the 2014 Commercial Building Stock Assessment from the Pacific Northwest. DEER uses an EUL of 20 years for window replacement, as the DEER EULs are capped at 20 years, per CPUC policy.
Exterior Lighting	15	This closely matches the highest EUL in DEER for outdoor lighting (16 years). NEMS does not break out exterior lighting, but all NEMS commercial lighting technology types have a 10-year EUL.
Interior Lighting	10	This is in line with the EULs in DEER for interior lighting, and matches the 10-year EUL for all commercial lighting technologies in NEMS.
HVAC	20	The highest EUL in DEER for HVAC is 20 years. For rooftop air conditioners, which serve by far the largest portion of the building stock, NEMS uses a 21-year EUL. NEMS HVAC EULs range from 9.5 years for window AC units up to 30 years for some boilers. ASHRAE includes 33 packaged DX rooftop units with a mean lifetime of 21 years, and appears to be the source of some NEMS HVAC lifetimes.
Service Water Heating (SWH)	15	The highest SWH EUL in DEER is 20 years for a tankless water heater. Most tank-based SWH equipment in DEER has an EUL of 15 years or less. NEMS non-solar SWH equipment EULs range from 10 to 15 years. ASHRAE includes 5 gas-fired water heaters with a mean lifetime of 15 years, and 36 electric water heaters with a mean lifetime of 10 years.
Interior Equipment (Plug and Process Loads)	15	This value was based on engineering judgment and is meant to represent an average over all types of plug and process loads. If plug and process loads are addressed in future iterations, splitting the plug and process loads into information technology (IT) equipment and other equipment will be investigated, as IT equipment typically has a higher turnover rate than other process loads, such as hospital equipment or commercial kitchen equipment. NEMS includes commercial kitchen equipment with an EUL of 12 years, commercial ice machines with an EUL of 8 years, commercial vending machines with an EUL of 13.5 years, and commercial refrigeration equipment with an EUL of 10 years.

the measures installed under the program are still in place and operable" (CPUC). In the reliability community, EUL is typically referred to as "median time to failure" (Texas Instruments), whereas ASHRAE uses the term "median service life" (Abramson, Wong, and Herman).

For ComStock, the primary source of EULs is the California Public Utilities Commission (CPUC) Database of Energy Efficiency Resources (DEER) (CPUC). Previous work on EULs indicates that there is wide variation in the quality of national EUL data, but it also indicates that the studies performed in DEER are generally the best available (Skumatz). The values in DEER were cross-referenced against the lifetimes used in the EIA NEMS Commercial Demand Module (EIA) and the ASHRAE Service Life and Maintenance Cost Database (ASHRAE). Table 5 shows the EULs assumed for different building systems in ComStock.

Building Envelope

For the building envelope (windows, wall insulation, and roof insulation), the DEER database was not informative, because the maximum EUL is capped at 20 years, per CPUC policy. Because of this, we sought out other sources of envelope lifetime information.

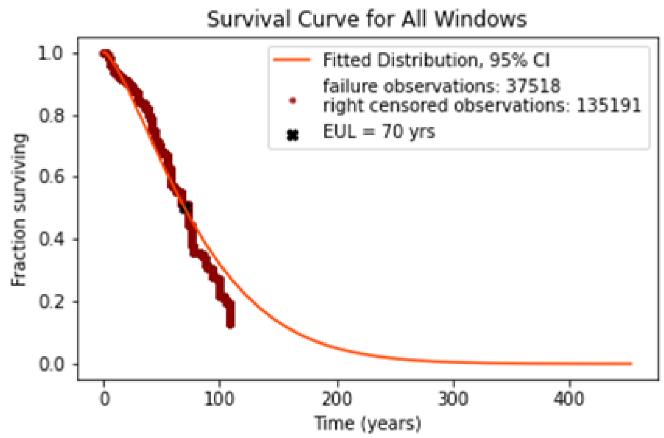

Figure 6. Reliability analysis for windows in commercial buildings, from 2014 CBSA (Navigant Consulting).

Windows

As part of the DOE-funded Advanced Building Construction initiative, a team collected information on windows from a variety of commercial building surveys, including a new survey of buildings built since roughly 2010. Unfortunately, while most of the surveys did ask about windows, only one survey had enough information to perform a reliability analysis (because windows are long-lived). This survey was the 2014 Commercial Building Stock Analysis (Navigant Consulting), which covers the Pacific Northwest. This survey included information on the age of the building, whether the windows had ever been replaced (and if so, an estimate of the year of replacement), and a weighting factor to describe how each sample fit into the whole building population. From these data, we performed a reliability analysis. Figure 6 shows the estimated survival curve. As indicated by the black cross mark on the figure, the EUL estimate for windows is 70 years. However, the maximum lifespan extends to more than 400 years. In practice, this indicates that windows on some buildings will never be replaced.

Walls and Roofs

None of the data sources we identified included information on EULs for walls and roofs, or, more specifically, the insulation on these surfaces. DEER EULs are capped at 20 years, per CPUC policy. NEMS does not appear to model wall turnover separately from whole-building replacement. Based on engineering judgment, we selected an EUL of 200 years to indicate that for most buildings, the wall and roof insulation will not be replaced before the building is demolished.

Distribution of Lifespans

The EUL estimates in Figure 6 represent the median lifespan for a given building system. However, not all systems will fail and be replaced after exactly that amount of time. To represent this diversity of failure rates we use a distribution.

The simplest approach would be to use a normal distribution centered on the EUL. However, studies of reliability data show that this is not a good assumption; instead, these studies often use a Weibull distribution to represent lifetimes. To check whether a Weibull distribution accurately represented the lifetimes of building equipment, we performed a reliability analysis on data from the ASHRAE Service Life and Maintenance Cost Database (ASHRAE). This analysis was performed following the methodology described in an ASHRAE journal article (Hiller), and was implemented using the reliability package (Reid) in Python. Four categories of equipment with a reasonable number of entries were investigated: air handling units, boilers, chillers, and air source DX equipment (all types of each available in the database).

As shown in Figure 7, Weibull distributions are a good fit for several categories of HVAC equipment failure data. Although the ASHRAE database includes data for many different types of HVAC equipment, it was not selected as the primary source for deriving EULs for ComStock due to the limitations and biases in the database described by

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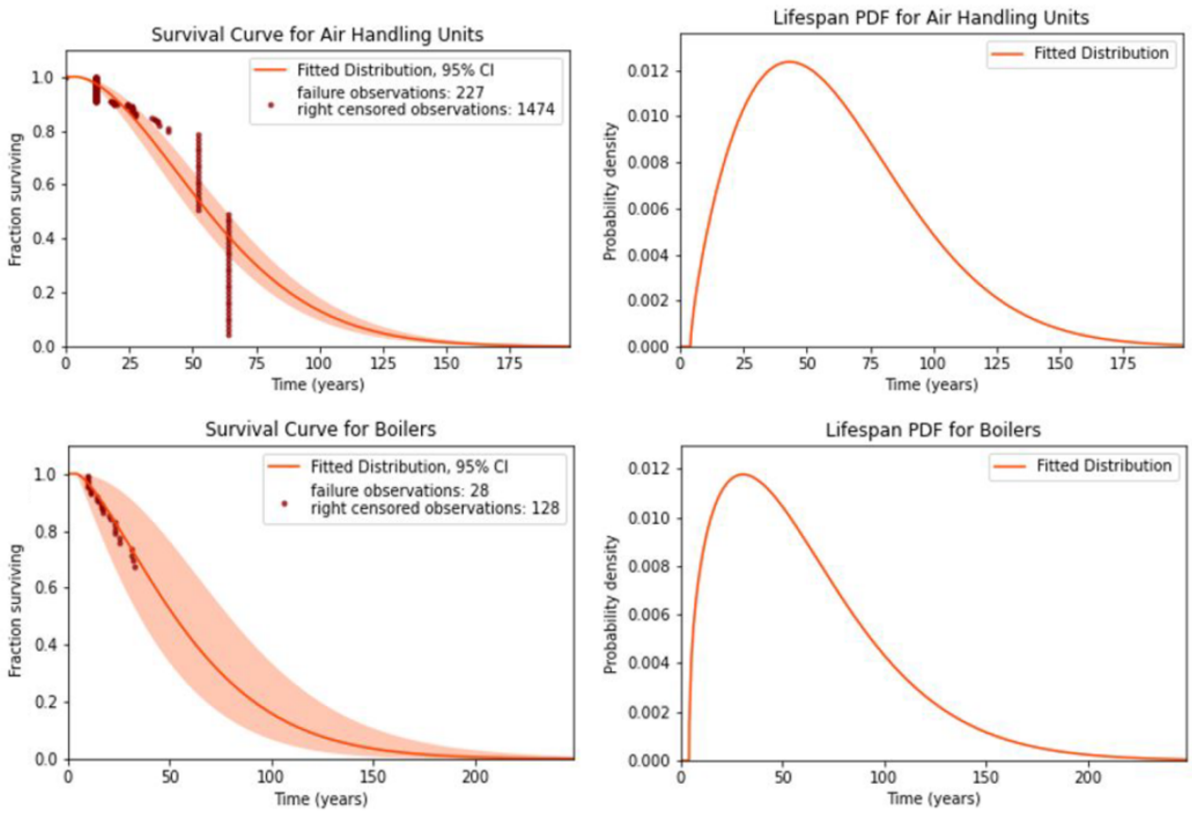

Figure 7. Survival curves and derived lifespan probability density functions for commercial HVAC equipment.

Table 6. Commercial Equipment Lifetime Weibull Distribution Parameters

EUL	Shape (beta)	Scale (alpha)	Shift (gamma)
10	1.6	EUL / 2 = 5	EUL * 0.6 = 6
15	1.6	EUL / 2 = 7.5	EUL * 0.6 = 9
20	1.6	EUL / 2 = 10	EUL * 0.6 = 12
70	1.3	91	0
200	1.0	1	200

its creators (Abramson, Wong, and Herman). Instead, we decided to use the EUL sources described in Table 5 and develop Weibull curve parameters around these EULs. The selected parameters are shown in Table 6. For the 70-year EUL, the parameters came from the window reliability analysis. For the 10-, 15-, and 20-year EULs, the only constraint was to match the EUL definition: 50% of the equipment would still be operable at the EUL. A minimum lifespan of 60% of the EUL was selected with the assumption that although individual components of a system might fail, it is unlikely that products on the market routinely fail at a whole-building scale in only a few years. The 200-year EUL parameters were selected to represent no failure for the life of the building.

4.1.6 Commercial Refrigeration Equipment

We represent commercial refrigeration equipment lifetimes using Weibull survival functions fit to effective useful lives (EULs) informed by the U.S. Department of Energy's *Commercial Refrigeration Equipment* Technical Support Document (DOE). Consistent with the TSD's market framing and industry practices, we differentiate between large grocery buildings (often owned or operated by national chains) and medium/small grocery buildings (more often independently owned).

For large groceries, we assume earlier replacement decisions driven by risk management, reliability requirements, and chain-wide retrofit programs that standardize fleets. We therefore assign a shorter EUL of 10 years. For medium and small groceries, where equipment is commonly retained until failure or when repair costs become prohibitive,

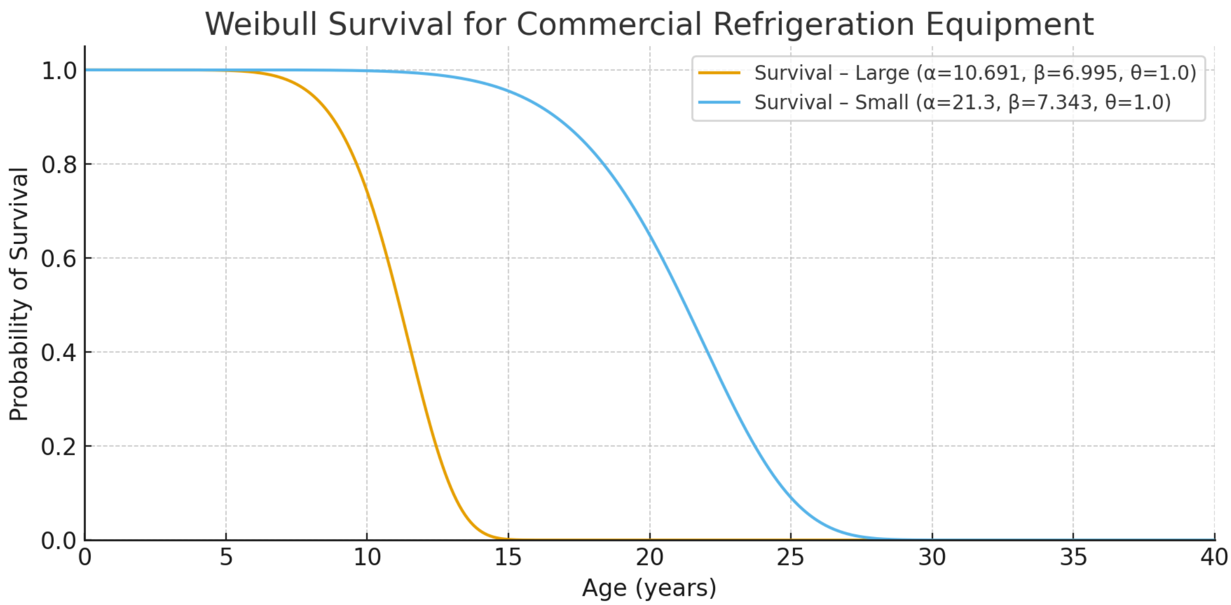

Figure 8. Weibull survival curves for commercial refrigeration equipment in large and small/medium grocery buildings.

we assign a longer EUL of 15 years. These assumptions align with the ownership and operations context underlying DOE's CRE analyses and shipments modeling (DOE).

We parameterize shifted-Weibull survival functions such that (i) 50% survival occurs at the EUL (our operational definition of EUL), and (ii) a minimum lifespan threshold of roughly 60% of the EUL avoids unrealistic early whole-system failures. The resulting parameters are listed in Table 7. These distributions produce the combined survival curves shown in Figure 8 and are used to schedule replacements and retirements in ComStock's stock-turnover logic.

Table 7. Commercial Refrigeration Equipment Weibull Distribution Parameters

EUL	Shape (beta)	Scale (alpha)	Shift (gamma)
10	6.995	10.691	1.0
15	7.343	21.300	1.0

4.1.7 Space Type Ratios

A space type refers to a portion of a building that has a distinct usage, purpose, occupancy schedule, thermostat set point, etc. Most buildings have multiple space types. For example, schools typically have classrooms, hallways, restrooms, cafeterias, etc. In ComStock, each building type is assumed to have a fixed ratio of various space types relative to the total building floor area. For buildings outside of California, the space type ratios were largely taken from the DOE commercial reference building models (Deru et al.). For buildings in California, the space type ratios were largely taken from the DEER prototype models (CPUC). There are certain building types that have altered ratios or are a mix of building types. For example in ComStock, warehouses include both unconditioned storage facilities and light manufacturing. Warehouse building subtypes alter the ratio of bulk storage. Retail strip mall buildings have different ratios of restaurant space types, with the default being 20%. Two examples of space type ratios are shown in Table 8. See Table 47 for the space type ratios for all building types.

4.1.8 Weather Data

ComStock can be run with two different types of weather data: typical meteorological year (TMY3) and actual meteorological year (AMY). AMY data is the data measured during a specific year, taken from weather stations such as those at airports. Because these data are from a particular calendar year, weather patterns that span large areas, such as nationwide heat waves, are captured in the data across multiple locations. Therefore, these weather patterns are captured in the outputs of ComStock. This is important for use cases where coordinated weather patterns

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Table 8. Space Type Ratio Example

Building Type	Building Subtype	Space Type	Ratio
Warehouse	warehouse_default	Bulk	66%
Warehouse	warehouse_default	Fine	29%
Warehouse	warehouse_default	Office	5%
Retail Strip Mall	strip_mall_restaurant20	Strip mall - type 1	20%
Retail Strip Mall	strip_mall_restaurant20	Strip mall - type 2	20%
Retail Strip Mall	strip_mall_restaurant20	Strip mall - type 3	40%
Retail Strip Mall	strip_mall_restaurant20	Dining	15%
Retail Strip Mall	strip_mall_restaurant20	Kitchen	5%

influence loads, such as peak load impacts for bulk power grid planning. TMY3 data, in contrast, take the "most typical" weather for each calendar month from a 30-year historical record and stitch these months together to form a complete year. The advantage of this method is that the weather data is less influenced by an extremely hot or cold year. However, this approach does not capture wide-area weather patterns, as the month of data used varies from location to location. For a more in-depth discussion of AMY and TMY3 weather data, see Wilson et al.

For geographic granularity, ComStock currently uses one weather file for each county in the United States. For counties with no weather data available (generally sparsely populated rural areas), data from the nearest weather station in the same climate zone are used. See (Wilson et al.) for a more in-depth discussion of the weather data sources, cleaning process, and assignment assumptions.

4.1.9 Soil Properties

Soil thermal conductivity and undisturbed ground temperature are location-dependent properties that are required in the ComStock model by several goethermal heat pump upgrade measures. Therefore, these properties are part of the ComStock sampling workflow and are stored as additionl properties in the building models, which can then be used by downstream measures. Soil thermal conductivity distributions by climate zone were dervied from a dataset produced by the Southern Methodist University Geothermal Lab, and are shown in Table 124 (Dedman College of Humanities and Sciences; Roy M Huffington Department of Earth Sciences). The soil thermal conductivity values range from 0.5 to 2.6 W/m-K. Average undisturbed ground temperatures by climate zone were derived from a 2014 Oklahoma State University study and are shown in Table 86 (Xing).

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4.2 Hours of Operation and Occupancy

4.2.1 Hours of Operation

Overview

Hours of operation are added to the model using operation start time and duration inputs. The start times and durations are assigned to each model through the sampling process using a set of distributions based on building type. They are then further broken down by weekday and weekend (Figure 9 and Figure 10). When applied to the model, the start time and duration are used to establish operating hour start and end times. These times are used to adjust the other schedules in the model (e.g., lighting, thermostat). This is achieved by stretching or shrinking the schedule on the temporal axis to align all schedules with the operating hours for the model. Note that because the weekday and weekend start times and durations are sampled independently, they are not aligned in a given building model.

Hours of Operation Derivation

We derived the hours of operation by applying the method introduced in Bianchi et al. to 1 year of AMI data from 6,070 buildings spread across eight utilities (the commercial schedules AMI data set). We first extracted the two-dimensional distribution of *High Load Start Time* and *High Load Duration* from this AMI data set, as an approximation of the schedule of hours of operations for each building type. Then, we compared this distribution with the inputs of ComStock at the start of the End-Use Load Profiles (EULP) calibration.

Figure 67 lists the number of buildings for each building type from each utility's AMI data set that was considered during the EULP project. The utility data sets and names are listed in Table 10 of the EULP Final Technical Report (Wilson et al.). Among the 15 building types considered in ComStock, 14 can be found in the commercial schedules AMI data set. The only exception is secondary schools, because all schools were grouped together in the AMI data.

We compared the distribution extracted from the commercial schedules AMI data set with the inputs of ComStock at the start of the EULP calibration. The results of the small office building type are presented in Figure 68 to illustrate the process, because this building type has the largest sample size in the AMI data set. We considered two day types, working day vs. non-working day, and two season definitions—one defined by month, and the other defined by daily average outdoor air temperature. The distribution of hours of operation is more diffuse in the AMI data set than in the ComStock inputs at the start of EULP calibration. Also, the duration of high load is smaller in the real AMI data than in the previous ComStock assumptions.

We explored whether and how the hours of operation are influenced by season (in Figure 68) and by utility (in Figure 69). Some differences can be observed; however, due to the modeling complexity and the desire to create a nationally applicable approach that avoids overfitting to a specific utility region, we combined the AMI data across seasons and utilities to generate a distribution of hours of operation for each building type. These new distributions were applied to ComStock in place of the existing distributions.

4.2.2 Occupancy

Occupancy Density

Occupants are assigned to individual space types as an occupancy density (people/1000 ft^2). This value, when multiplied by the total zone floor area, determines the maximum number of people in a zone. Tables 38 to 44 show the occupancy densities for all space types included in ComStock.

The majority of the ComStock occupancy density values are from the DOE prototype models. These are derived primarily from ASHRAE 62.1-2004 (ASHRAE), with some space type densities originating from the International Building Code 2003 (ICC). Prototype hotel guest rooms were assumed to have 1.5 occupants each, and occupancy rates for the two hotel models were assumed to be 65% to align with the industry average occupancy rate and Jiang et al. Rooms were randomly assigned occupants so that 65% of the rooms were occupied. Most of the DOE prototype hospital and outpatient space type occupancy densities were replaced with values from the 2007 Green Guide for Healthcare (GGHC), which includes typical occupancy densities for healthcare space types (Healthcare).

Occupancy Schedules

The maximum number of people in a zone (calculated from occupancy density and zone floor area) is multiplied by an hourly occupancy schedule with values ranging from zero to one to capture the variation in building occupancy

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throughout the day. Figures 11 and 12 show the national base occupancy schedules used in ComStock, broken down by building type. For the California occupancy schedules, please see figures 70 and 71 in the Appendix. For buildings in all states except California, the base schedules are the DOE prototype occupancy schedules. California uses schedules from DEER prototype models (CPUC). The DOE prototype documentation (Deru et al.) notes that there are few data sources that provide operating schedules for use in building energy simulations. Thus, the schedules in the prototype models were derived from two primary data sources: the Advanced Energy Design Guide Technical Support Documents (Jiang et al.; Bonnema et al.; Liu et al.; Pless, Torcellini, and Long) and ASHRAE 90.1-1989 Section 13 (ASHRAE). These schedules were then modified to account for real-world building operation, based on the experience of the engineers who created the DOE prototype models. Classroom occupancy schedules for primary and secondary schools were adjusted by factors of 0.75 and 0.70, respectively, to meet the student numbers documented in Pless, Torcellini, and Long. Table 45 lists the data sources for occupancy schedules in each of the prototype buildings (both DOE and DEER). Occupancy schedules in ComStock buildings are further adjusted so that the total daily occupancy in the building stock does not exceed the average daily occupancy of the United Stated building stock as derived from analysis of locations in the American Time Use Survey (BLS) Activity file. This adjustment applies a 23% reduction factor to all occupant schedule values, resulting in a peak daily total occupancy in ComStock models of approximatly 115M people.

These base occupancy schedules are stretched, compressed, or shifted in time to reflect the model's assigned hours of operation. For example, the base occupancy schedule for large offices is 9 a.m.–5 p.m. (8 hours of operation). If one large office model is assigned a start time of 8 a.m. and an operating duration of 10 hours, the base schedules in the model will be stretched so that the occupied period is an additional two hours long. All schedules in the model (occupancy, lighting, thermostat, plug load, etc.) are modified in the same manner to ensure coordination between occupancy, lighting, etc.

Occupancy Activity Schedules

Occupancy activity schedules represent the total heat gain per person, including convective, radiant, and latent heat. An internal EnergyPlus algorithm determines the fraction of the total load that is sensible and latent. The sensible portion is further divided into radiant and convective using the default fraction radiant value. DOE prototype activity levels are fixed for a given building type and range from 120–132 watts per person across the various building types. DEER prototype activity levels vary by space type and range from 117–331 watts per person. Table 46 lists the occupancy activity schedules used in ComStock.

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Figure 9. Operating hours' start time distributions.

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Figure 10. Operating hours' duration distributions.

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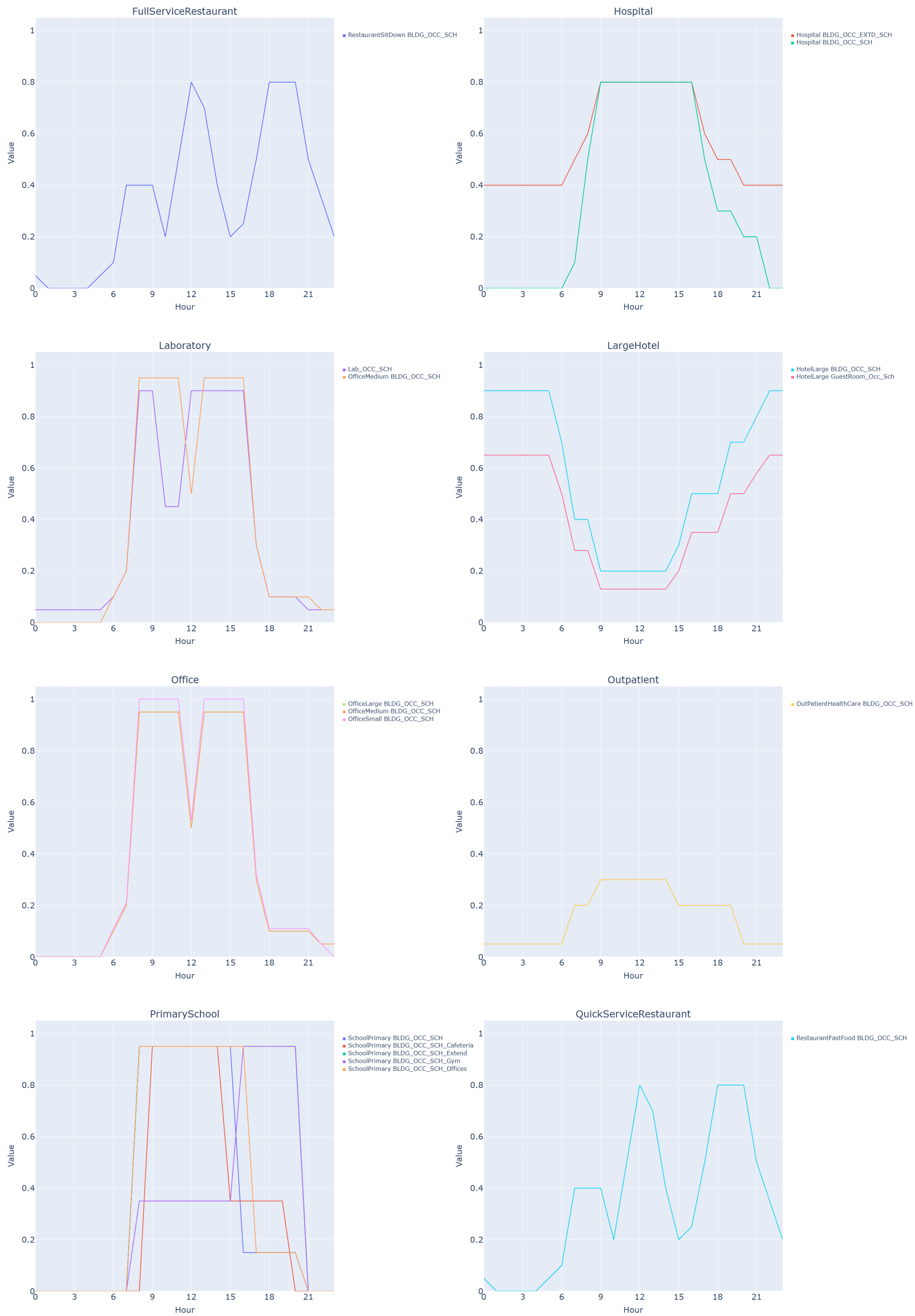

Figure 11. National base occupancy schedules for food service, lodging, healthcare, and education ComStock building types, excluding California. See Figure 70 for California.

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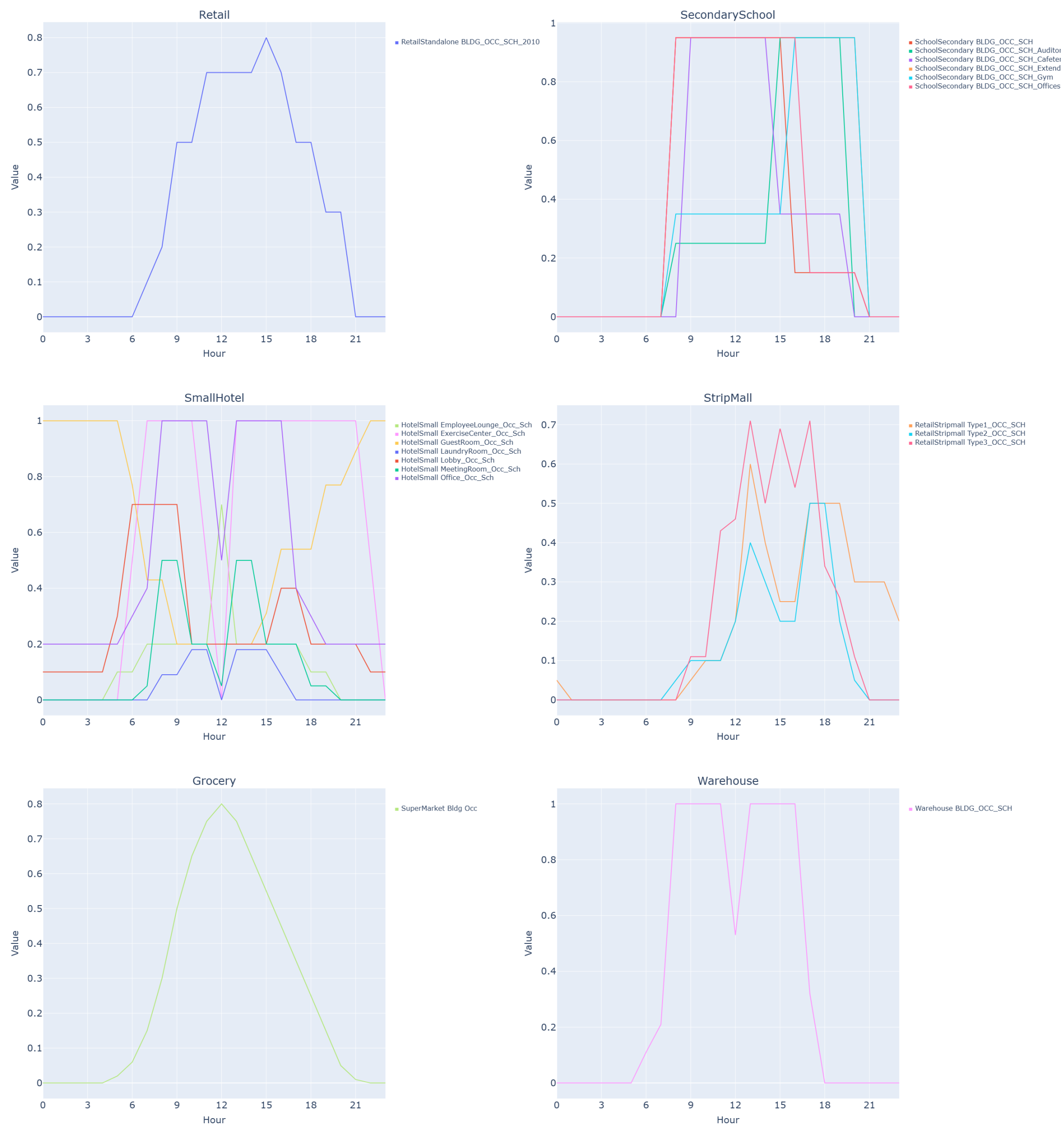

Figure 12. National base occupancy schedules for retail, office, and warehouse ComStock building types, excluding California. See Figure 71 for California.

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4.3 Geometry

4.3.1 General

A building's geometry influences several aspects of its associated building energy model. It impacts the building envelope by dictating the orientation of windows, the surface-to-volume ratio, and the ratio of one surface type to another. Geometry also impacts how prevalent solar heat gain is for a given building through the building's orientation and shape. ComStock uses seven characteristics to define a building energy model's geometry: floor area, shape, aspect ratio, rotation, number of floors, floor height, and window-to-wall ratio (WWR). The majority of these characteristics are assigned to the models as part of the sampling process. Combined, they create a virtual building model geometry like the example shown in Figure 13. All building models are variations of rectangular prisms with flat roofs and windows wrapping around the exterior. This simple geometry allows ComStock to easily scale properties and generate the number of individual building models needed for a national stock model. The following subsections describe each of the seven characteristics that define a building energy model's geometry in ComStock.

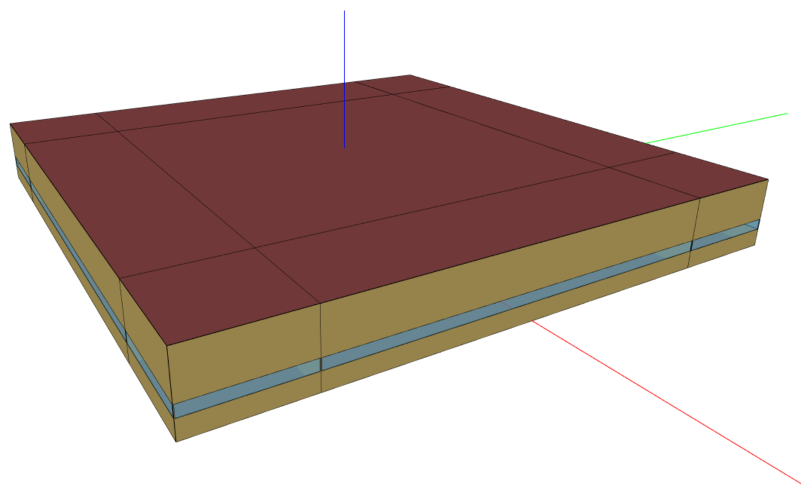

Figure 13. Example building geometry for a small office.

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4.3.2 Area

Building floor area is assigned to each model through the sampling process. Probability distributions were generated using CoStar (CoStar) for most building types. HSIP (DHS) was used for schools and hospitals, as neither are well represented in CoStar.

Figure 14 shows the breakdown of each building type in the national building stock by building size category (referred to as “rentable area”). Notice that the categories are presented as ranges. At this time, ComStock uses the area in the middle of the range, with the exception of "_1000" and "over_1mil," which use 1000 square feet and 1 million square feet, respectively. This method could be improved by adding variability to the building areas by selecting a variety of areas within the range.

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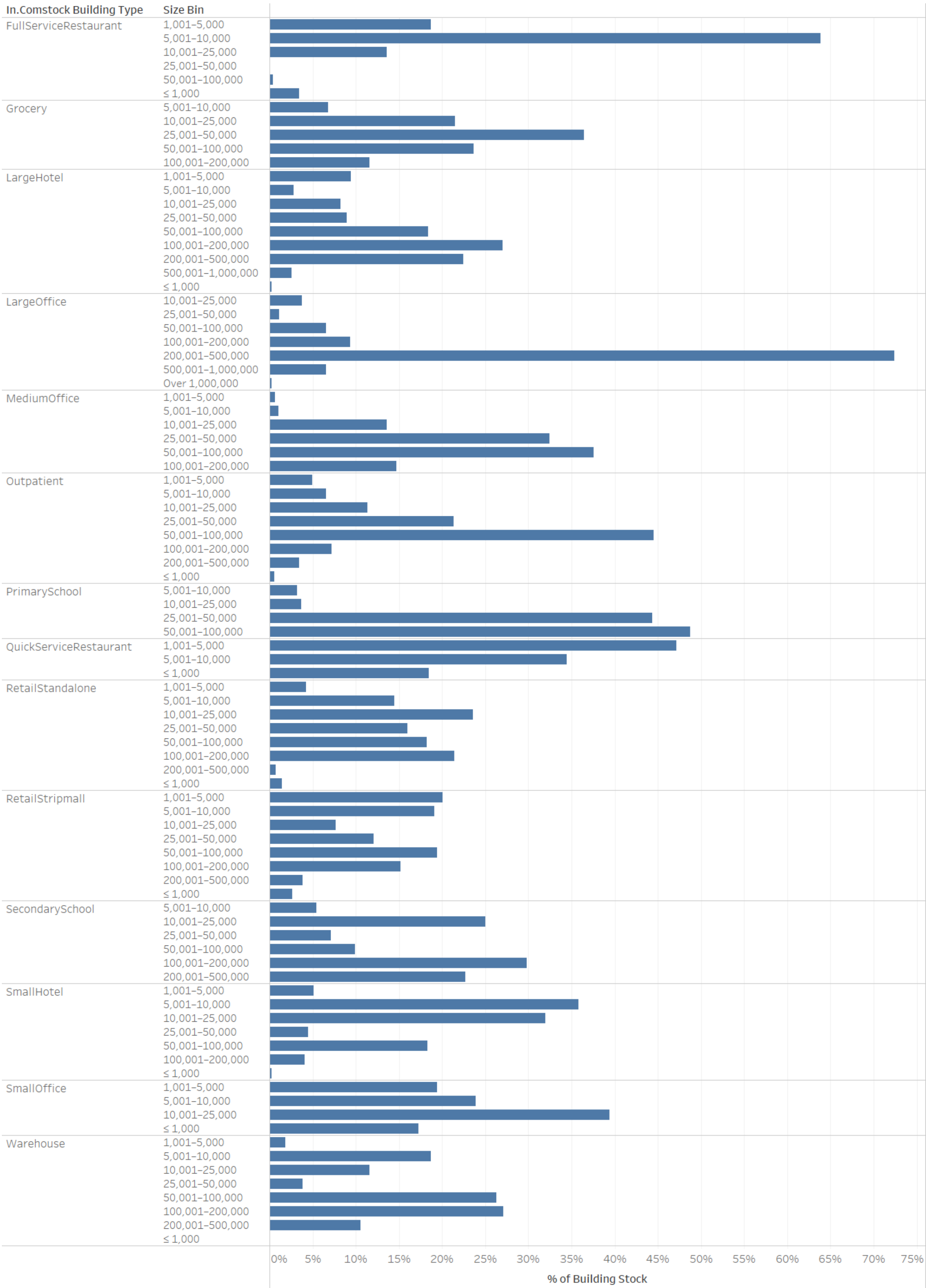

Figure 14. Distribution of rentable area by building type. The x-axis represents rentable area (square feet), and the y-axis represents the fraction of the building stock.

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4.3.3 Building Shape

Building shape is an intermediate characteristic assigned to the model during the sampling process. It is not a direct input to the model, as ComStock assumes a rectangular footprint for all buildings. Its function is as a dependency for aspect ratio (see next section 4.3.4). Probability distributions for building shape were generated from 2012 CBECS data, based on building type (EIA). CBECS uses numbers to represent many of the answers to survey questions, and ComStock adopted these numbers to represent building shapes.

Figure 15 shows the breakdown of the national building stock by building shape and type.

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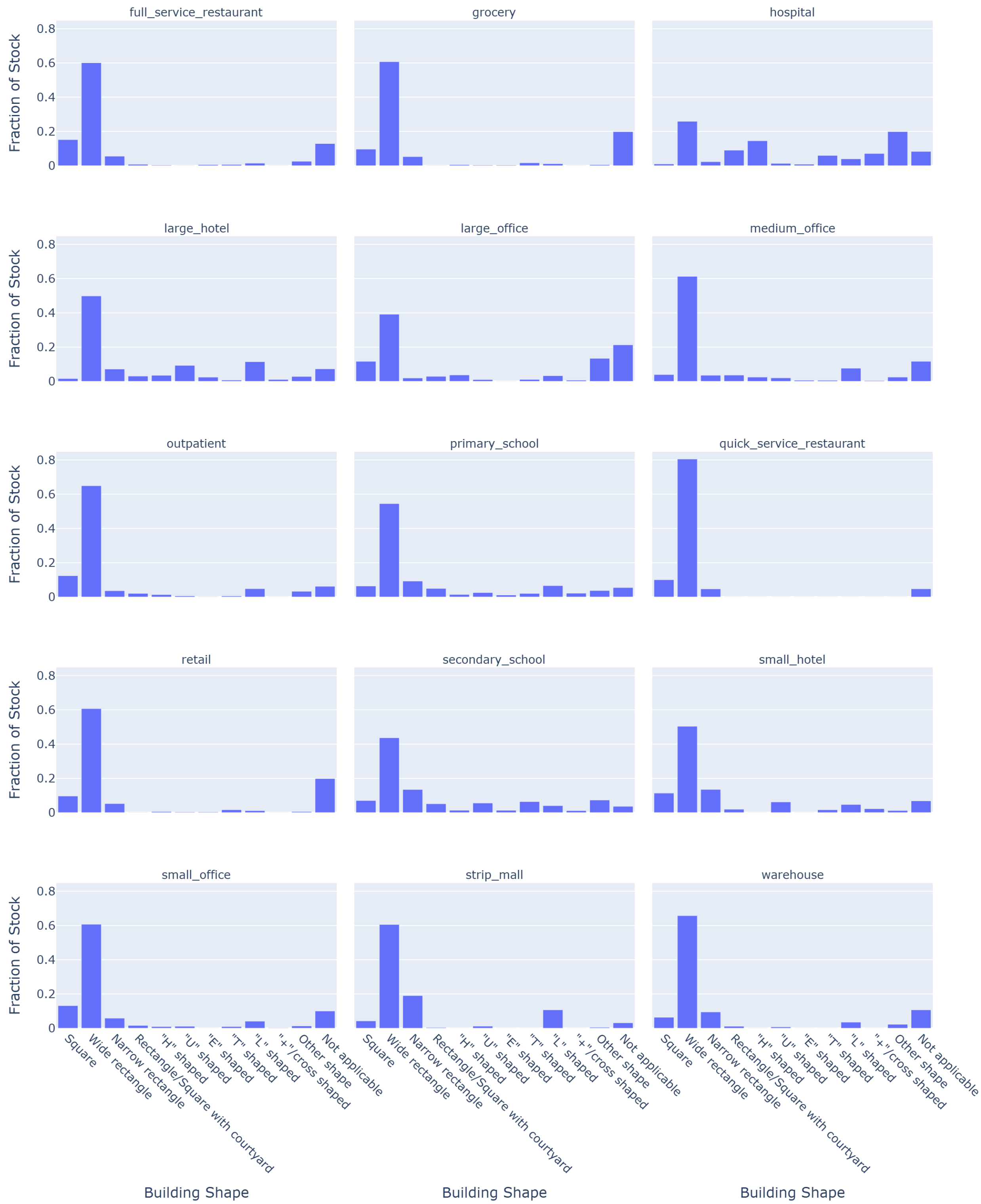

Figure 15. Distribution of building shape by building type. The x-axis represents the building shape, and the y-axis represents the fraction of the building stock.

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4.3.4 Aspect Ratio

Aspect ratio is defined as the overall length in the east–west direction divided by the overall length in the north–south direction. It is assigned to the building models during the sampling process. Probability distributions based on building shape were generated from 2012 CBECS data (EIA).

Figure 16 shows the breakdown of the national building stock by aspect ratio. The aspect ratios are integers from one to six, which represent a building's north-south:east-west ratio.

Figure 16. Distribution of aspect ratio by building type. The x-axis represents the aspect ratio (an integer from 1–6), and the y-axis represents the fraction of the building stock.

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4.3.5 Rotation

Rotation defines the orientation of the building relative to the cardinal directions. In ComStock, there are eight rotation options, ranging from 0 to 315 degrees at 45-degree intervals. Ninety and 270 degrees correspond to a north-south length and east-west width (Figure 17). Rotations are evenly distributed throughout the building stock due to a lack of available data for more detailed distributions. This will be improved if new data becomes available.

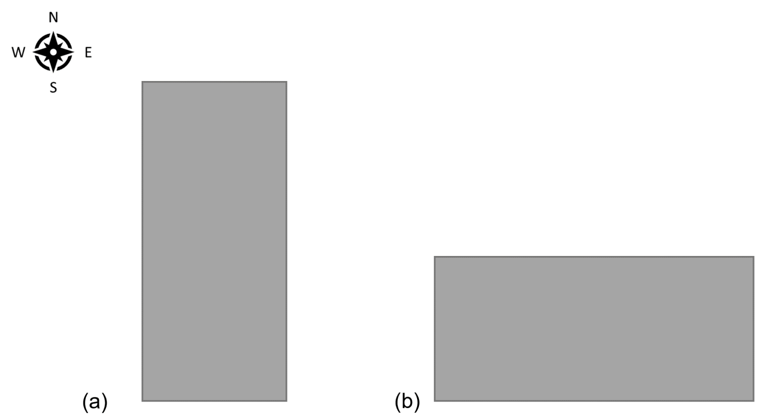

Figure 17. Illustration of building rotation. (a) Buildings with either 90 or 270 degree rotation have a north-south length. (b) Buildings with either 0 or 180 degree rotation have an east-west length.

4.3.6 Floor Height

Floor height is represented in the models as floor-to-floor height. ComStock uses the floor-to-floor heights found in the DOE prototype buildings, which were established using expert opinion (Deru et al.). These floor-to-floor heights are summarized in Table 9.

Table 9. Floor-to-Floor Heights by Building Type

Building Type	Floor-to-Floor Height (feet)
Full Service Restaurant	10
Hospital	14
Large Hotel	Ground: 13; Upper: 10
Large Office	13
Medium Office	13
Outpatient	10
Primary School	13
Quick Service Restaurant	10
Retail	20
Secondary School	13
Small Hotel	Ground: 11; Upper: 9
Small Office	10
Strip Mall	17
Warehouse	28

4.3.7 Number of Floors

ComStock assigns a number of floors to each model during the sampling process to create a distribution of building heights in the stock. This value represents the number of aboveground floors for a given model. No buildings in ComStock have belowground stories.

For most of the building types, we generated probability distributions based on county and building type using CoStar (CoStar). We used HSIP (DHS) for schools and hospitals, as neither are well-represented in CoStar.

Figure 18 shows the breakdown of the national building stock by number of floors and building type.

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Figure 18. Distribution of number of aboveground floors by building type. The x-axis represents the number of floors, and the y-axis represents the fraction of the building stock.

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4.3.8 Window-to-Wall Ratio (WWR)

The ComStock window-to-wall ratio (WWR) assumptions were created as part of the EULP project. WWR is defined as the fraction of abovegrade wall area that is covered by fenestration. Previously, ComStock used the WWR from the DOE prototype building models. Although each building type had a different WWR, there was no variability within each building type, which is not representative of the building stock. To address this issue, we referenced the NFRC Commercial Fenestration Market Study conducted by Guidehouse (Ciraulo et al.). The study characterized the national commercial window stock through data collection and analysis. Six primary data sources representing all regions of the United States were used in the study—a 2020 Guidehouse survey, NEEA CBSA, DOE Code Study, CAEUS, CBECS, and RECS (multifamily). A variety of window properties were collected, including WWR, number of panes, frame material, glazing type, low-emissivity coating, gas fill, and many others. In total, the database contained approximately 16,000 samples, each with an appropriate weighting factor based on the coverage, completeness, and fidelity of each data source. We incorporated the WWR results from this study into the ComStock model, and we may incorporate other fields in the future to further refine our window modeling methodology.

From the Guidehouse data, we developed a WWR distribution for each combination of building type, floor area, and vintage. We first analyzed the WWRs separately by building type, floor area, geographic location, and vintage to determine which filters were appropriate to use for the final distributions. Geographic location did not have a significant impact on WWR, so it was left out of the final distributions. As can be seen in Figures 19 and 20, there is a noticeable change in the WWR of buildings built after 2014, indicating that new buildings are trending toward larger windows. Similarly, there is a distinct trend in the WWR as a function of floor area; larger buildings tend to have more windows. Whereas the previous methodology only varied WWR by building type, these new distributions introduce more WWR variability by considering vintage and floor area.

The WWR distributions for all buildings before and after incorporating the NFRC data are shown in Figure 21. The distinct bins in the graph are a result of the way WWR is binned in the CBECS Show Card: 0%–1% WWR is binned to 0.0, 2%–10% to 0.06, 11%–25% to 0.18, 26%–50% to 0.38, 51%–75% to 0.63, and 76%–100% to 0.88. The final distributions do not change the stock total energy consumption significantly, but they do add realistic variability within building types. For example, previously, all large offices had the same WWR of 0.15, whereas using the new distributions, large office WWRs vary from 0.01 to 0.88.

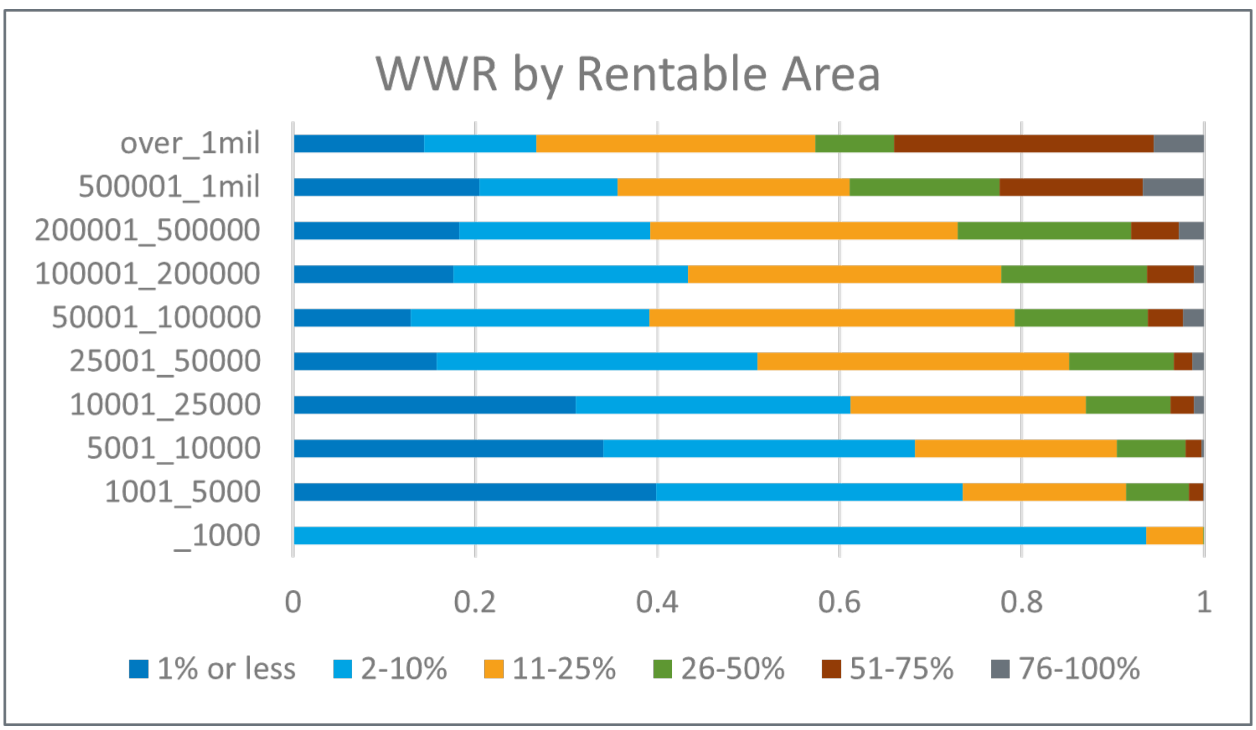

Figure 19. Window-to-wall ratio by rentable floor area.

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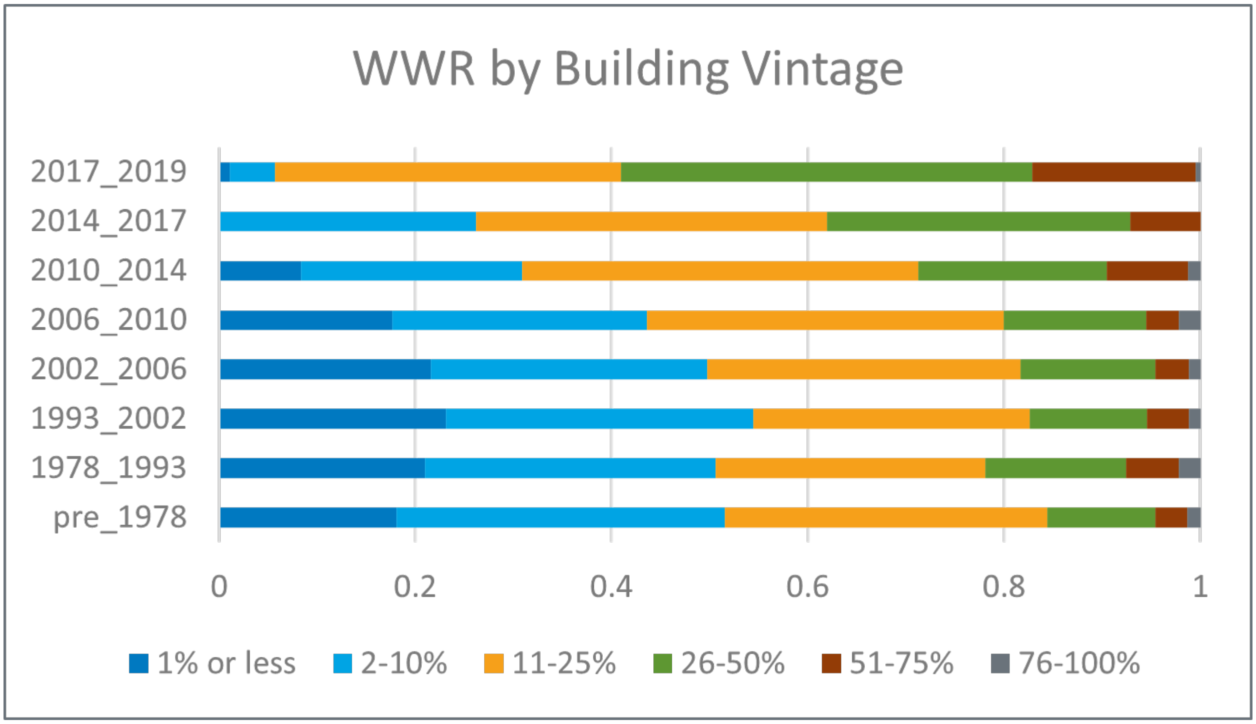

Figure 20. Window-to-wall ratio by building vintage.

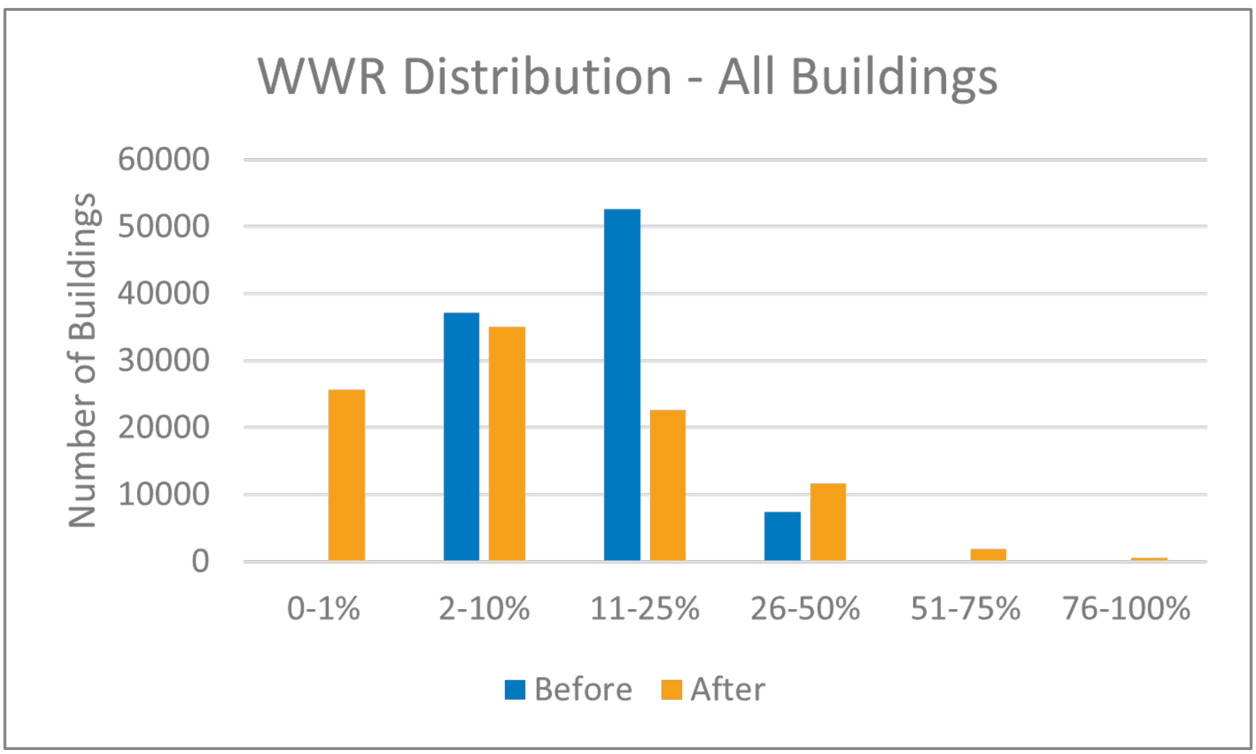

Figure 21. Window-to-wall ratio distribution in all building types before and after incorporating NFRC data.

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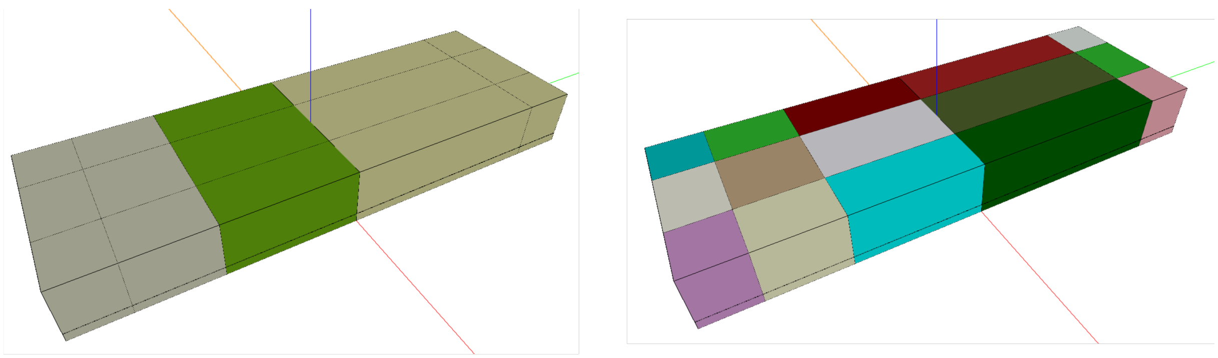
4.3.9 Space Programming and Thermal Zoning

As described above, all ComStock building models are a rectangular prism with a prescribed aspect ratio, floor area, etc. Within each building, there are one or more space types, as described in Section 4.1.7. Space types are represented within the rectangular geometry as "slices" through the building that correspond to the floor area fractions of each space type. This is shown in Figure 22(a). In the cases of very small buildings, this can sometimes result in spaces which are unrealistically long and narrow for space types that make up only a small fraction of the building.

For larger buildings where the length and width are both greater than 37.5 feet, each space type is divided into core-and-perimeter thermal zones with a 15-foot depth (Figure 22(b)). Notice that the space types adjacent to the shorter ends of the building are each broken into six thermal zones, whereas the space types in the center of the building are each broken into three thermal zones. In multistory buildings, space types are often found on more than one floor, and in some cases, a floor will be a single space type. The downside to this thermal zoning approach is that thermal zones—and, as a follow-on, the HVAC systems that serve them—may be unrealistically small or large for certain geometry and building type combinations. These may later be modified to set a minimum and maximum size threshold for thermal zones.



(a) (b)

Figure 22. Example building geometry colored by (a) space type and (b) zone.

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4.4 Envelope

4.4.1 Walls

Wall Construction Type

First, we selected the general types of wall construction methods to be represented in ComStock. We chose the four general wall types commonly used in commercial building energy codes because they cover the most common wall construction types and can be linked to nominal thermal characteristics. The definitions of these types from ASHRAE are as follows, with the corresponding ComStock enumerations shown in parentheses:

- **Mass wall** (Mass): A wall with a heat capacity exceeding (1) 7 Btu/ft^2·F or (2) 5 Btu/ft^2·F, provided that the wall has a material unit weight not greater than 120 lb/ft^3.
- **Metal building wall** (Metal Building): A wall whose structure consists of metal spanning members supported by steel structural members (i.e., does not include spandrel glass or metal panels in curtain wall systems).
- **Steel-framed wall** (SteelFramed): A wall with a cavity (insulated or otherwise) whose exterior surfaces are separated by steel framing members (i.e., typical steel stud walls and curtain wall systems).
- **Wood-framed and other walls** (WoodFramed): All other wall types, including wood stud walls.

To determine the prevalence of each wall construction type, we queried a database, LightBox, containing building type, number of stories, location, and wall construction. The database did not use the same wall construction types selected for ComStock, so we created a mapping between the database entries and the wall construction types listed above, as shown in Table 48. Some construction types in the database were excluded from the mapping, either because the meaning was ambiguous or because they represented an insignificant fraction of the entries in the database. The excluded constructions represent only 5% of the total samples, with 4.5% labeled “OTHER” (which there was no clear way to map).

Upon reviewing the data, we identified two instances that were likely misclassifications. The first was buildings higher than five stories with the wall construction type“WoodFramed”. Historically, it was not possible to use Wood-Framed construction for buildings over five stories, and even today, this practice is uncommon. Buildings with this combination were reassigned to “Mass” walls, based on the assumption that people were observing large wood internal structural members in old buildings and classifying them as WoodFramed. The second was buildings higher than two stories with “MetalBuilding” walls. Based on experience, this construction technique is commonly reserved for 1–2 story buildings only. Buildings with this combination were reassigned to “SteelFramed,” based on the assumption that this would be the most likely alternative classification if a person observed steel structural elements.

After mapping each entry in the database to one of the ComStock construction types, we analyzed the data to determine other building characteristics in the database were correlated with construction type. Older buildings were slightly more likely to use mass constructions, but the change over time was minor. Construction type varied significantly as a function of the number of stories. Shorter buildings were much more likely to be wood-framed, whereas taller buildings were more likely to be mass, and very tall buildings were likely to be steel-framed (steel studs or curtain wall). Based on a spot-checking of the database, we found the building type classification to be less reliable than other building characteristics. Although there was some correlation between building type and wall construction, there was also a correlation between building type and number of stories. Because of the joint correlation, we selected number of stories instead of building type. There was a clear correlation between climate zone and construction type—most notably, there was a much lower incidence of mass walls in cold climate zones. There was some correlation between construction type and building floor area. However, there was also a correlation between the number of stories and the building area. Because the construction type is physically limited by a building’s height, it was more logical to use the number of stories as a driving characteristic for construction type. Following this analysis, we concluded that the number of stories and climate zone should be used as drivers of wall construction type. The probabilities for each combination of number of stories and climate zone were calculated and then used as the input distribution for wall construction type in ComStock. This distribution is summarized in Table 49.

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Wall System Turnover Rate

As described in Section 4.1.5, we assume that some building systems, including exterior walls, are replaced over the lifespan of the building. Typically, for exterior walls, the structural elements of the wall are maintained, while the cladding, insulation, sheathing, etc. are be replaced. As noted in Section 4.1.5, the EUL for exterior walls is assumed to be 200 years, which means that most buildings are modeled with the walls they were built with. Once the wall construction type probabilities and distributions of building types, sizes, and vintages are carried through the sampling process and simulations are created, the distribution of construction types and energy code levels can be reviewed. As shown in Figure 23, because the majority of the building stock is older, and wall systems are replaced at a low rate, most of the building floor area is assumed to have walls that follow the oldest energy codes.

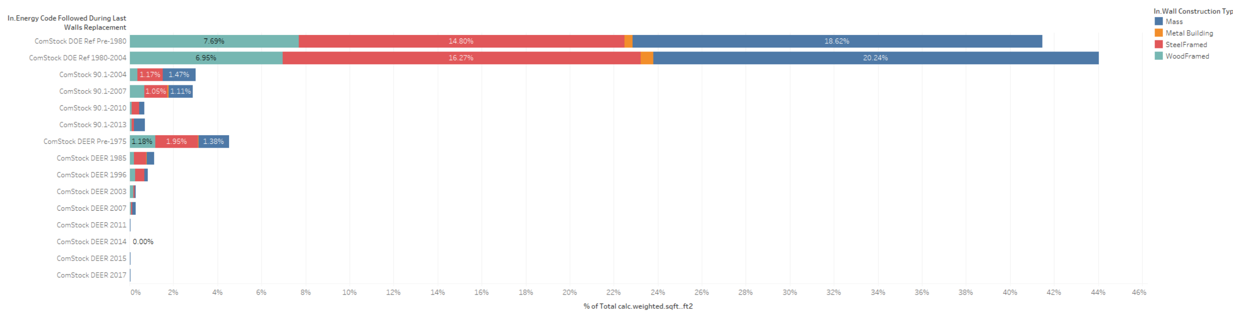

Figure 23. Weighted floor area by energy code followed during last wall replacement and wall type.

Wall Thermal Performance

We did not find any data sources that contained the thermal performance (U-Value/R-Value) of walls in the commercial building stock. This is likely because surveys would need to either find building plans, which can be difficult or impossible for older buildings, or disassemble part of the structure to look inside the walls, which building owners are unlikely to allow. To account for the lack of data, we estimated wall thermal performance based on an estimate of the energy code followed when the wall was last replaced. Section 4.1.4 describes how the energy code was determined. The thermal performance of walls for each energy code varies based on climate zone and construction type, as shown in Table 50 and Table 51. Note that although these thermal performance values do include the thermal bridging inherent in the clear field wall, they do not include thermal bridging at intermediate floors, parapets, and glazing transitions. These additional thermal bridges are expected to lower the overall thermal performance of the wall assembly.

As previously described, most of the building stock's walls are assumed to be older. Therefore, the thermal performance assumptions for older vintages have a much higher impact on the overall heating and cooling demand than those for newer vintages. The ComStock DOE Ref Pre-1980 assumptions, taken from Deru et al., are originally from a study of only offices (Briggs, Belzer, and Crawley). Unfortunately, this study no longer appears to be available. Following the methodology in Deru et al., these values are used for all wall construction types and all building types. Figure 24 shows the final prevalence of each wall construction type by building type. Most notable is the low prevalence of metal building walls across the stock, even in warehouses. This might be surprising, but it is supported by the available data. Table 52 shows the average wall thermal performance by ASHRAE Standard 169–2006 climate zone.

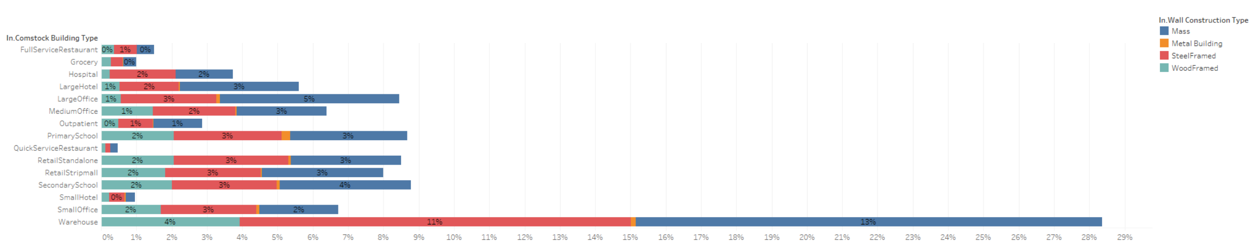

Figure 24. Weighted floor area by wall type and building type.

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4.4.2 Windows

Window Construction Type

Data from the NFRC Commercial Fenestration Market Study was used to develop the modeling approach for windows in ComStock. This study, conducted by Guidehouse in collaboration with NFRC, characterized the national commercial window stock through data collection and analysis. Six primary data sources representing all regions of the United States were used in the study—a 2020 Guidehouse survey, NEEA CBSA, DOE Code Study, CAEUS, CBECS, and RECS. A variety of window properties were collected, including the window-to-wall ratio, number of panes, frame material, glazing type, low-E coating, gas fill, solar heat gain coefficient (SHGC), U-factor, and many others. In total, the database contained approximately 16,000 samples, each with an appropriate weighting factor based on the coverage, completeness, and fidelity of each data source. The WWR data was already incorporated into the ComStock baseline during the EULP project. Some of the other key window properties such as thermal performance were then used to create the new baseline window constructions and distributions discussed later in this section. A summary of the data sources and their associated information is shown in Table 53.

Four window properties—number of panes, glazing type, frame material, and low-E coating—were used to create the baseline window configurations. These four parameters were selected based on which characteristics have the most impact on window performance, which have the most data available from the various data sources, and which inputs we trust from the average building owner or survey recipient. The options for each property are shown in Figure 25.

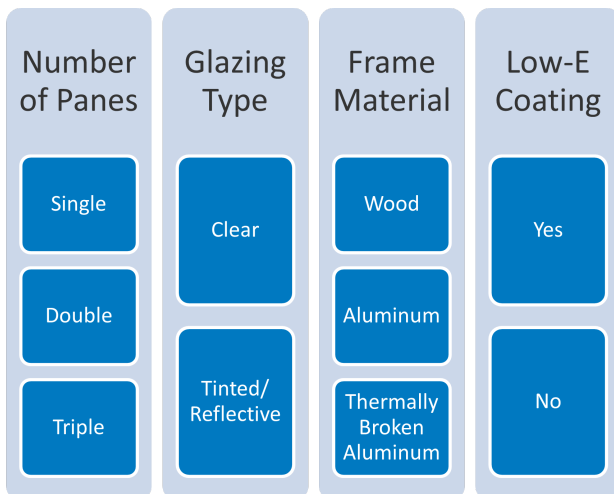

Figure 25. Window characteristics for number of panes, glazing type, frame material, and low-E coating.

Modeling every combination of these four properties would result in 36 different window configurations, which would add significant complexity to the sampling process. Instead, we selected 12 combinations to be modeled, based on which combinations are most common and most realistic. There are four single-pane, six double-pane, and two triple-pane configurations. The unrealistic/uncommon combinations that were eliminated include:

- Single pane with thermally broken aluminum frame
- Single pane with low-E coating
- Double pane with wood frame
- Triple pane with no low-E coating
- Triple pane without thermally broken aluminum frame
- Thermally broken double or triple pane without low-E coating.

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Table 10. Window Configurations

Number of Panes	Glazing Type	Frame Material	Low-E Coating
Single	Clear	Aluminum	No
Single	Tinted/Reflective	Aluminum	No
Single	Clear	Wood	No
Single	Tinted/Reflective	Wood	No
Double	Clear	Aluminum	No
Double	Tinted/Reflective	Aluminum	No
Double	Clear	Aluminum	Yes
Double	Clear	Aluminum With Thermal Break	Yes
Double	Tinted/Reflective	Aluminum	Yes
Double	Tinted/Reflective	Aluminum With Thermal Break	Yes
Triple	Clear	Aluminum With Thermal Break	Yes
Triple	Tinted/Reflective	Aluminum With Thermal Break	Yes

The 12 remaining window configurations are shown in Table 10.

We created a sampling distribution for the new window constructions for the entire country using the initial data set. Overall, single-pane windows make up approximately 54% of the stock, double-pane windows make up 46%, and triple-pane windows make up <1%. Initially, we created distributions based on census division to incorporate geographic location into the sampling. Upon further analysis, we found that it was also necessary to incorporate the energy codes into distributions to prevent scenarios where a single-pane window was sampled for a certain location, but, according to the energy code for that location, a double-pane window was required. For this reason, we modified the sampling distribution to include two dependencies—climate_zone and energy_code_followed_during_last_-window_replacement.

To generate these sampling distributions, we used the maximum U-values specified for each climate zone in each version of ASHRAE 90.1, using climate zones defined by ASHRAE 169–2006. For each combination of climate zone and energy code, the 12 window configurations were evaluated to determine which were both realistic and met code (i.e., had a U-value lower than the code maximum U-value). For the older energy codes, we made several assumptions about technology adoption to determine which window configurations were realistic:

- Low-E coating—not adopted until DOE Ref 1980–2004
- Thermally broken aluminum frame—not adopted until 90.1-2004
- Triple pane—not adopted until 90.1-2004.

Each combination of climate zone and energy code included 2–12 window configurations that met the criteria. After limiting the distributions to these configurations, we renormalized the percentages from the national distribution to 100%. This kept the percentages from the national distribution while also incorporating intelligent assumptions based on climate zone and energy code. Table 11 provides an example of the window configurations that were sampled for each code year in climate zone 4A.

As can be seen in Table 11, for DOE Ref Pre-1980, the only windows that met code and are realistic are single-pane or double-pane windows with no low-E coating. For DOE Ref 1980–2004, the maximum U-value dropped significantly, such that single-pane aluminum windows no longer met code. However, double-pane low-E windows became available on the market at that time. For 90.1-2004 through 90.1-2010, code required a U-value equivalent to double-pane low-E or better, and in 90.1-2013, the code improved again, meaning that double-pane low-E with a thermal break or better was required. This type of logic was applied to all combinations of climate zone and energy code. Then, we converted the data into the distributions used in sampling.

A small adjustment was made to the final distributions because some states and localities do not follow or enforce energy codes strictly. Following the code exactly would likely overestimate window performance. Therefore, in

Table 11. Window Distribution Assumptions Example from Climate Zone 4A

Energy Code Followed During Last Windows Replacement	Pre-1980	1980-2004	90.1-2004	90.1-2007	90.1-2010	90.1-2013
Allowable Assembly Maximum U-Value	1.22	0.59	0.57	0.55	0.55	0.42
Allowable Assembly Maximum SHGC	0.54	0.36	0.39	0.4	0.4	0.4
Single - No LowE - Clear - Aluminum U-1.178 SHGC-0.744	X					
Single - No LowE - Tinted/Reflective - Aluminum U-1.178 SHGC-0.579	X					
Single - No LowE - Clear - Wood U-0.91 SHGC-0.683	X	X				
Single - No LowE - Tinted/Reflective - Wood U-0.91 SHGC-0.525	X	X				
Double - No LowE - Tinted/Reflective - Aluminum U-0.749 SHGC-0.484	X	X				
Double - No LowE - Clear - Aluminum U-0.746 SHGC-0.646	X	X				
Double - LowE - Clear - Aluminum U-0.559 SHGC-0.386		X	X	X	X	
Double - LowE - Tinted/Reflective - Aluminum U-0.557 SHGC-0.274		X	X	X	X	
Double - LowE - Clear - Thermally Broken Aluminum U-0.499 SHGC-0.378			X	X	X	X
Double - LowE - Tinted/Reflective - Thermally Broken Aluminum U-0.496 SHGC-0.266			X	X	X	X
Triple - LowE - Clear - Thermally Broken Aluminum U-0.3 SHGC-0.328			X	X	X	X
Triple - LowE - Tinted/Reflective - Thermally Broken Aluminum U-0.299 SHGC-0.224			X	X	X	X
	X = This window type meets code minimums					

scenarios where single-pane windows were technically below code, we assumed that 5% of all windows in the stock would still have the worst-performing single-pane windows installed. The distributions were adjusted accordingly by subtracting 5% total from the double-pane configurations and adding to the single-pane aluminum configurations. After making this manual adjustment, the new distributions had the same overall breakdown as the national distribution generated from the Guidehouse data—54% single-pane and 46% double-pane .

Window Thermal Performance

Once the 12 new window constructions were determined, a team from Lawrence Berkeley National Laboratory's (LBNL's) Windows and Daylighting Group used the WINDOW program to assign thermal performance properties to each construction. SimpleGlazing objects in EnergyPlus were chosen to represent windows to reduce complexity. This choice also simplifies the process of applying upgrades, because all fenestration objects in the baseline models use the same object type. The inputs for the SimpleGlazing object are U-factor, solar heat gain coefficient (SHGC), and visible light transmittance (VLT). For each window configuration, LBNL assigned a frame ID and window ID from the WINDOW database. They also filled in the respective U-factors, SHGCs, and VLTs, which are shown in Table 54.

The U-factors originally ranged from U-1.18 Btu/h·ft^2·F for the worst-performing single-pane window to U-0.30 Btu/h·ft^2·F for the best-performing triple-pane window. As mentioned earlier in this section, the maximum U-Factor that EnergyPlus can model with a simple glazing object is U-1.02 Btu/h·ft^2·F, which is governed by the limitations of a 2D heat transfer model when interior and exterior air films are included. Therefore, we adjusted the U-factor for the first two single-pane windows to be U-1.02 Btu/h·ft^2·F rather than U-1.18 Btu/h·ft^2·F. This allowed these windows to be modeled in ComStock. This results in a slight overestimate of the thermal performance of single-pane windows.

4.4.3 Roof

Roof Construction Type

First, we reviewed the general types of roof construction methods that could be represented. The three general roof types commonly used in commercial building energy codes were chosen because they cover the most common roof construction types and can be linked to nominal thermal characteristics. The definitions of these types from ASHRAE are as follows:

- **Roof with insulation entirely above deck (IEAD)**: A roof that has all insulation installed above (outside of) the roof structure and that is continuous (i.e., uninterrupted by framing members).

- **Metal building roof**: A roof that is constructed with a metal, structural weathering surface; has no ventilated cavity; and has the insulation entirely below deck (i.e., does not include composite concrete and metal deck construction or a roof framing system that is separated from the superstructure by a wood substrate). In addition, the roof structure consists of one or more of the following configurations: (a) metal roofing in direct contact with the steel framing members, (b) metal roofing separated from the steel framing members by insulation, or (c) insulated metal roofing panels installed as described in a or b.
- **Attic and other roof**: All other roofs, including roofs with insulation entirely below (inside of) the roof structure (e.g., attics, cathedral ceilings, and single-rafter ceilings); roofs with insulation both above and below the roof structure; and roofs without insulation (excluding metal building roofs).

The analysis of roof properties in EIA, shown in Figure 26, indicates that about 90% of the commercial floor space covered by ComStock has flat or shallow pitch roofs, and that the large majority of the buildings with flat or shallow pitch roofs do not have attic space. Given these factors and the complexity associated with modeling the geometry of pitched roofs, we decided to model the entire stock as having flat roofs.

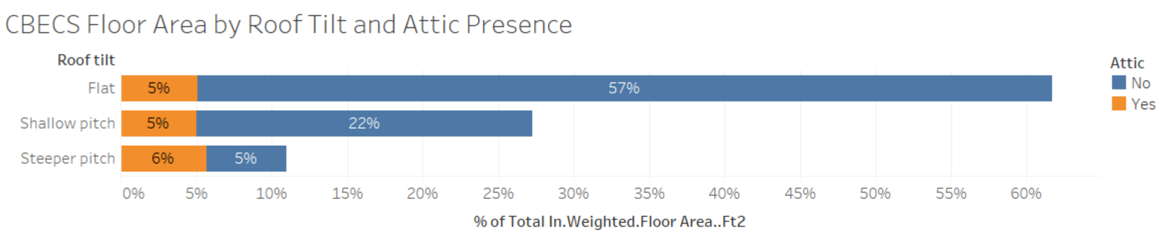

Figure 26. Weighted floor area by roof tilt and attic presence.

No data sources for roof construction type were found. For buildings outside of California, a single roof construction type was chosen for each building type. As shown in Table 57, most buildings are assumed to use IEAD roofs, which is consistent with the assumption of flat roofs. For buildings in California, the construction types from the DEER prototype buildings were used (CPUC).

Roof System Turnover Rate

As described in Section 4.1.5, some building systems, including roofs, are assumed to be replaced over the lifespan of the building. Typically, for roofs, the structural elements are maintained, while the roof membrane and insulation are replaced. As noted in Section 4.1.5, the EUL for roofs was assumed to be 200 years, which means that most buildings are modeled with the roof insulation they were built with. Once the roof type probabilities and distribution of building types, sizes, and vintages are carried through the sampling process and simulations are created, the distribution of energy code levels can be reviewed. As shown in Figure 27, because the majority of the building stock is older, and roof systems are replaced at a low rate, most of the building floor area is assumed to have roofs that follow the oldest energy codes.

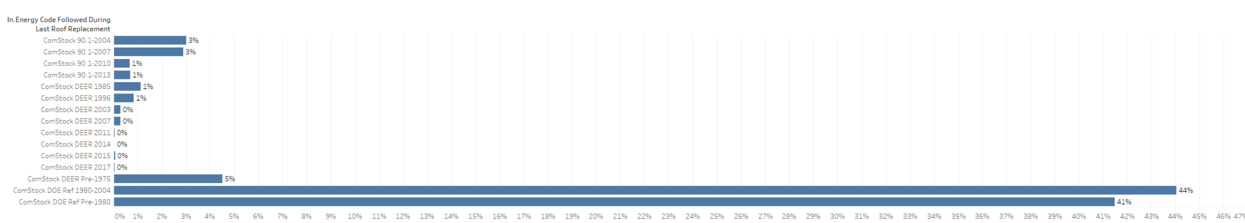

Figure 27. Weighted floor area by energy code followed during last roof replacement.

Roof Thermal Performance

We did not find any data sources that contained the thermal performance (U-Value/R-Value) of roofs in the commercial building stock. This is likely because surveys would need to either find building plans, which can be difficult or impossible for older buildings, or disassemble part of the structure to look inside the roofs, which building owners are unlikely to allow. To account for the lack of data, we estimated roof thermal performance based on an estimate of the energy code followed when the roof was last replaced. Section 4.1.4 describes how the energy code was determined. The thermal performance of roofs for each energy code varies based on climate zone and construction type, as shown in Tables 55 and 56. While these thermal performance values do include the thermal bridging inherent in the clear field roof, they do not include thermal bridging at parapets, skylight curbs, or roof penetrations for HVAC systems. These additional thermal bridges are expected to lower the overall thermal performance of the roof assembly.

As previously described, most of the building stock's roofs are assumed to be older. Therefore, the thermal performance assumptions for older vintages have a much higher impact on the overall heating and cooling demand than the assumptions for newer vintages. The ComStock DOE Ref Pre-1980 assumptions, taken from Deru et al., are originally from a study of only offices (Briggs, Belzer, and Crawley). Unfortunately, this study no longer appears to be available. Following the methodology in Deru et al., these values are used for all roof construction types and all building types.

4.4.4 Floor

In ComStock, all buildings are assumed to be built using slab-on-grade construction and to have no cantilevered thermal zones. Thus, the only heat transfer into the building through floors is assumed to happen through the floor in contact with the ground. All floors between stories are internal surfaces, and any heat transfer through these surfaces occurs between zones within the building, not between the building and the outside environment.

Floor Thermal Performance

We did not find any data sources that contained the thermal performance of floors in the commercial building stock. This is likely because surveys would need to either find building plans, which can be difficult or impossible for older buildings, or excavate under a slab edge, which is impractical. To account for the lack of data, we estimated floor thermal performance based on an estimate of the energy code followed when building was first constructed. Section 4.1.4 describes how the energy code was determined. The thermal performance of floors for each energy code varies based on climate zone, as shown in Table 58. It is notable that only buildings built to the newest energy codes in the coldest climates assume any sort of slab insulation.

4.4.5 Thermal Bridging

Thermal bridging includes the impact of uninsulated structural elements that undermine the overall thermal resistance of an opaque assembly. These include linear thermal bridges, such as along corners, roof parapets, and fenestration, and point thermal bridges, such as protruding steel beams. These are formalized by psi factors multiplied by the length of a thermal bridge, and chi factors multiplied by the number of a thermal bridge. ASHRAE publishes psi and chi factors for common major thermal bridges, and thermal bridging requirements were recently added to the envelope section of ASHRAE 90.1-2022 (ASHRAE). See Appendix section A10.2 of ASHRAE 90.1-2022 for details on calculating thermal bridges.

Thermal bridging in ComStock is implemented with the Thermal Bridging and Derating (TBD) ruby gem (Bourgeois and Macumber). The gem detects the presence of common major thermal bridges in the model (corners, parapets, etc.), and derates the adjacent opaque surface construction (walls and roofs) to account for the thermal bridging. TBD gem version 3.4.1 includes default ASHRAE 90.1-2022 psi and chi factors for different kinds of thermal bridges. These vary by wall construction type (steel frame, mass, wood) and whether thermal bridges are considered mitigated or unmitigated. By default, ComStock assumed the unmitigated 90.1-2022 psi and chi factors by wall construction type. Specific values are listed in the TBD gem (Bourgeois and Macumber).

4.4.6 Infiltration and Natural Ventilation

Infiltration

Infiltration in ComStock uses the same model as EnergyPlus (*EnergyPlus, Version 00*), detailed in equation 4.1.

$$Infiltration = I_{design} * F_{schedule} * [A + B * |(T_{zone} - T_{odb})| + C * WindSpeed + D * WindSpeed^2] \tag{4.1}$$

where:

- $\mathbf{I_{design}}$ is the design infiltration flow rate, in m^3 per s per m^2 exterior surface area
- $\mathbf{F_{schedule}}$ is a fractional schedule, usually tied to HVAC system operation
- **A** is the coefficient for constant infiltration
- **B** is the coefficient for temperature difference driven infiltration
- $\mathbf{T_{zone}}$ is the zone air temperature, in degrees Celsius
- $\mathbf{T_{odb}}$ is the outdoor dry bulb temperature, in degrees Celsius
- **C** and **D** are linear and quadratic coefficients for wind driven infiltration
- **WindSpeed** is the local windspeed, in m per s.

The selection of the design infiltration rate is somewhat arbitrary, as it depends on the assumed natural pressure at typical conditions. The coefficients need to be paired with an assumed natural pressure.

Infiltration Rates

Infiltration rates are calculated from measured airtightness data from (Emmerich and Persily). There are significant differences in building airtightness due to differences in wall construction, shown in Figure 6 of the NIST reference. Airtightness does not vary significantly by building type or vintage. Airtightness does depend on size, but this is inherently captured by larger buildings having smaller surface area to volume ratios. Air barriers greatly reduce leakiness, but they are rare in existing buildings, and only recently have been required in some jurisdictions. Airtightness of buildings in ComStock follow lognormal distributions with airtightness means by wall construction type matched to those in (Emmerich and Persily), shown in Figure 28. Airtightness values are measured at 75 Pa and are 6-sided, meaning the infiltration is normalized by total building exterior surface area including wall, roof, and ground surfaces.

The design infiltration rate is calculated from the airtightness value assuming a 4 Pa design pressure, shown in 4.2

$$I_{\text{design}} = \text{airtightness} \cdot \left(\frac{1\ \text{hr}}{3600\ \text{s}}\right) \cdot \left(\frac{5\ \text{sided area}}{6\ \text{sided area}}\right) \cdot \left(\frac{4.0\ \text{Pa}}{75.0\ \text{Pa}}\right)^{0.65} \tag{4.2}$$

where:

- **airtightness** is the measured airtightness at 75 Pa in m^3 per hr per m^2 6-sided exterior surface area
- $\mathbf{I_{design}}$ is the design infiltration rate at 4 Pa in m^3 per s per m^2 5-sided exterior surface area

Infiltration Coefficients

NIST derived coefficients by building CONTAM models of all of the DOE prototype buildings, as explained in (Ng, Dols, and Emmerich). The coefficients assume a 4 Pa design pressure. The coefficients include A, B, and D terms, with C being 0. Coefficients are by building type, with separate coefficients for whether the HVAC system is on or off. The NIST report includes separate coefficients for buildings with air barriers, but ComStock does not assume buildings have air barriers.

NIST did not model all DOE prototype buildings, and does not include HVAC system off coefficients for some buildings if the prototype was modeled as always on. ComStock building types not available in the NIST data use

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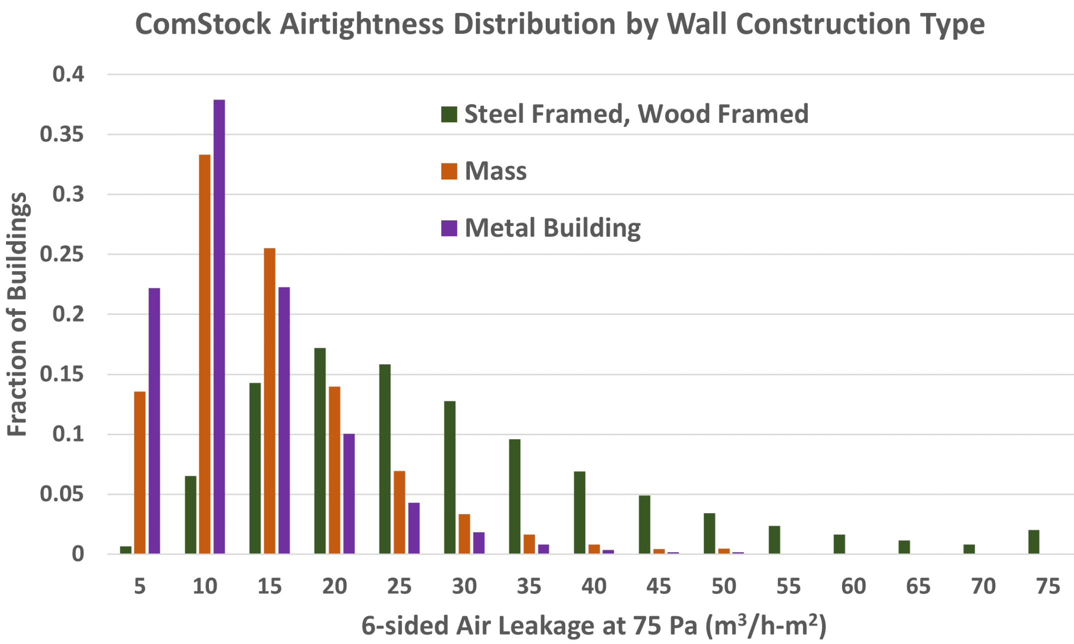

Figure 28. 6-sided airtightness distributions by wall construction type. Distributions are log-normal, with means matched to means by wall construction type in (Emmerich and Persily).

coefficients for either the Office or Retail building types. If off coefficients are not available, the building uses the on coefficients instead.

Natural Ventilation

Natural ventilation is not modeled in ComStock because it is not common in the building stock.

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4.5 Lighting

4.5.1 Interior Lighting

Interior lighting follows a technology baseline approach, meaning that energy consumed by lighting is set by an assumed distribution of a particular lighting technology (e.g., T8 or linear LEDs), rather than following a lighting power density (LPD) allowance defined in a specific energy code version. The technology baseline approach recognizes that buildings typically do not use their full lighting power allowance. It also explicitly labels lighting technology and subsystems in the energy model for granular energy efficiency measure analysis.

Two components specify interior lighting: the lighting power density and the interior lighting schedule. The lighting power density is determined by the distribution of lighting technologies in the stock, the lighting technology properties, and the space type properties. The lighting schedule is determined by a default lighting schedule by space type, occupancy hour adjustments, and magnitude variability.

Determining Lighting Power

The technology baseline approach follows a similar process to how the ASHRAE 90.1 lighting subcommittee determines the LPD allowance for a given space type in ASHRAE 90.1. In the lighting subcommittee model (LSM), there are four kinds of lighting systems that together contribute to a target horizontal illuminance:

LPD = General Lighting + Task Lighting + Supplemental Lighting + Wall Wash Lighting

$$LPD = \frac{\%LS_1 \cdot fc}{RSDD \cdot TF_1} + \frac{\%LS_2 \cdot fc}{RSDD \cdot TF_2} + \frac{\%LS_3 \cdot fc}{RSDD \cdot TF_3} + \frac{\%LS_4 \cdot fc}{RSDD \cdot TF_4} \tag{4.3}$$

where:

- **$\%LS_i$** is the percent of the target horizontal illuminance value met by a specific lighting system
- **fc** is the target horizontal illuminance value in lumens per ft^2
- **RSDD** is room surface dirt depreciation, an estimate of how much surface dirt reduces light from reaching the horizontal plane
- **TF_i** is the total lighting factor, where TF = source luminous efficacy * coefficient of utilization * lighting loss factor (LFF)
- **Source luminous efficacy** is the lighting technology efficacy in lumens per watt
- **Coefficient of utilization** is a term that captures how much lighting from the luminaire reaches the horizontal plane
- **LLF** is the lighting loss factor, where LLF = luminaire dirt depreciation (LDD) * lamp lumen depreciation (LLD)

Values for all these terms are specified in the LSM. The LSM is exact, using a specific lighting product, room geometry, distribution of lighting systems, and other properties to determine the lighting power density allowance for a given space type. ComStock differs from the LSM in several important ways.

First, ComStock generalizes lighting technology (e.g., T8 linear fluorescent luminaires for general lighting) rather than modeling a specific lighting product. Source efficacy, lighting loss properties, and radiant fractions are tied to lighting technology. Source efficacy values come from Buccitelli et al. for older lighting technologies and Yamada et al. for LEDs. Radiant heat gain fractions come from Fisher and Chantrasrisalai for older lighting technologies and Liu et al. for LEDs.

Second, lighting technologies are broken out into lighting generations depending on the most common space lighting technology in that generation, as general lighting accounts for most (∼80%–90%) of total lighting. High bay is treated as general lighting, and the lighting measure uses the general high bay technology for rooms with height

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≥20 ft. Lighting generations 4–8 are all LED, with improving efficacy over time. Lighting generations and their technologies are detailed in Table 12, and lighting technology properties are detailed in Table 59.

Third, the coefficient of utilization depends on both the luminaire properties and the room geometry, which complicates the calculation in the LSM. The ComStock model associates the coefficient of utilization entirely with room propertiesthat are independent of lighting technology. ComStock further assumes that rooms of the same space type have similar enough properties that they can use the same coefficient of utilization. To retain some of the variation from the luminaire properties, each kind of lighting system has a different coefficient of utilization for each space type.

Table 60 in Appendix A details the target horizontal illuminance value, the fraction of the target illuminance met by the kind of lighting system, and the lighting system coefficient of utilization for each lighting space type. Lighting space types are defined in 90.1 and are determined based on a mapping of openstudio-standards space types to prototype lighting space types.

Fourth, the LSM assumes a high fraction of non-general lighting systems for certain space types. For example, half of the illuminance in retail sales spaces is from supplemental and wall wash lighting systems. In older lighting generations, there is a significant difference in source efficacy between general and non-general lighting systems. In lighting generation 2, general lighting assumes T8 linear fluorescent lamps at 94 lumens per watt, and supplemental and wall wash lighting assume halogens at 15 lumens per watt. For retail spaces using the LSM values, that means half the lighting comes from lighting technologies roughly 6 times less efficient than the general lighting technology. Although this may be appropriate for setting a code lighting allowance, most retail spaces meet a much greater percentage of their illuminance from more efficient general lighting technologies. ComStock adjusts the lighting system fractions for commonly used space types so that around 80%–90% of lighting comes from the general lighting system. These changes are reflected in Table 60 in Appendix A.

Lastly, the LSM offers a generous allowance for lighting power density to account for the lighting loss factor over time. Including lighting losses and depreciation can result in a lighting power density 40% higher than when these terms are ignored. This resulted in unreasonably high installed lighting power densities; thus, ComStock assumes that most existing lighting systems were not designed to account for depreciation over time, and therefore excludes lighting loss and depreciation terms from the lighting power calculation.

With these changes, the LPD calculation simplifies to:

$$LPD = \frac{\%LS_1 \cdot fc}{\text{efficacy} \cdot CU_1} + \frac{\%LS_2 \cdot fc}{\text{efficacy} \cdot CU_2} + \frac{\%LS_3 \cdot fc}{\text{efficacy} \cdot CU_3} + \frac{\%LS_4 \cdot fc}{\text{efficacy} \cdot CU_4} \tag{4.4}$$

where:

- **$\%LS_i$** is the percent of the target horizontal illuminance value met by a specific lighting system
- **fc** is the target horizontal illuminance value in lumens per ft^2
- **Efficacy** is the source luminous efficacy of the lighting technology in lumens per watt
- **CU** is the coefficient of utilization, a term that captures how much lighting from the luminaire reaches the horizontal plane.

The resulting LPDs are shown in Figure 29.

Table 12. Interior Lighting Generations and 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	HID Mercury Vapor	Incandescent A-Shape	Incandescent Decorative	Incandescent Decorative
Gen 2	T8 Linear Fluorescent	HID Metal Halide	Halogen A-Shape	Halogen Decorative	Halogen Decorative
Gen 3	T5 Linear Fluorescent	HID Metal Halide	Compact Fluorescent Screw	Compact Fluorescent Pin	Compact Fluorescent Pin
Gen 4–8	LED Linear	LED High Bay Luminaire	LED General Purpose	LED Decorative	LED Directional

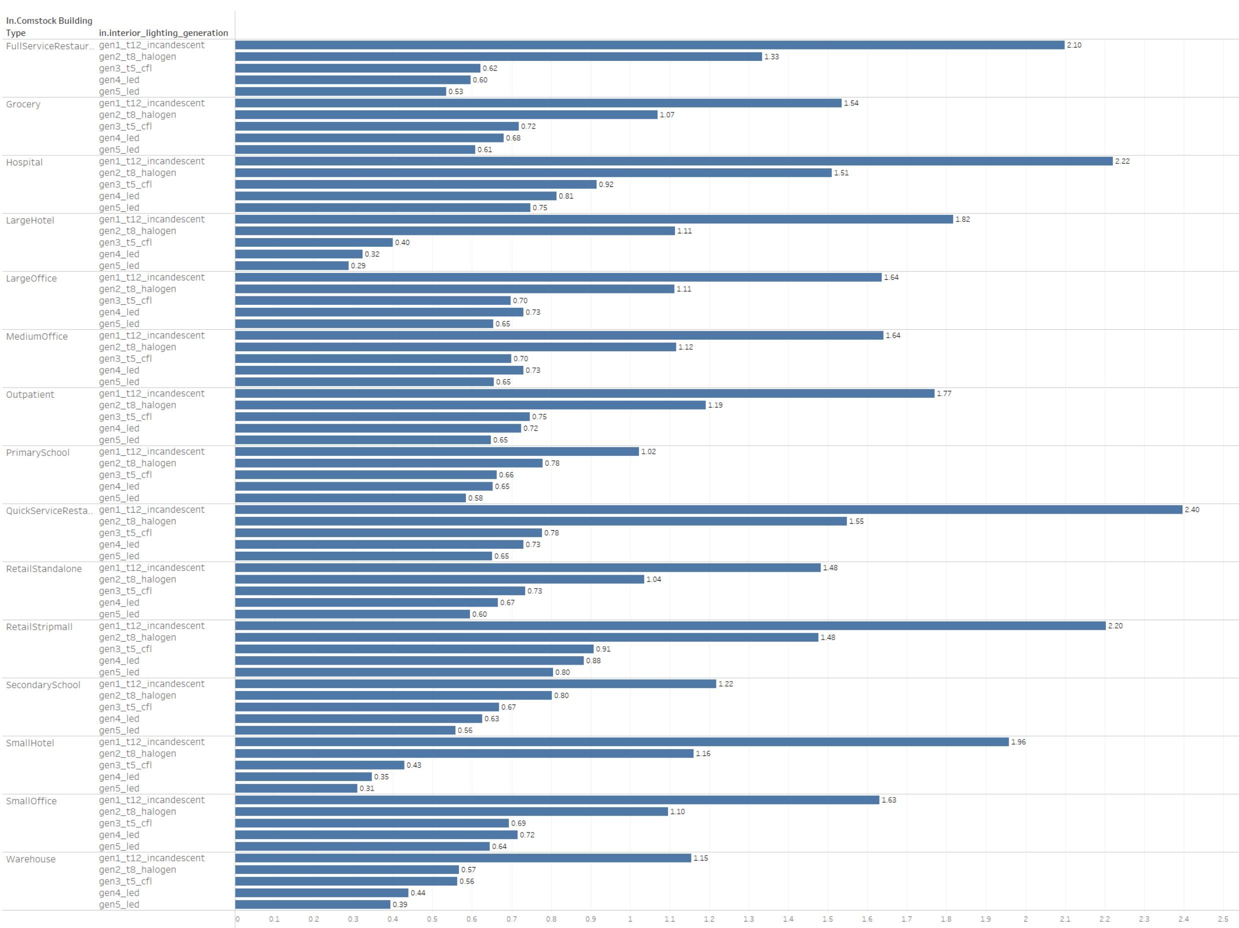

Figure 29. Average interior lighting power density by building type and lighting generation.

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Table 13. Interior Lighting Generation Cutoff by Energy Code

Energy Code in Force	Cutoff Generation
ComStock DOE Ref Pre-1980	gen1_t12_incandescent
ComStock DOE Ref 1980–2004	gen1_t12_incandescent
ComStock 90.1-2004	gen1_t12_incandescent
ComStock 90.1-2007	gen2_t8_halogen
ComStock 90.1-2010	gen2_t8_halogen
ComStock 90.1-2013	gen2_t8_halogen
ComStock 90.1-2016	gen3_t5_cfl
ComStock 90.1-2019	gen4_led
ComStock DEER Pre-1975	gen1_t12_incandescent
ComStock DEER 1985	gen1_t12_incandescent
ComStock DEER 1996	gen1_t12_incandescent
ComStock DEER 2003	gen1_t12_incandescent
ComStock DEER 2007	gen2_t8_halogen
ComStock DEER 2011	gen2_t8_halogen
ComStock DEER 2014	gen3_t5_cfl
ComStock DEER 2015	gen3_t5_cfl
ComStock DEER 2017	gen4_led
ComStock DEER 2020	gen4_led

Distribution of Lighting Technologies

Lighting generations were assigned to each building model during sampling based on the year of, and energy code in force during, the last interior lighting replacement. Probability distributions were generated first by using an approximate start and end year for when each technology generation was being installed in commercial buildings (Table 61). A Gaussian distribution was generated for each lighting generation using these start and end years, and the resulting distribution for each year of last interior lighting replacement was normalized to create 0–1 probabilities. The probability distributions were duplicated for each energy code in force and were further modified to ensure they were realistic (i.e., generation 1 was not installed in a ComStock 90.1-2013 building). This was done using a cutoff generation for each energy code in force (Table 13). Each of the lighting generations were also assigned an arbitrary weight to scale the distributions. This was done to represent realistic installation trends. For example, although the installation years of generation 2 (T8s) and generation 3 (T5s) overlapped, generation 2 (T8s) was more popular. T5s were not that much more efficient than T8s compared to the difference between T8s and T12s, and T5s cost more. Furthermore, T5s have different bi-pin geometry compared to T8s and T12s, meaning replacing T8s or T12s with T5s requires changing fixtures in addition to lamp costs. For those reasons, generation 2 (T8s) are a greater portion of the stock than generation 3 (T5s).

Finally, an additional level of diversity was added to the process. Small commercial buildings (<50,000 ft^2) tend to retrofit their lighting technology less frequently than large commercial buildings (>50,000 ft^2) (Cadmus Group). To capture this, we changed the interior lighting lifespan values so that large buildings updated their lighting every seven years on average and small buildings updated their lighting every 13 years. These time spans average to 10 years, which matches the median EUL interior lighting used previously.

The distributions were validated against data from the 2015 Lighting Market Characterization Study (Buccitelli et al.) and the 2019 Solid State Lighting Report (Yamada et al.). ComStock sampling results from 2017 and 2020 simulation years were compared against the data from these two studies from the same years, which is referred to as "truth" data in this document. The comparison results for 2017 and 2020 simulation years, as well as the data from the two reports for 2015, 2025, 2030, and 2035, are shown in Figure 30.

Simulation years 2017 and 2020 were the focus of validation because they represent the range of simulation years typically run for ComStock. Additionally, for a given iteration of the lighting generation distributions, the comparison results were inconsistent across simulation years. For example, for a set of lighting generation distributions that showed close comparisons for 2017 and 2020, years 2025–2035 were significantly different compared to the other future projections. With improvements to the script that produces the distributions, close comparisons across all simulation years should be feasible.

Table 62 provides a snapshot of the final probability distributions, which show a gradual shift to higher generations as the year of the last interior lighting replacement increases. For this code year (ComStock 90.1-2013), generation 1 lighting technologies would likely not be installed. This is reflected in the distributions, as the minimum lighting generation installed is at least generation 2. The relative popularity of each generation is also apparent in the distributions: generation 2 has a much higher probability of being installed in any year than generation 3, a less popular technology set.

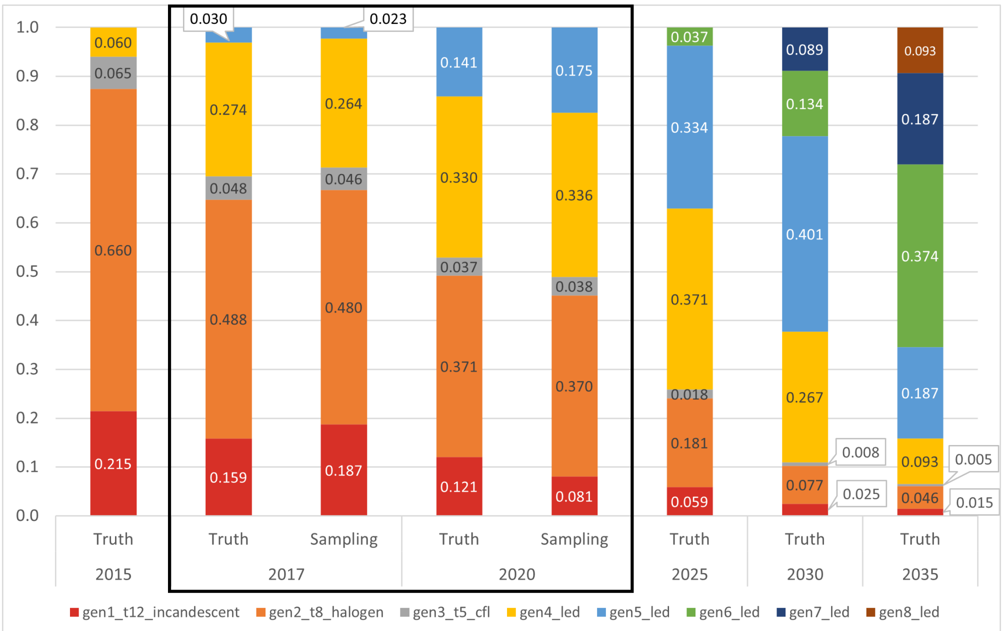

Figure 30. "Truth" lighting generation distribution data from Buccitelli et al. and Yamada et al., and comparison of 2017 and 2020 ComStock sampling results.

There are two primary areas for improvement for this process:

- The first is in the initial Gaussian distributions. Although there is good data about when the lighting generations were first installed and when they finally lost popularity, information about when the generations peaked in their install popularity is not available. The current method assumes that the peak is at the midpoint of the start and end year. This is most likely incorrect. If data on the peak year of each generation could be collected, this would improve the distribution generation process.

- The second improvement area is the final weighting process. The weights are currently determined using a guess-and-check method. Further improvements to the distribution script would make this method more robust (e.g., using an optimization algorithm).

Figure 31 shows the breakdown of lighting generation distribution (by count) by building size for 2018, the year the current ComStock data set represents the United States building stock. Small buildings are under 50,000 ft^2 and are assumed to have slower retrofit frequency than larger buildings (>50,000 ft^2). The data trend matches this assumption, as there is a larger percentage of smaller building models that have generation 1 and 2 lighting technologies.

Figure 32 provides a breakdown of lighting generation distributions by building type. There is not huge variation among the building types. However, building types that are typically smaller (quick service restaurants, small offices, strip malls) lag behind the other building types in terms of lighting technology. This is consistent with the data in Figure 31.

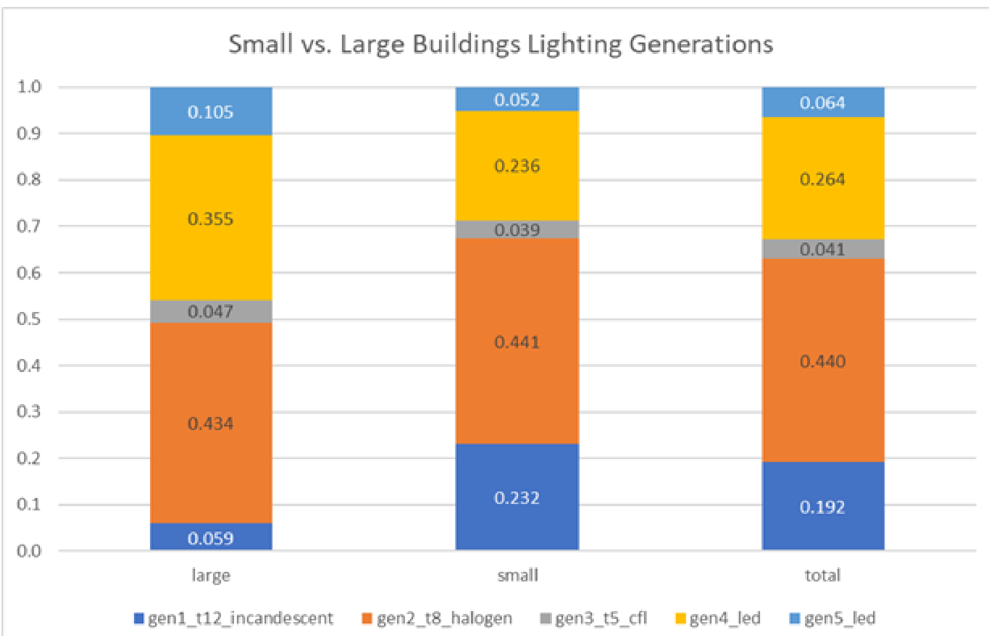

Figure 31. Fraction of installed lighting generations by building size (count-based distribution).

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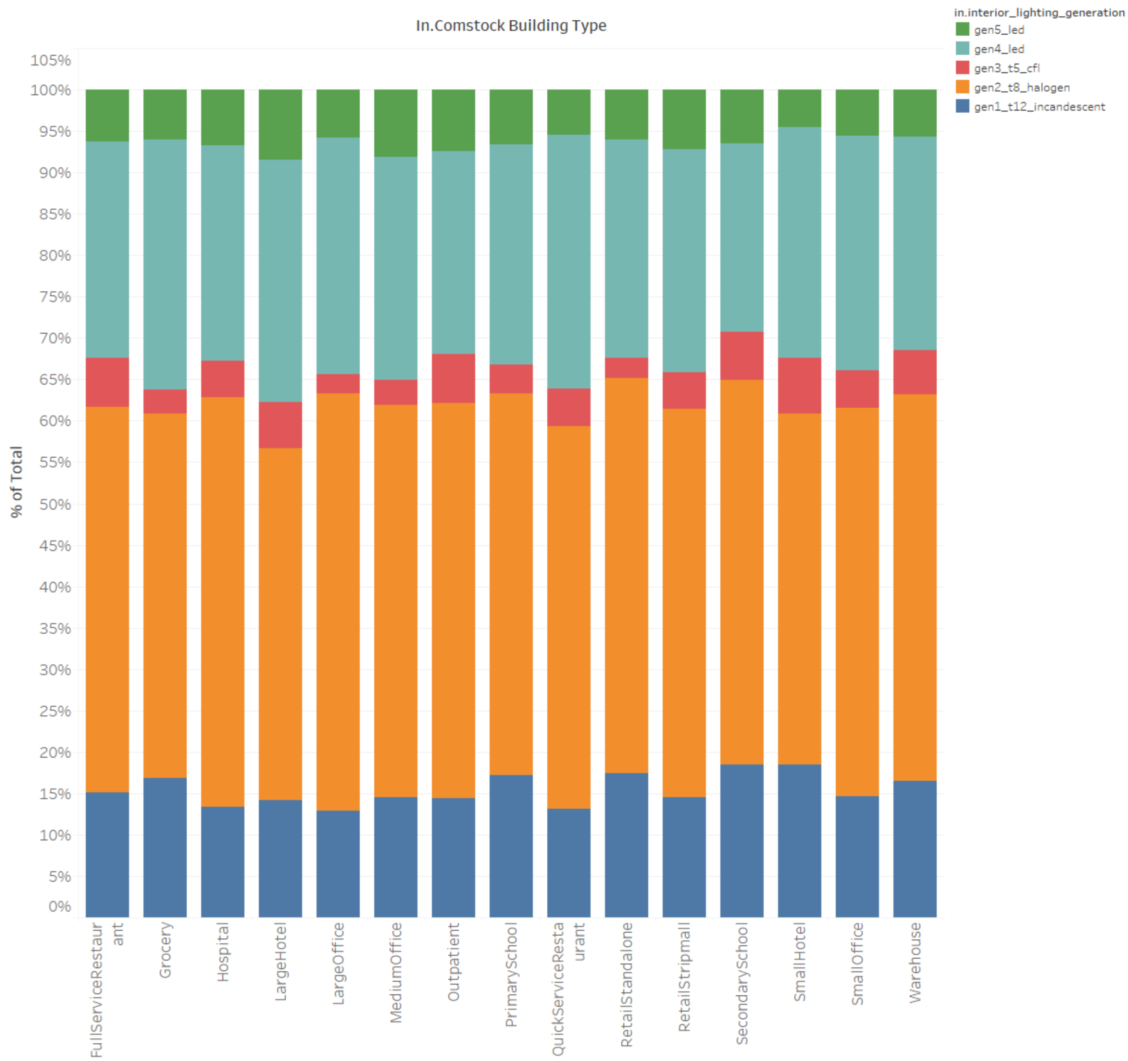

Figure 32. Fraction of installed lighting generation by building type (count-based distribution).

Default Interior Lighting Schedules

Default interior lighting schedules come from the openstudio-standards DOE prototype building models (Deru et al.). The End-Use Load Profiles project derived new default lighting schedules for restaurant, retail, education, office, and warehouse buildings, detailed in Section 3.3.1 of the EULP report: "Interior Lighting Schedules" (Wilson et al.). A full list of default ComStock schedules is available as a schedules .json file on the openstudio-standards GitHub repository.

Additional changes to default schedules include:

- The peak lighting value in the end-use data derived hourly schedule for office spaces is now 0.85 instead of the original 0.5.
- Quick service restaurants and kitchens use the FoodService_Restaurant BLDG_LIGHT_EndUseData schedule rather than the prototype schedule.
- All large hotel guest room lighting schedules use HotelLarge BLDG_LIGHT_GUESTROOM_SCH_2013.

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- All small hotel guest rooms follow the same default lighting schedule, with the midday lighting fraction changed from the prototype schedule value of 0.3 to 0.15. Vacant guest rooms use an always off lighting schedule.

Interior lighting schedules are adjusted to correspond with the building's operating hours, as described in Section 4.2.

Interior Lighting Schedule Magnitude Variability

Section 3.3.4 in the End-Use Load Profiles project report, "Interior Lighting Schedule Magnitude Variability" (Wilson et al.), details the derivation of base-to-peak values applied to the default lighting schedules.

Figure 33 shows the distribution of base-to-peak ratios (BPRs) in the stock by building type for weekdays and weekends. Note that this methodology was not applied to hospital, outpatient, small and large hotel, and warehouse building types, due to a lack of data.

4.5.2 Exterior Lighting

Exterior lighting is all outdoor lighting at the building site, including lighting for parking, walkways, doorways, canopies, building facades, signage, and landscaping.

Parking Area Lighting

Parking area lighting accounts for the majority of exterior lighting in the stock (Buccitelli et al.). Parking lighting is calculated as the parking area times the installed lighting power per unit of parking area. Parking area is based on the estimated number of parking spots per student for schools, per unit for hotels, per bed for hospitals, and per building floor area for all other building types. Parking spots are assumed to be 405 ft^2. Table 63 details these assumptions.

Lighting power for a given parking area is determined from the 2015 U.S. Lighting Market Characterization report, which assumes an average of 216 Watts (W) per parking lighting system, or 0.0410 W/ft^2 (per equation 4.5). Base parking lighting power allowance values for each vintage were reduced by a calculated factor such that the building-count weighted parking lighting power density came out to the 0.0410 W/ft^2 target. Note that this calculation is from 2015, so it overestimates the amount of exterior lighting in the stock, which has been changing over to use LEDs. The values for each vintage are shown in Table 64.

$$LPD = \left(\frac{216\,W}{\text{lighting system}}\right) \cdot \left(\frac{1\,\text{lighting system}}{13\,\text{parking spots}}\right) \cdot \left(\frac{1\,\text{parking spot}}{405\,\text{ft}^2}\right) = 0.0410\,W/\text{ft}^2 \tag{4.5}$$

Other Exterior Lighting

Non-parking exterior lighting is determined by the exterior lighting allowance specified in ASHRAE 90.1 for exterior lighting zone 3 (All Other Areas). Length and area estimates are determined from the values in Table 65. The building facade area is calculated from the model as the ground floor exterior wall area. The lighting power allowance is matched to the 90.1 code for each vintage. The exterior lighting power allowances are shown in Table 64. Note that although 90.1 includes exterior lighting, the only forms of exterior lighting included in ComStock are parking areas, building facades, main entry doors, other doors, drive through windows, entry canopies, and emergency canopies. Notably, ComStock does not include lighting for exterior signage.

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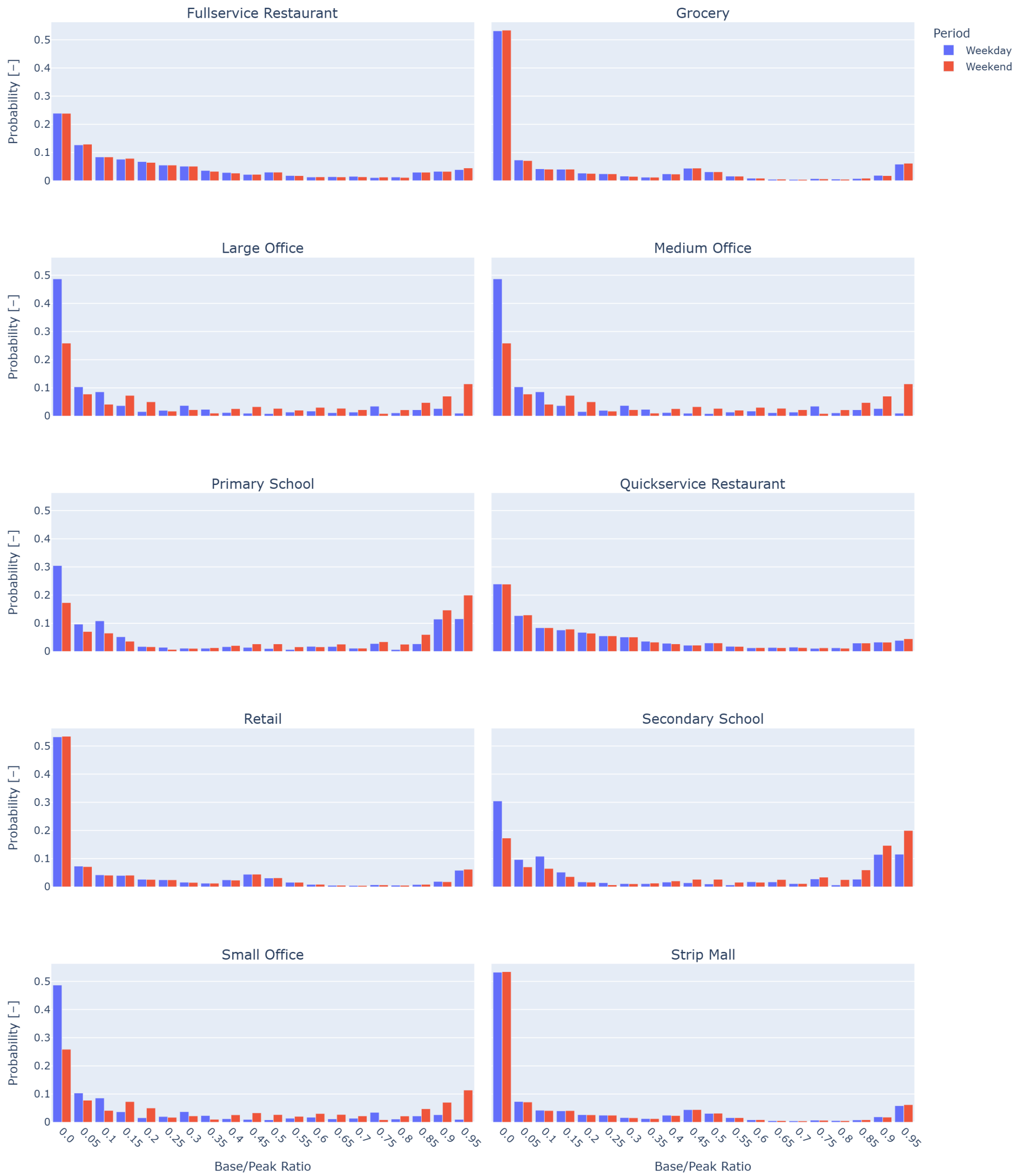

Figure 33. Weekday and weekend lighting base-to-peak ratios by building type. Base-to-peak ratio is on the x-axis, and fraction of the stock is on the y-axis.

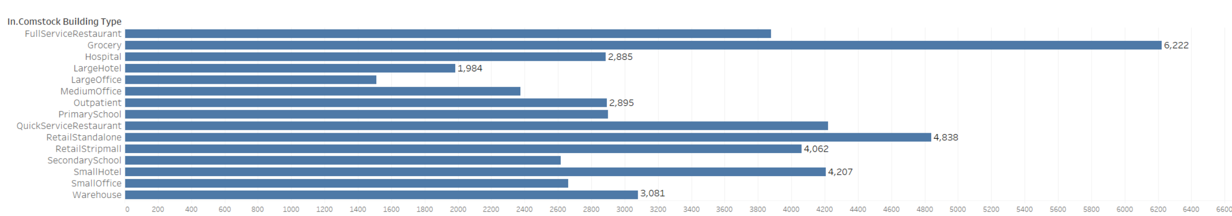

Figure 34. Average interior lighting equivalent full load hours by building type.

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4.6 Plug and Process Loads

Plug and process loads (PPLs) are all electrical or gas building loads that do not fall under lighting, heating, cooling, ventilation, or water heating. As lighting and HVAC equipment becomes more efficient, PPLs represent an increasing percentage of commercial building energy consumption—up to 50% in high-performance buildings. This section describes how electric equipment, gas equipment, data centers, elevators, and kitchen equipment are modeled in ComStock.

4.6.1 Electric Equipment

Electric equipment is a broad category that encompasses any type of load that is powered by an AC outlet. This can include computers, monitors, printers, kitchen or bathroom appliances, laundry equipment, phone chargers, and more. Because there are so many types of electric equipment, ComStock does not model each technology separately, but instead uses an equipment power density (EPD) value for each space type, in watts per square foot.

The EPDs are derived from the DOE prototype buildings; however, some of the values were adjusted during the end-use load profiles calibration process. Using end-use-level data provided by two industry sources for a variety of building types, we increased or decreased some EPD assumptions to better reflect the actual building data. Building types that were affected by the EPD adjustments included Full Services Restaurant (FullServiceRestaurant), Primary School (PrimarySchool), Quick Service Restaurant (QuickServiceRestaurant), Retail (Retail), Secondary School (SecondarySchool), and Strip Mall (StripMall).

The EPDs are dependent on building type, space type, and DOE Reference Building template. The interior equipment template is a function of the vintage of the building, as well as equipment turnover assumptions. In most cases, the EPD remains constant for all templates; however, some values increase or decrease in newer templates. An increase in the EPD in newer templates for a particular space type most likely indicates that new types of plug loads or technologies are assumed to be in the space. By comparison, a decrease in EPD indicates that plug loads in that space have become more efficient as buildings upgrade to newer equipment. For example, EPDs in the "MediumOffice - Conference" space type decrease beginning with the 90.1-2004 template, reflecting an assumption that conference equipment such as projectors and monitors have become more efficient. On the other hand, EPDs in "MediumOffice - Breakroom" increase drastically, likely due to the addition of new kitchen appliances and accessories.

The EPDs in the ComStock model for each combination of building type, space type, and template are shown in Table 66.

4.6.2 Gas Equipment

Gas equipment refers to any natural gas-powered interior equipment that is not used for space heating or water heating. Similar to electric equipment, there are many different types of gas equipment, so ComStock does not model each technology individually, but rather uses a gas intensity in BTU per hour per square foot. Gas kitchen equipment makes up the majority of the gas equipment modeled in ComStock. Kitchen equipment will be discussed separately in Section 4.6.5. There are only three non-kitchen space types in our models that contain non-zero gas equipment values, and the values used are shown in Table 14.

The space types that contain gas equipment are the laundry and operating room space types in hotels and outpatient buildings, respectively. Gas laundry equipment represents gas clothes dryers, which are common in commercial drying applications. In operating rooms, a small amount of gas equipment represents steam sterilizers or autoclaves, which are used for sterilization during surgical procedures.

Table 14. Gas Equipment Power Density (Btu/hr*ft^2)

		Template					
Building Type	**Space Type**	**Pre-1980**	**1980–2004**	**90.1-2004**	**90.1-2007**	**90.1-2010**	**90.1-2013**
LargeHotel	Laundry	170.0	170.0	170.0	170.0	170.0	170.0
Outpatient	OR	23.9	23.9	23.9	23.9	23.9	23.9
SmallHotel	Laundry	58.4	58.4	129.9	129.9	129.9	129.9

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4.6.3 Data Centers

Data centers are a high-intensity type of PPL that house IT and computing equipment. Large standalone data centers are not currently modeled in ComStock, but this building type may be added in the future. Instead, ComStock models data centers as a space type within large and medium office buildings. This is meant to represent an IT closet or high-performance computer that is located within an office building and used by a business or organization.

The data center is divided into two space types—a core data center and an IT closet. The core data center represents about 96% of the data center floor area and has an equipment power density of 45 W/ft^2. The IT closet represents the remaining 4% of the data center floor area and has an equipment power density of 20 W/ft^2. The area-weighted equipment power density of the whole data center is 44 W/ft^2, which is approximately 20–50 times the equipment load of most other space types (Goel et al.).

In the DOE large office prototype model, the data center represents 2.5% of the total floor area. The medium office prototype model does not contain a data center space type. If we used the exact space type ratios from the prototype models for ComStock, all large offices would contain a data center, but no medium or small offices would contain this space type. In reality, not all office buildings contain data centers, and they can be present in offices of different sizes. Therefore, ComStock models data centers in a portion of large and medium office buildings. To determine these distributions, we used CBECS 2012 data to understand how prevalent data centers are in office buildings of different sizes. In addition, we used CBECS responses to determine what percent of a typical office building's floor area is dedicated to the data center. From this analysis, we decided that 38% of large offices and 20% of medium offices should contain data centers. In buildings with data centers, that space should make up approximately 2% of the total square footage of the building. We also determined that data centers are uncommon in small offices; therefore, there is no data center space type in the small office models.

Data centers follow a very different schedule than the rest of a building's plug and process loads. This type of IT equipment often runs 24 hours a day; therefore, the data center space type has a constant schedule year round. The start and stop time and base-to-peak ratio (BPR) schedule adjustments do not affect the data center space type.

4.6.4 Elevators

Elevators are a high power density equipment load present in many commercial buildings. According to the Americans with Disabilities Act (ADA), elevators are required in all commercial buildings with three or more stories, or when the square footage of each floor is more than 3,000 square feet. Although not a requirement, many two-story buildings also contain elevators for accessibility and convenience. Therefore, ComStock includes elevators in all buildings with two or more stories.

Hydraulic elevators are assumed to be installed in buildings with two to six stories, and traction elevators are assumed to be installed in buildings taller than six stories. Hydraulic elevators use a fluid-driven piston to lift the cab, and typically operate at speeds of 150 feet per minute or less. Hydraulic elevators are more affordable and can carry heavier loads, but because of their slow speeds, they are typically only used in buildings up to five stories. For buildings with six or more stories, traction elevators are used because they operate at much higher speeds (up to 500 feet per minute). Traction elevators use a counterweight and pulley system, making them more energy efficient because the motor does not have to move as much weight. The drawbacks, however, include high installation and maintenance costs and limits on cab weights. The motor power is assumed to be 16,055 W for hydraulic elevators and 20,370 W for traction elevators.

Elevators are modeled as a zone load in EnergyPlus, meaning the elevator equipment load and associated heat gain are attributed to a thermal zone. Elevator load is reported out as part of the electric equipment end use. With hydraulic elevators, the elevator room is typically located in the basement, so the equipment load and heat gain are added to the first floor core zone. With traction elevators, the elevator equipment is located on the roof, so the equipment load and heat gain are added to the top floor core zone.

The number of elevators installed in a ComStock building depends on the building type. For most building types, the number of elevators is based on the floor area. The exceptions are hospitals and hospitality buildings, for which assumptions are based on the number of hospital beds or hotel rooms, respectively. ComStock differentiates between passenger elevators and freight elevators in order to properly capture the elevator load in certain building types with industrial or service elevators. Passenger elevators are modeled in all building types, whereas freight elevators are only modeled in hospital, large hotel, large office, and warehouse buildings. The assumptions for the number of passenger and freight elevators modeled by building type are shown in Tables 67 and 68.

The equipment schedule for elevators is irregular and unpredictable. Therefore, this load does not follow the typical plug load schedule for its associated space type. We decided to approximate an elevator's schedule by relating it to the number of people who are entering or exiting the building at each time step—in other words, the derivative of the occupancy schedule of the building. We also made assumptions regarding the number of people per elevator ride (five), the amount of time per ride (calculated from the elevator speed and number of stories), and the amount of inter-floor traffic that is not captured by the change in building occupancy (added a factor of 1.2x). Elevator data and metrics like this are not commonly measured or available, so these assumptions are based primarily on engineering judgment.

From these calculations and assumptions, we derived an elevator schedule for each building type and each day of the week. An example of the elevator schedule for medium offices is shown in Figure 35 for weekdays, Saturdays, and Sundays. On weekdays, the most elevator traffic occurs at the beginning and end of the day, when people are coming in or leaving work for the day. There is also significant traffic during the lunch hour, as some people choose to leave the building for lunch. At all other times during the workday, the elevator load is approximately 40% of the total load to account for inter-floor traffic and minimal change in the total building occupancy. For some buildings, the occupancy schedules are reduced on Saturdays and include no occupancy on Sundays, which is reflected in the elevator schedule.

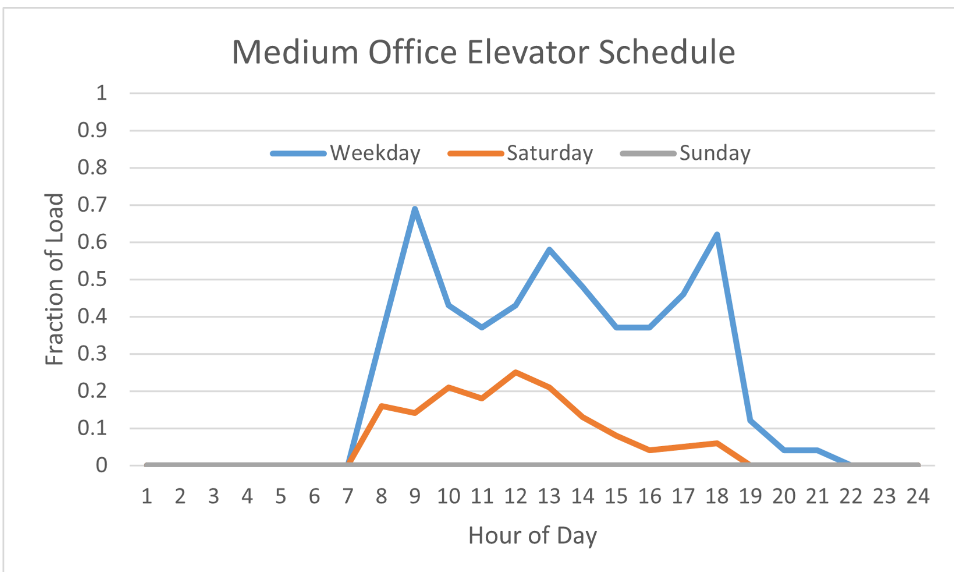

Figure 35. Elevator fractional load schedule for medium offices on weekdays, Saturdays, and Sundays.

The final aspect of modeling elevators is accounting for lighting and fans inside the elevator. Although these are minimal loads compared to the total elevator energy, they are still modeled in ComStock. The elevator lighting and fans are defined in the model by a total power in watts. These wattage values were calculated based on the number of elevators and the subsystem template in the model, thereby ensuring higher efficiencies for newer lighting and ventilation systems. The elevator lighting and fan schedules are assumed to be at full load at all times when the elevator schedule is greater than 0.

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4.6.5 Kitchen Equipment

Kitchens are one of the most energy-intensive space types. In ComStock, kitchen space types are modeled in six building types—FullServiceRestaurant, Hospital, LargeHotel, PrimarySchool, QuickServiceRestaurant, and SecondarySchool. In some building types, namely restaurants, the kitchen space type represents a significant proportion of the floor area. In these cases, kitchen loads have a major impact on the total building EUI. In hotels, hospitals, and schools, the kitchen space type only represents a small fraction of the total floor area. Table 15 shows the percent of the total floor area represented by the kitchen space type for each building type. Note that some of the strip malls in ComStock contain some fraction of the "QuickServiceRestaurant" building type to account for food service that is often found in strip malls.

Table 15. Kitchen Space Type Percentage of Total Floor Area

Building Type	Space Type	Percentage of Total Floor Area
FullServiceRestaurant	Kitchen	27.3%
Hospital	Kitchen	4.1%
LargeHotel	Kitchen	0.9%
PrimarySchool	Kitchen	2.4%
QuickServiceRestaurant	Kitchen	50%
SecondarySchool	Kitchen	1.1%

Commercial building energy modeling often assumes an energy intensity per area for cooking equipment, like what is used in the DOE prototype buildings (Zhang et al.). However, applying these power densities directly to the various building sizes in ComStock assumes cooking loads scale linearly with kitchen square footage, which does not necessarily represent reality (EIA, Zhang et al.). Further, it does not allow for straightforward analysis of specific cooking equipment since it is represented by a single aggregate load. However, little information exists regarding representative equipment-specific modeling of cooking appliances, as well as how cooking equipment scales with building area. The CBECS survey does provide some level of guidance for area-based intensity as they disaggregate cooking energy consumption separately and provide building area for their samples, but this end use energy consumption data is derived using statistical means from monthly billing data rather than directly measured making it less reliable (EIA, Zhang et al.).

ComStock uses published data to create representative probability distributions of commercial cooking equipment counts, by building type, for both gas and electric appliances. Additionally, the equipment distributions are scaled by area to represent the non-linear scaling suggested in the literature. Although other building types likely include some degree of cooking equipment as well, such as larger offices (EIA), the current implementation of ComStock only includes cooking equipment in the previously-mentioned six building types plus quick service restaurants found in strip malls.

Commercial kitchens can contain electric or gas cooking equipment, or a mix of both. The prevalence of gas and electric fuel types for each equipment type used in ComStock are derived from a DOE study (Goetzler et al.). ComStock requires rated input power values and fractions of radiant, latent, and lost heat for gas and electric kitchen equipment. These values are primarily derived from the ASHRAE Fundamentals Handbook (ASHRAE) after comparisons with other kitchen equipment studies and commercially available products. More details about how these values were determined can be found in the End Use Savings Shapes documentation (Praprost).The assumptions used in ComStock for prevalence, rated input power, and fractions radiant, latent, and lost for gas and electric appliances are shown in Table 16.

Kitchens in ComStock models are assigned a quantity of each equipment type. These can be found in the ComStock metadata files for each model. Equipment quantities are assigned using probability distribtuions with dependencies on building type and food service floor area. The quantities used in the probability distributions are determined using an older dataset of equipment counts per restaurant type combined with the prevalence of the restaurant type (Rahbar et al.). The restaurant types were mapped to ComStock building types. This is summarized in Table 85. Unfortunately, little data of this type was found in literature, so this older source was ultimately used for equipment counts. However, even with changes in culinary trends, it is not expected that counts of equipment types in a restaurant would have changed drastically over the past few decades. Additionally, a "None" restaurant type was created for schools, with a prevalence determined by the fraction of schools in CBECS that have kitchens (EIA).

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Table 16. Cooking Equipment Fuel Type Prevelance and Rater Power

Appliance	Fuel Prevalence Fraction		Rated Power		Fraction Radiant		Fraction Latent		Fraction Lost	
	Gas	Electric	Gas (Btu/h)	Electric (kW)	Gas	Electric	Gas	Electric	Gas	Electric
Broiler	0.91	0.09	96,000	10.8	0.12	0.35	0.1	0.1	0.68	0.45
Griddle	0.58	0.42	90,000	17.1	0.18	0.39	0.1	0.1	0.62	0.41
Fryer	0.5	0.5	80,000	14	0.23	0.36	0.1	0.1	0.57	0.44
Oven	0.55	0.45	44,000	12.1	0.08	0.22	0.1	0.1	0.72	0.58
Range	0.91	0.09	145,000	21	0.11	0.1	0.1	0.1	0.69	0.7
Steamer	0.33	0.67	200,000	27	0.1	0.1	0.1	0.1	0.7	0.7

This workflow also includes modifiers to the equipment counts shown in Table 85 to scale equipment count for different kitchen sizes. As mentioned previously, it is not expected that equipment scales linearly with kitchen size, but there is little information in the literature to suggest appropriate scaling (Zhang et al.). To account for equipment count scaling, we assume most typically-sized kitchens will have the same quantity of equipment. However, especially small and large kitchens will include scaling factors to account for very large changes in kitchen area that would likely correlate to higher/lower meals served. These factors were determined using engineering judgment and are summarized in Figure 36.

In summary, ComStock determines quantity and fuel type of cooking equipment based on sampling our probability distributions. A restaurant type is sampled for each model as per the prevenances shown by building type in Table 85. This yields the corresponding equipment counts for the restaurant type shown in Table 85, with square footage modifiers applied based on building size and type. Next, the equipment fuel type is sampled as per the prevalence shown in Table 16 for each piece of equipment. Combined, this yields quantities of gas and electric cooking equipment for each ComStock sample. Note that kitchen spaces in ComStock additionally include some prevalence of electric load to account for non-major electrical appliances such as microwaves, heating lamps, toasters, coffee machines, electric kettles, etc. Additionally, the current implementation of cooking equipment in ComStock utilizes the same schedule for each equipment type. Future work could include implementing equipment-specific schedules for the various equipment types, which may better represent reality.

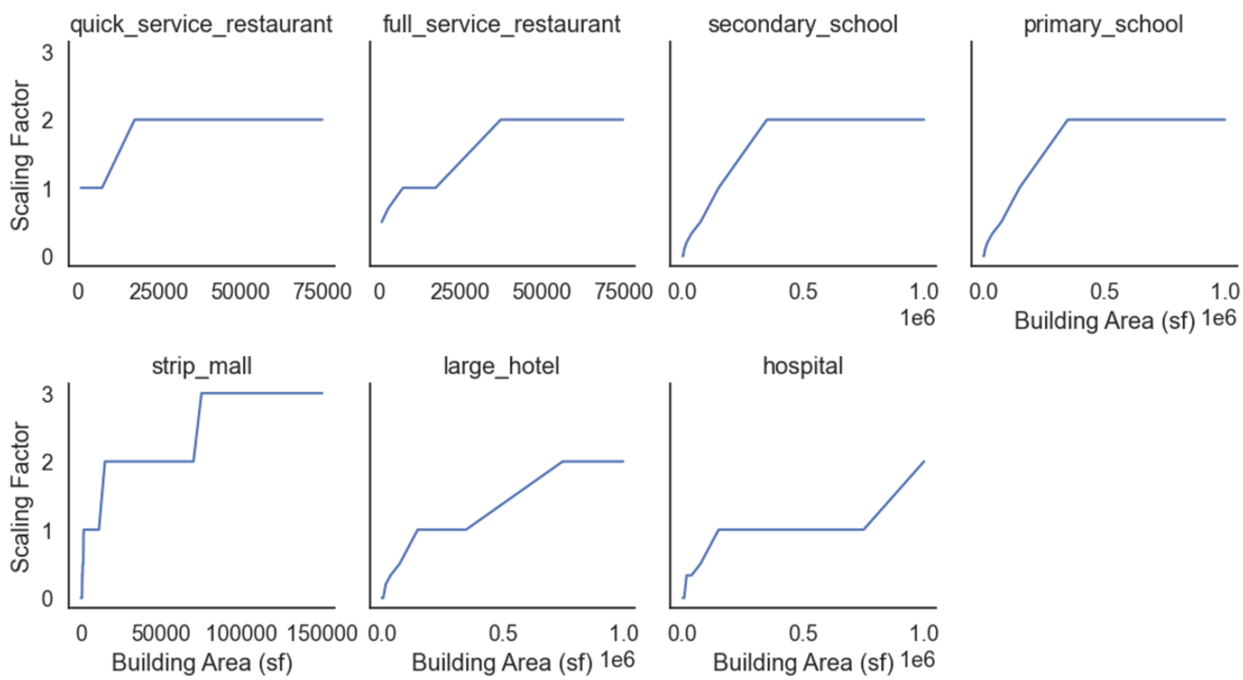

Figure 36. Cooking equipment count scaling factors by building type and area.

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4.7 Service Water Heating

Service water heating (SWH) includes all water heating usage other than space heating and process requirements. This includes general water heating for uses such as sink faucets and showers, but also building-type-specific uses like commercial dish washing and laundry. This section describes how SWH equipment, fuel type, and usage is incorporated into ComStock models.

4.7.1 Service Water Heating Fuel Type

It would be logical to assume that the SWH system in a building would use the same fuel as the space heating system. An examination of the CBECS 2012 data (EIA) shows that this is the most common case, but it is not always true. In particular, it appears that building types that have large SWH loads, such as hotels and hospitals, are much more likely to use natural gas for SWH, regardless of what their space heating fuel is, presumably because of fuel cost differences. In contrast, building types with low SWH loads are more likely to use electricity for SWH, presumably because of the ease and cost of running wiring compared to installing natural gas piping.

To represent this variability, we used the CBECS 2012 data to create a distribution of SWH fuels for each combination of space heating fuel and building type. The resulting distribution of floor area served by various SWH fuels is shown in Figure 37. As described in Section 4.8, the prevalence of different space heating fuel varies considerably by county. Because the service water heating fuel depends on the space heating fuel, the probabilities at a stock level are heavily skewed toward the more common space heating fuels, as shown in Figure 38.

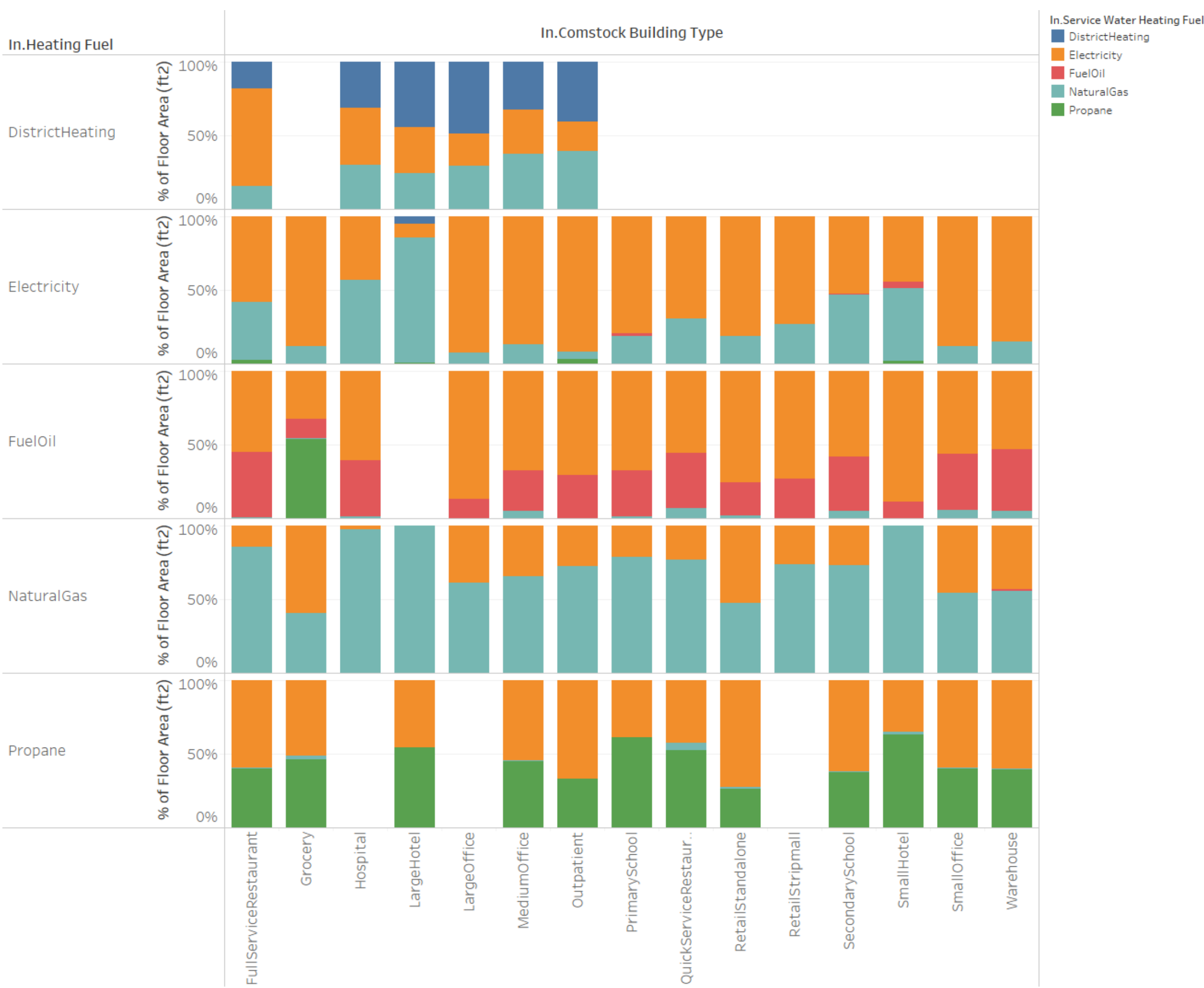

Figure 37. Area-weighted distribution of service water heating fuel by space heating fuel and building type.

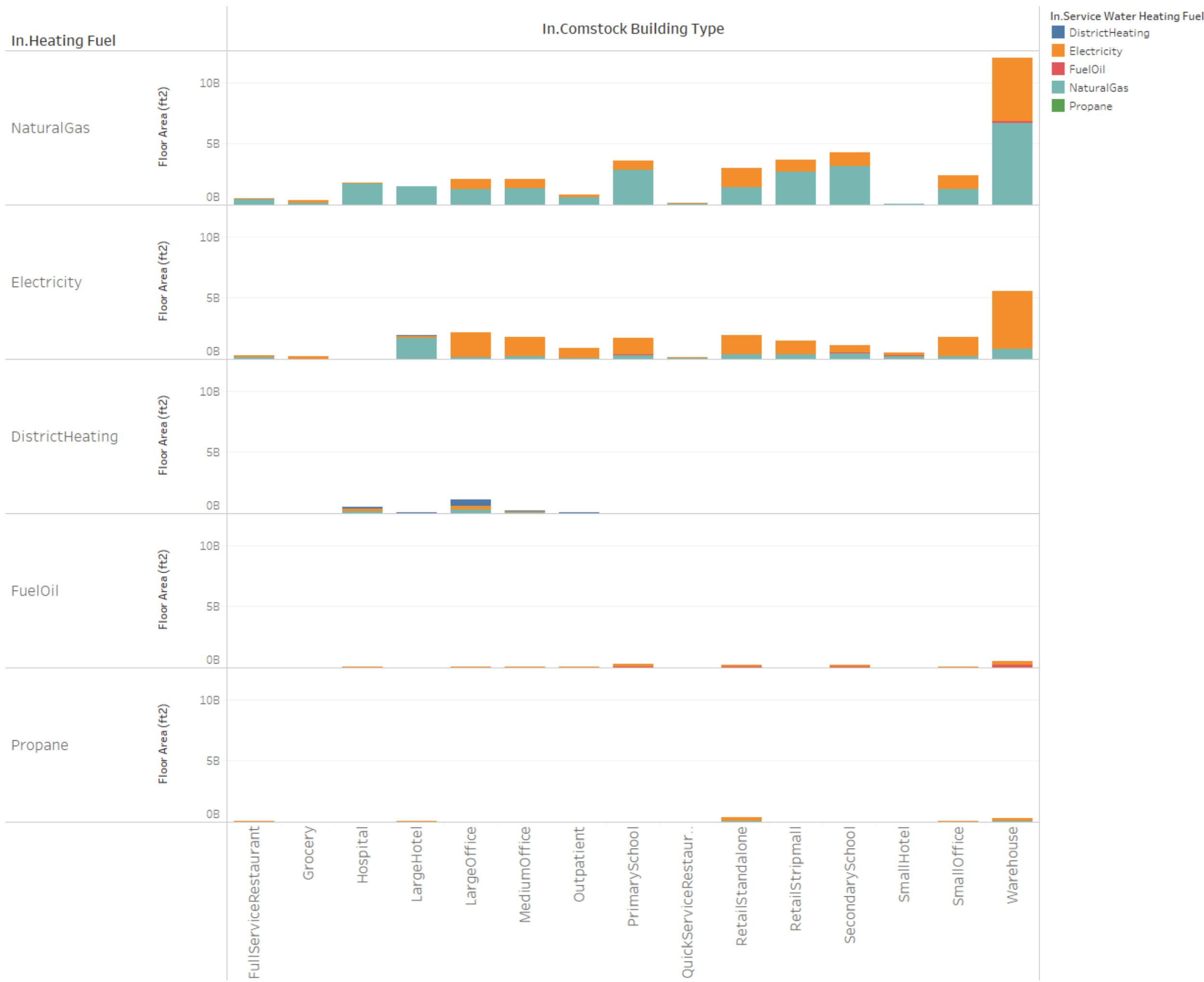

Figure 38. Floor area served by each service water heating fuel by space heating fuel and building type.

4.7.2 Service Water Heating System Type

Service water heaters in ComStock models are all storage tank style, and are either fuel combustion (natural gas, fuel oil, or propane) or electric resistance, as discussed in Section 4.7.1. Service water heaters with district heating as the fuel type receive hot water from off-site; therefore, these models do not include an on-site water heater. ComStock does not currently model instantaneous water heaters or heat pump water heaters. A single water heater is used to meet the demands of the entire building, unless a booster water loop is used, in which case a separate water heater system will be modeled for the boost loop. Booster loops are included for buildings with kitchen space types. These booster water heaters increase the temperature for some portion of the water for uses that need higher temperatures such as dishwashing. See Section 4.1.7 for details on the space type ratios for each building type. In space types with booster water heaters, 60% of peak flow is assigned to the booster water heater, and the remaining 40% is assigned to the standard water heater.

The design temperature of standard water heaters in ComStock is 140°F with a 3.6°F deadband temperature difference allowance. Booster water heaters for kitchens have a target temperature of 180°F; this assumption comes from the DOE prototype models to account for dishwashing in kitchens. The ambient air temperature for tank heat loss is assumed to be 72°F. No parasitic losses or part load performance modifiers are included at this time.

4.7.3 Service Water Heating Efficiencies

ComStock water heater efficiencies follow the requirements of ASHRAE-90.1. ComStock currently only models non-condensing units, so water heaters with a combustion fuel source are all roughly 80% efficient, whereas electric

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resistance water heaters are roughly 100% efficient. The efficiency parameters used to calculate the exact water heater efficiencies are summarized in Table 69 based on SWH template, SWH fuel type, and SWH heater capacity.

4.7.4 Service Water Heating Usage and Schedules

SWH usage for a given time step is based on a design peak gal/min flow rate multiplied by a usage fraction schedule. For example, if a given model has a design SWH flow rate of 10 gal/min, and the schedule value for the time step is 0.5, the SWH flow rate for the time step will be 5 gal/min. The flow rate values in ComStock come from the DOE prototype/reference building models, and are summarized in Tables 70 through 72.

In ComStock, the design flow rates are specified at the space type level. Then, these rates are aggregated to form a building-level design flow rate. The exception to this is SWH loads for kitchens, which are grouped into their own separate water heater system. These design flow rates are then multiplied by the usage fraction schedules, which specify the fraction of the design flow rate drawn for each time step. The usage fraction schedules in ComStock are derived from the DOE prototype/reference Buildings, and are summarized for each building type in Figures 72 through 84. The default schedule assignments for each space type and vintage are shown in Tables 70 through 72. However, these schedules are modified according to the hours of operation of the building, as described in Section 4.2.

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4.8 Heating, Ventilating, Air Conditioning, and Refrigeration

4.8.1 HVAC System Heating Fuel Type

Commercial HVAC equipment can use various heating fuel types, with the most common being natural gas, electricity, propane, fuel oil, and district heating. To reflect the variability of heating fuels in the real building stock, the ComStock workflow creates probability distributions of heating fuel types per building type at the county level. These distributions are used to assign a heating fuel type to each ComStock building model during the sampling process.

The probability distributions are informed by two data sources. First, there are the CBECS 2012 microdata, which include data on heating fuel(s), building type, and census division for the surveyed buildings. This data can be used to produce probability distributions for heating fuel by building type at the census division level. However, several data sources suggest notable variation within census divisions, which indicates that increased granularity may be needed (beyond what CBECS can provide). The heating fuel type probability distributions used in ResStock—which provides data for residential buildings at the county level—were used to add granularity. However, initial comparisons showed discrepancies between the ResStock data and the CBECS data, which is likely due to inherent differences between residential and commercial buildings. This indicated that the ResStock data should not be used directly. To rectify this, the county-level ResStock data were scaled to align with the CBECS data. This preserved the county-level variation in fuel type prevalence provided by the ResStock data, while also preserving the census division totals provided by the CBECS commercial data. District heating values were not available in the ResStock data, so the per-building-type CBECS values were used for all counties in a given census division.

In some cases, filtering down to a specific region and building type in the CBECS data yields very few samples. This can lead to unreliable conclusions for a region. To mitigate this, we took a blended approach, where some fraction of the CBECS region fuel type percentage comes from the regional samples only, and some fraction comes from the national sample for the building type. If more than 15 samples exist for a given building type and region, then 100% of the fuel type prevalence comes from that specific region. (The threshold of 15 samples was selected baced on engineering judgment to balance process reliability and regional variability.) If there are fewer than 15 samples, the number of samples divided by 15 will be the fraction used for the region, and the remainder will use the national numbers. For example, if a region has only 12 office samples, 80% (12/15) of the effective CBECS regional value will come from the CBECS region, and the other 20% will come from the national CBECS value for the building type. This will cause region/building type combinations with lower sample sizes to have a stronger inheritance of the national characteristics than the regional characteristics when we lack sufficient evidence to support this level of detail.

Some commercial building HVAC systems use multiple fuel types. For example, a VAV system with a gas furnace in the air handling unit and electric resistance coils in the reheat boxes, or a gas furnace DOAS with variable refrigerant flow (VRF) heat pumps serving the zones. This can complicate the categorization of these systems into a single primary fuel type. To address this, we determine the primary heating fuel type for the mixed fuel systems. The primary heating fuel is the heating fuel expected to carry the majority of the heating load. For example, the previously mentioned example of a VAV system with gas heat at the air handler and electric reheat would be classified as an electric-heated system, since the majority of heating for multizone VAV systems usually comes from the reheat. A full list of ComStock HVAC systems and their fuel type categories are shown in Table 17. Further detail on model HVAC system assignment methodology can be found in Section 4.8.2.

Figure 39 compares the prevalence of heating fuel type by stock floor area for CBECS 2012 and ComStock, by building type. In most cases, ComStock closely aligns to the CBECS 2012 values. However, there are some differences between the two sources due to randomness in the sampling process and from the use of other data sources to achieve county-level granularity in fuel type prevalence. The largest difference is in small hotels where ComStock shows 87% of the floor area using electric heating while CBECS suggest 74%, an absolute difference of 12%.

The county-level prevalences of different heating fuel types are shown in Figure 40 (natural gas), Figure 41 (electricity), Figure 42 (fuel oil), Figure 43 (propane), and Figure 44 (district heating).

Building Type	CBECS 2012 Fuel Type Prevalence					ComStock Fuel Type Prevalence					Absolute Difference				
	DistrictHeating	Electricity	FuelOil	NaturalGas	Propane	DistrictHeating	Electricity	FuelOil	NaturalGas	Propane	DistrictHeating	Electricity	FuelOil	NaturalGas	Propane
full_service_restaurant	3%	36%	2%	54%	6%	2%	37%	1%	55%	5%	-1%	1%	-1%	2%	-1%
hospital	22%	7%	5%	66%	0%	26%	12%	2%	60%	0%	4%	5%	-3%	-6%	0%
large_hotel	11%	50%	0%	38%	2%	12%	60%	0%	27%	1%	1%	11%	0%	-10%	-1%
large_office	23%	36%	1%	40%	0%	21%	37%	2%	41%	0%	-2%	0%	0%	1%	0%
medium_office	6%	37%	2%	53%	1%	7%	39%	2%	51%	1%	0%	2%	0%	-3%	0%
outpatient	4%	40%	5%	50%	1%	4%	46%	4%	46%	1%	0%	6%	-1%	-5%	0%
primary_school	0%	26%	7%	66%	0%	0%	30%	7%	62%	1%	0%	3%	1%	-4%	0%
quick_service_restaurant	0%	45%	3%	50%	2%	0%	49%	1%	48%	2%	0%	4%	-2%	-3%	0%
retail	1%	33%	4%	57%	5%	1%	36%	5%	53%	5%	0%	4%	0%	-4%	-1%
secondary_school	2%	21%	6%	71%	0%	2%	23%	5%	69%	0%	1%	2%	-1%	-2%	0%
small_hotel	0%	74%	0%	21%	4%	0%	87%	0%	11%	2%	0%	12%	0%	-10%	-2%
small_office	0%	40%	2%	56%	2%	0%	40%	2%	56%	2%	0%	0%	0%	0%	0%
strip_mall	0%	29%	0%	71%	0%	0%	26%	0%	74%	0%	0%	-3%	0%	2%	0%
warehouse	0%	32%	3%	62%	2%	1%	32%	3%	63%	2%	0%	0%	0%	0%	0%

Figure 39. Comparison of heating fuel type prevalence by floor area between CBECS 2012 and ComStock.

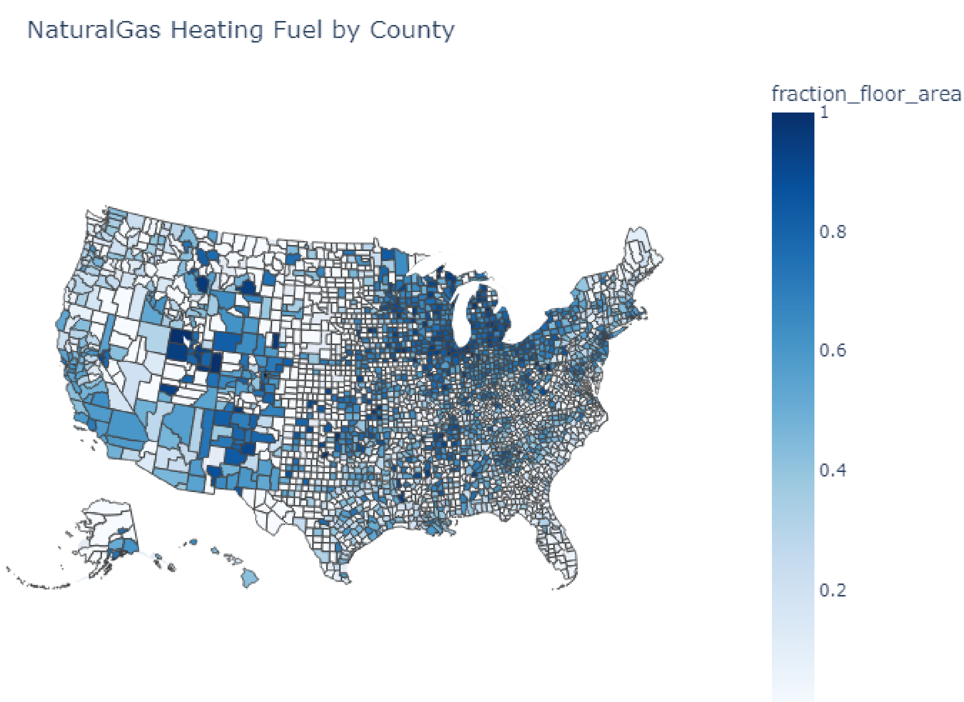

Figure 40. Fraction of ComStock models using natural gas heating per county.

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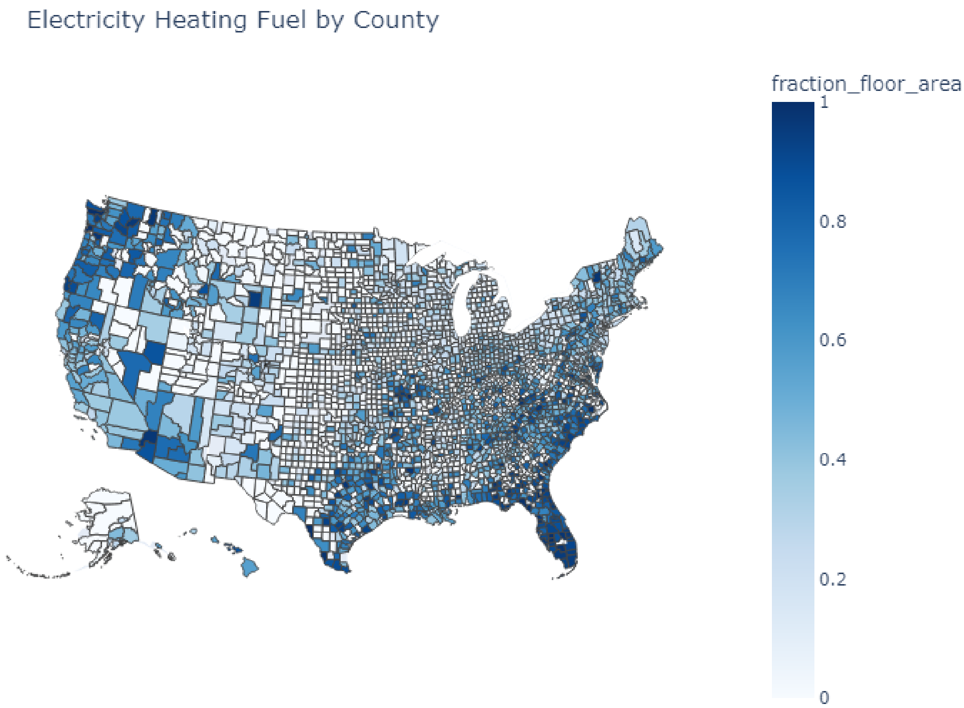

Figure 41. Fraction of ComStock models using electric heating per county.

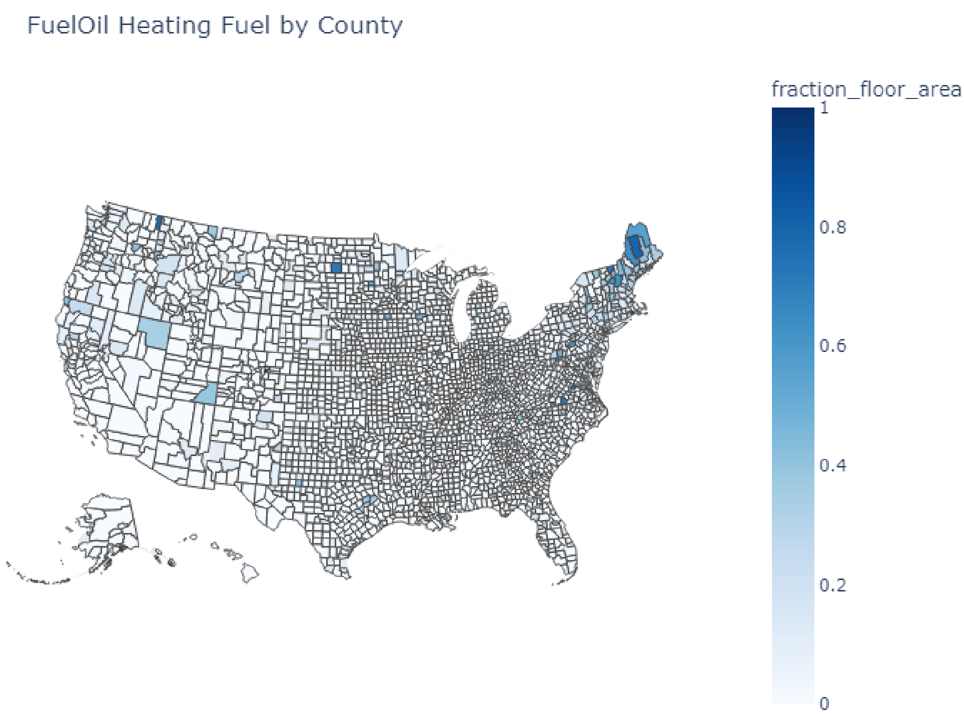

Figure 42. Fraction of ComStock models using fuel oil heating per county.

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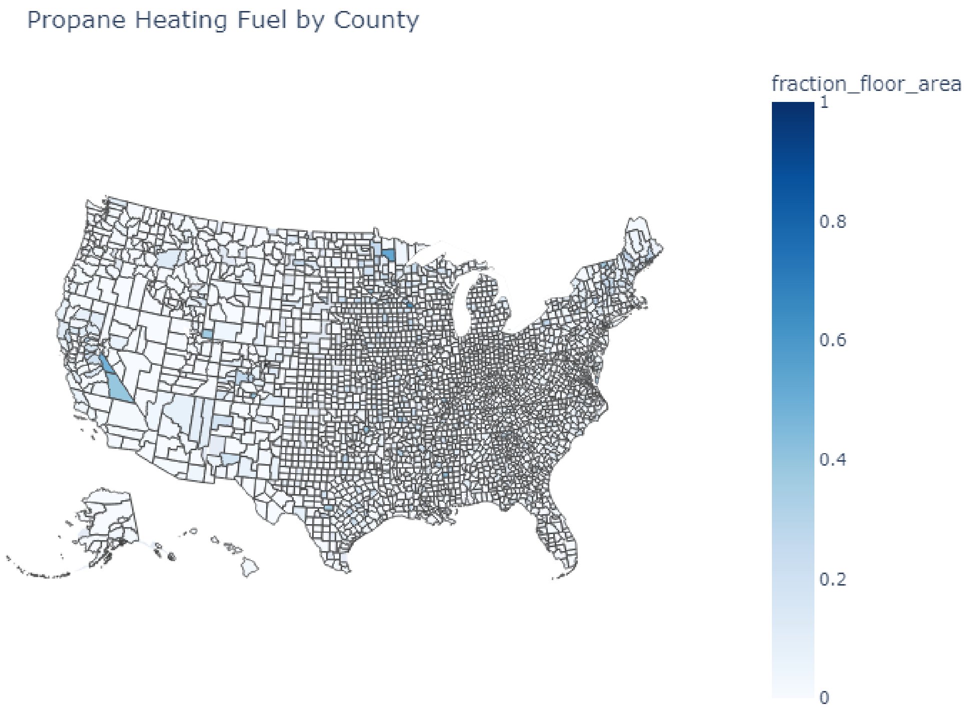

Figure 43. Fraction of ComStock models using propane heating per county.

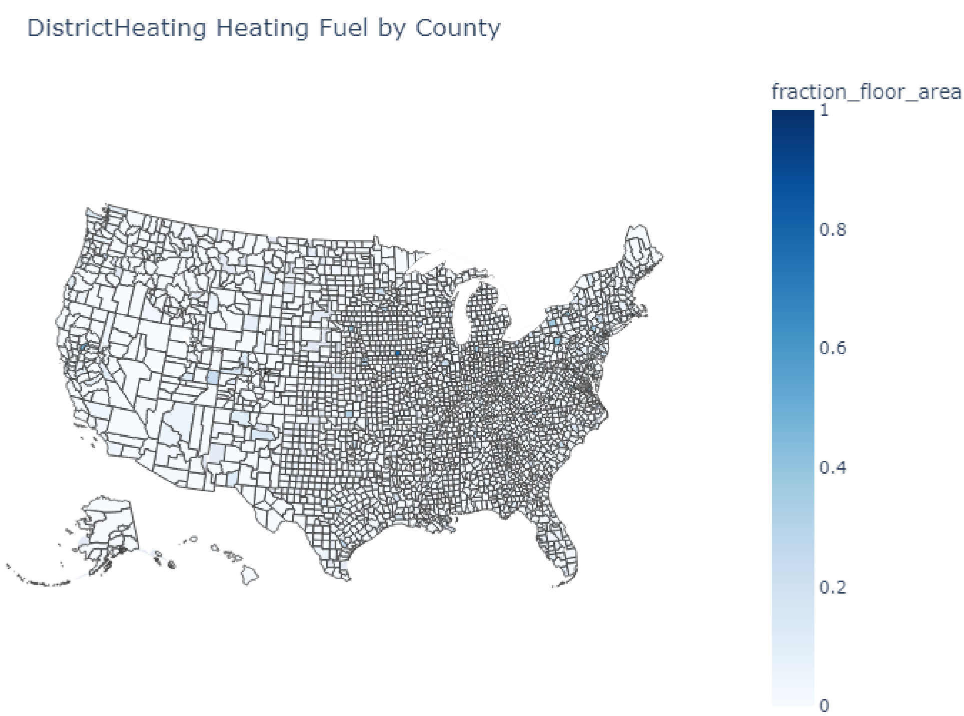

Figure 44. Fraction of ComStock models using district heating per county.

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4.8.2 HVAC System Types Probability Distributions

Each ComStock model is assigned a comprehensive HVAC system type. The full list of ComStock HVAC system types is shown in Table 17. HVAC system types are assigned to ComStock models through sampling informed by representative probability distributions. These probability distributions depend on building type, census division, and heating fuel type. For example, the distributions provide the fraction of gas-heated retail buildings in the West North Central Census Division that use each HVAC system type from Table 17. The probability distributions are derived from CBECS 2012 microdata, which include data on building type, census division, heating fuel type, and HVAC system type.

Table 17. Fuel Type Category for ComStock HVAC System Types

HVAC System Type	Heating Fuel Category
DOAS with fan coil air-cooled chiller with boiler	Fuel
DOAS with fan coil chiller with baseboard electric	Electricity
DOAS with fan coil chiller with boiler	Fuel
DOAS with fan coil chiller with district hot water	District_Heating
DOAS with fan coil district chilled water with baseboard electric	Electricity
DOAS with fan coil district chilled water with district hot water	District_Heating
DOAS with water source heat pumps cooling tower with boiler	Fuel
DOAS with water source heat pumps with ground source heat pump	Electricity
PSZ-AC with district hot water	District_Heating
PSZ-AC with electric coil	Electricity
PSZ-AC with gas boiler	Fuel
PSZ-AC with gas coil	Fuel
PSZ-HP	Electricity
PTAC with electric coil	Electricity
PTAC with gas boiler	Fuel
PTAC with gas coil	Fuel
PTHP	Electricity
PVAV with PFP boxes	Electricity
PVAV with district hot water reheat	District_Heating
PVAV with gas boiler reheat	Fuel
PVAV with gas heat with electric reheat	Fuel
Residential AC with residential forced air furnace	Fuel
Residential forced air furnace	Fuel
VAV air-cooled chiller with PFP boxes	Electricity
VAV air-cooled chiller with district hot water reheat	District_Heating
VAV air-cooled chiller with gas boiler reheat	Fuel
VAV chiller with PFP boxes	Electricity
VAV chiller with district hot water reheat	District_Heating
VAV chiller with gas boiler reheat	Fuel
VAV district chilled water with district hot water reheat	District_Heating

CBECS HVAC System Type Analysis

To derive probability distributions of HVAC system types from the CBECS data, we first assigned one of the comprehensive ComStock HVAC system types shown in Table 17 to the CBECS microdata samples. Historically, this analysis was based solely on the CBECS 2012 data set; however, our updated methodology now integrates data from both the CBECS 2012 and CBECS 2018 data sets. To combine these data sources, we apply a weighted average based on the number of samples from each data set to ensure appropriate representation.

CBECS includes questions regarding the primary HVAC system type of the building; however, it also contains dozens of additional questions about HVAC system components, fuel types, and technologies. In several cases, these responses may conflict with one another, making it difficult to derive a deterministic HVAC system type for the CBECS building samples. Interpretation of the numerous HVAC characteristics into a complete HVAC system type needed for energy modeling involves user discretion and judgment. On multiple occasions, the combinations of survey responses related to the HVAC system were questionable, incomplete, or conflicting based on engineering judgment. This could be due to the survey respondent lacking information about the nuances of the building's HVAC system, the survey respondent skipping relevant questions, or the building having multiple system types, perhaps due to various activities in the building or retrofits and expansions over time. Any of these issues could create a combination of equipment for a CBECS sample that would be difficult to translate into a single, comprehensive HVAC system type without firsthand knowledge of the building. Thus, reliably discerning an HVAC system type from the survey questions can be challenging for some of the CBECS samples and requires some degree of assumption.

Based on survey responses, some CBECS samples appear to utilize multiple types of HVAC systems. For example, one sample responded affirmatively to having a chiller, packaged terminal air conditioners (PTACs), heat pumps, and a swamp cooler. However, there is no indication as to the fraction of the building serving each system type in the survey. Additionally, ComStock is not trying to model buildings with several HVAC system types. To address this, we needed to determine prioritization rules when multiple system types for a single CBECS sample appeared to be prevalent. To achieve this, we grouped systems into the following four categories: VAVs, single-zone RTU, DOAS with zone terminal units (e.g., DOAS with heat pumps, VRF), and miscellaneous single-zone equipment.

There were several cases where the assigned HVAC system for a CBECS sample was unlikely given the size and type of the building. For example, only a small percentage of small office buildings would be expected to use large, multi-zone VAV systems. Similarly, only a small percentage of very large office buildings would be expected to use single-zone RTUs or zone terminal equipment with no DOAS. To address this, we introduced "size bins" to our distributions to ensure system types were correctly assigned based on building size. These size bins were incorporated into the sampling methodology, described in Section 3.4.3, to further refine system type assignments and improve the alignment between system types and building characteristics. Additional heating-only system types were assigned to building zones whose thermostat setpoints (see 4.8.7) described heating-only operation. This primarily affected warehouse buildings in California, representing approximately 13% of the total stock warehouse floor area, which moved from the primary system type to heating-only gas unit heaters or electric baseboard systems, depending on primary heating fuel source.

Overall, we produced 1,162 probability distributions from the combined CBECS 2012 and 2018 HVAC analysis, with dependencies based on building type, size bin, heating fuel, and census region. These distributions are used with the ComStock sampling process, described in Section 3.4.3, which ensures that HVAC system types are applied to the correct proportion of models. The prevalence of each HVAC system type in ComStock for all building types is shown in Figure 85 through Figure 99.

4.8.3 HVAC System Sizing

HVAC system design sizing is determined from several EnergyPlus design day sizing runs. Equipment capacity is hardsized, meaning it is explicitly set in the model. Design day conditions come from the same weather location as the weather file. Design days include the annual heating 99.6% drybulb temperature, annual cooling 0.4% drybulb temperature, annual cooling 0.4% wetbulb temperature for cooling towers and evaporative coolers, and monthly 0.4% drybulb temperature for August, September, and October to account for buildings with solar-gain driven cooling load maximums.

Per ASHRAE 90.1 Appendix G, HVAC systems are oversized by 15% for cooling and 25% for heating. Note that sizing results for a model will be impacted by several control properties specific to the model, such as supply air temperature control, thermostat set points, and outdoor ventilation rates, which are described in later sections.

4.8.4 Outdoor Air Ventilation Rates

Commercial buildings require outdoor ventilation air when the building is occupied. The design outdoor air rate for a system is the minimum amount of outdoor air the system must supply while the building is occupied. The amount of outdoor air required for an HVAC system is calculated by the combined needs of the space type(s) served by a system.

ComStock design outdoor air ventilation rates follow the requirements set forth by ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality (non-California models), or by DEER (California models). Both of these sources dictate the minimum design outdoor air flow rate by space type. The minimum outdoor air requirements for each space type are composed of a flow rate per person, a flow rate per area, and in some cases, an exhaust rate.

Table 18. Design Outdoor Air Rates by Building Type and HVAC Code Template for Buildings Outside California

Building Type	Pre-1980 (cfm/sf)	1980–2004 (cfm/sf)	90.1-2004 (cfm/sf)	90.1-2007 (cfm/sf)	90.1-2010 (cfm/sf)	90.1-2013 (cfm/sf)
FullService-Restaurant	1.103	1.103	1.107	1.048	1.067	1.077
Grocery	0.225	0.225	0.225	0.175	0.175	0.175
Hospital	-	0.258	0.254	0.258	0.258	0.258
LargeHotel	0.240	0.240	0.240	0.224	0.234	0.226
LargeOffice	0.098	0.098	0.098	0.098	0.098	0.098
MediumOffice	0.100	0.100	0.100	0.098	0.098	0.098
Outpatient	0.215	0.215	0.223	0.215	0.215	0.215
PrimarySchool	0.376	0.376	0.378	0.374	0.374	0.374
QuickService-Restaurant	0.935	0.935	0.935	0.849	0.884	0.886
RetailStandalone	0.276	0.276	0.276	0.268	0.270	0.270
RetailStripmall	0.449	0.461	0.461	0.449	0.451	0.453
SecondarySchool	0.547	0.547	0.547	0.543	0.542	0.542
SmallHotel	-	-	0.138	0.100	0.100	0.100
SmallOffice	0.100	0.100	0.100	0.100	0.098	0.098
Warehouse	0.049	0.049	0.049	0.051	0.051	0.051

Combined, these components determine the design outdoor air requirement for each space and its respective HVAC system. Table 18 and Table 19 show the average design outdoor air flow rate per area (cfm/m^2) for non-California models and California models, respectively. These averages are influenced by the number of buildings of each type and their vintage. Both methods are heavily influenced by the space type composition of the model; ComStock models assume space type ratios for building types, with some building types having variation in the space type ratios. ComStock space types are described further in Section 4.1.7.

Some ComStock HVAC system types are residential style systems (denoted "residential" in Table 17). These systems do not include ventilation air and are an exception to the aforementioned ASHRAE-62.1 outdoor air methodology. Although commercial buildings all require outdoor ventilation air per code, some commercial buildings in the stock use residential systems without outdoor air. This is reflected in ComStock through the use of these residential system types. ComStock's HVAC system selection methodology is described further in Section 4.8.2.

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Table 19. Design Outdoor Air Rates by Building Type and HVAC Code Template for Buildings Inside California

Building Type	DEER Pre-1975 (cfm/sf)	DEER 1985 (cfm/sf)	DEER 1996 (cfm/sf)	DEER 2003 (cfm/sf)	DEER 2007 (cfm/sf)	DEER 2011 (cfm/sf)	DEER 2014 (cfm/sf)	DEER 2015 (cfm/sf)	DEER 2017 (cfm/sf)
FullService-Restaurant	0.540	0.540	0.540	0.540	0.540	0.540	0.540	0.540	0.540
Grocery	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240	0.240
Hospital	-	0.152	0.152	0.152	0.152	0.152	0.152	0.152	-
LargeHotel	0.000	0.104	0.104	0.104	0.104	0.104	0.104	0.104	0.104
LargeOffice	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108
MediumOffice	-	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108
Outpatient	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108	0.108
PrimarySchool	-	0.447	0.447	0.447	0.447	0.447	0.447	0.447	0.447
QuickService-Restaurant	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439	0.439
RetailStandalone	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268	0.268
RetailStripmall	0.327	0.323	0.323	0.323	0.323	0.323	0.325	0.323	0.323
SecondarySchool	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433	0.433
SmallHotel	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069
SmallOffice	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.077
Warehouse	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.150

4.8.5 Fan Systems

Fans are used in all ComStock HVAC systems except those that rely on radiant heat transfer, such as baseboards. Fans induce pressure in the air stream of HVAC equipment, producing the airflow needed for space conditioning and/or outdoor air ventilation.

Fan Power

Fan power determines the amount of energy it takes a fan system to provide a certain amount of airflow. The fan power requirements of each HVAC system are a function of the total pressure drop of the air stream that the fan system will need to overcome (e.g., from filters, coils, air ducts) as well as the efficiency of the fan blades and fan motor.

Fan power in ComStock is determined by ASHRAE-90.1 code requirements. ASHRAE-90.1 determines fan power primarily based on the system type. Constant air volume, variable air volume, and unitary zone equipment are all assigned different fan power allowances.

For implementation in ComStock, fan power is determined based on the static pressure of the air delivery system, the efficiencies of the fan/motor system, and the airflow of the system. The static pressure is based on the HVAC system type and the maximum airflow of the system, as shown in Table 20. The fan motor efficiencies are a function of the motor size and HVAC code year, as shown in Table 75.

The addition of energy recovery ventilators (ERVs) in HVAC air loops can add additional static pressure to the air system and therefore result in a higher fan power requirement. ComStock accounts for this additional fan power in the ERV wheel power rather than the fan itself; this allows for improved accuracy during ERV bypass modes (where the airflow bypasses the additional static pressure of the ERV system). See Section 4.8.10 for more information on ComStock ERV systems.

Fan Controls

This section describes the operation of fan systems during the hours a building is occupied. Details on the operation of fan systems during unoccupied hours are described in Section 4.8.8.

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Table 20. Fan Pressure Rise and Efficiency

Fan Type	Max Airflow (cfm)	Pressure Rise (in. H_2O)	Fan Power Minimum Flow Fraction	Fan Impeller Efficiency	Motor Efficiency	Total Fan Efficiency
Constant Volume and DOAS	<7,437	2.5	1	0.65	See motor efficiency lookup table	(Fan Impeller Eff.) X (Motor Eff.)
	≥7,537 and <20,000	4.46				
	≥20,000	4.09				
Variable Air Volume	<4,648	4	0.25			
	≥4,648 and <20,000	6.32				
	≥20,000	5.58				
PTAC/PTHP, WSHP, VRF	>0	1.33	1	0.55		
Four Pipe Fan Coil	>0	1.09	1			
Unit Heater	>0	0.2	1			

HVAC Systems Providing Outdoor Air

As required by ASHRAE-90.1, HVAC systems in commercial buildings must constantly provide the minimum design outdoor air flow rates when the building is occupied. HVAC systems in ComStock follow this control requirement. For constant volume systems, the fan system will run continuously at design airflow during occupied hours. For VAV systems, the fan system will run continuously between the minimum and maximum airflow of the system during occupied hours, always ensuring that the total system airflow meets the airflow needs of every zone.

HVAC Systems Not Providing Outdoor Air

Systems that do not directly provide outdoor air, such as zone-level unitary systems coupled with a DOAS, do not need to run fans continuously. Therefore, these systems are controlled to cycle the fan system on only when required to maintain zone thermostat set points. Otherwise, the fans are allowed to turn off. This is also the control logic for any residential-style system in ComStock that does not provide outdoor air.

4.8.6 Pump Systems

Pumps are used to induce flow in building hydronic loops. This includes heating water loops, cooling water loops, condenser water loops, and ground-source heat pump water loops.

Pump Power

Pump power is a function of the pressure head of the hydronic loop and the pump efficiency. The pressure heads in ComStock hydronic systems are set to reflect the baseline requirements specified in ASHRAE-90.1, noting that each hydronic loop type has its own specifications. The pressure heads used for the various ComStock hydronic loop types are specified in Table 21. Primary-only pump configurations use a single hydronic loop system between the boilers/chillers and the heating/cooling coils for space conditioning. A primary-secondary system uses a primary loop for circulating water between the boilers/chillers, and a secondary loop for supplying the the plant fluid to the heating/cooling coils. Pump motor efficiencies are derived using the same motor efficiency lookup tables used for fans (Table 75).

Pump Controls

All pumps in ComStock are set to use intermittent controls, meaning that they can cycle off when there is no load present in the loop. Constant volume pumps are controlled to ride the pump curve, as specified by ASHRAE-90.1, whereas variable speed pumps can adjust their speed to modulate flow as needed. Variable speed pumps all have a minimum flow ratio of 0% in ComStock. This value is likely too low and underestimates pumping energy, as most pump systems can only reduce flow as low as 30%–50% in order to maintain proper operation of chillers, boilers, etc. The assignment methodology for variable speed pumps is specified in Table 21.

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Table 21. Pump Configuration and Pressure Rise for Hydronic Loops

Loop Type	Pump Configuration	Primary Pump Head (ft w.c.)	Secondary Pump Head (ft w.c.)	VFD Pump?
Hot Water Loop District Heating Loop	Primary-only	60	-	Variable speed when building area >120,000 ft^2
Water-Cooled Chiller Loop	Constant-primary, variable-secondary	15	45	Secondary pump always variable speed
Air-Cooled Chiller Loop District Cooling Loop	Primary-only	60	-	Variable speed when cooling capacity >300 tons
Condenser Water Loop	Primary-only	50	-	Always constant speed
GSHP Condenser Water Loop	Primary-only	60	-	Always constant speed

4.8.7 Thermostat Set Points

Thermostat set points, both heating and cooling, dictate the target indoor temperature range for the HVAC system to satisfy. The cooling thermostat set point will set the upper temperature limit, whereas the heating thermostat set point will set the lower temperature limit.

Thermostat set points are implemented in ComStock through square-wave schedules. Each model is assigned a set point temperature, which is the temperature the HVAC system must maintain during occupied hours, and a setback temperature, which is the temperature the HVAC system must maintain during unoccupied hours (note that some models have no setback temperature). The set point and setback temperatures used in the models are described later in this section. The timing of the set point and setback temperatures align with the building occupancy schedules discussed in Section 4.2.

Thermostat Set Points Informed by Building Automation System Data

This section outlines the ComStock thermostat set point assignment methodology for the following building types: full service restaurant, large office, medium office, primary school, quick service restaurant, retail standalone, retail strip mall, secondary school, and small office.

All ComStock building types, excluding hospitals, outpatient, warehouses, and hotels, utilize building automation system (BAS) data to inform distributions of thermostat set points. The methodology behind this approach is described in this section. The intent is to include heating and cooling thermostat set point variability between ComStock models to reflect the thermostat set point variability between real buildings. For example, some offices could be expected to set their heating thermostat to 72°F, whereas others might set it to 70°F. The ComStock methodology allows this variation to exist in the models.

Building automation data from three industry-provided private data sources with over 3,700 buildings were used to derive the distributions of thermostat set points that are used to assign set points to the applicable ComStock models. Table 22 shows the counts of buildings with thermostat data available in the data set by building type. The data set includes the time series heating and cooling set points that were used to determine the occupied heating and cooling set points for each building. In turn, these were used to create probability distributions of thermostat set points by building type when aggregating across the data set. For building types with less than 25 samples in the data set, the distribution for all building types was used, as smaller sample sizes cannot reliably be extrapolated to represent a population. The resulting heating and cooling probability distributions, per applicable building type, are shown in Figure 45 and Figure 46, respectively. Note that some outliers exist in the data set at very low prevalence, such as offices with heating set points of 61°F. These outliers are incorporated into ComStock models at a similar low prevalence to reflect the wide diversity of commercial buildings.

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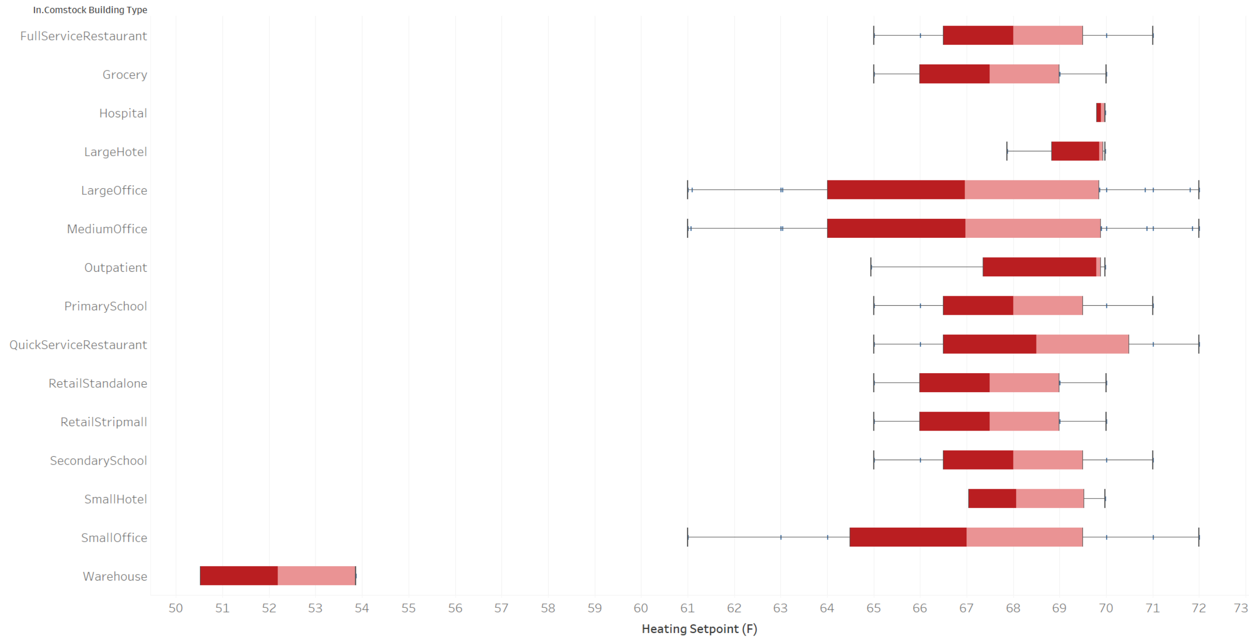

Figure 45. Heating thermostat set point (Fahrenheit) distributions per building type.

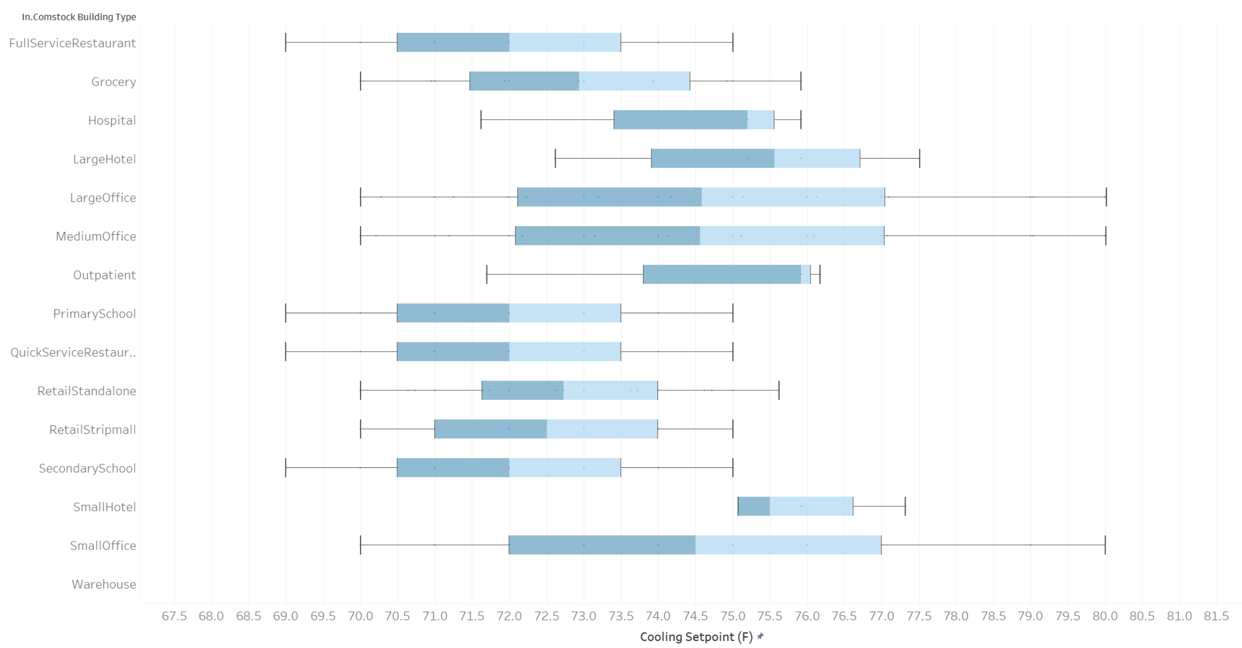

Figure 46. Cooling thermostat set point (Fahrenheit) distributions per building type.

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Table 22. Building Counts With Thermostat Data by Building Type

Building Type	Building Count
Food Service/Restaurant	1,817
Mercantile Retail	1,692
Food Sales/Grocery	164
Office	31
School	16
Warehouse	4
Hotel	4
Hospital	2
Outpatient	2

Table 23. Fraction of ComStock Buildings With Thermostat Setbacks by Building Type

Building Type	Fraction of Models With Thermostat Setback
FullServiceRestaurant	0.57
Grocery	0.63
LargeOffice	0.77
MediumOffice	0.76
PrimarySchool	0.9
QuickServiceRestaurant	0.46
RetailStandalone	0.63
RetailStripmall	0.9
SecondarySchool	0.95
SmallOffice	0.77
Warehouse	0.56

Unoccupied Thermostat Setbacks

An unoccupied thermostat setback defines the difference in the temperature set point from the occupied thermostat set point, for either heating or cooling, which is used during periods where the building is unoccupied. For example, an office might have an occupied heating set point of 71°F, but an unoccupied thermostat setback of 6°F for when the building is unoccupied, resulting in an unoccupied thermostat set point of 65°F (71°F - 6°F). This setback would be expected to save HVAC energy by relaxing the temperature requirements when there are no occupants in the building. This section describes ComStock's methodology for assigning unoccupied thermostat setback prevalence, as well as the setback temperature delta, for both heating and cooling.

The prevalence of thermostat setbacks in ComStock models is determined by building type using CBECS 2012. Each building type has some fraction of buildings with a thermostat setback, and some fraction without. The CBECS survey does not provide details on thermostat set point and setback temperatures, but it does provide survey responses as to whether heating and cooling setbacks are used, and whether these setbacks are manual. The survey responses are summarized by building type in Figure 100. However, it seems likely that many respondents who claim to implement manual setbacks do not reliably do so; we made a conservative assumption that only 20% of manual setbacks would be counted as reliably practicing thermostat setbacks (manually adjusting the thermostat every night before leaving and every morning upon entering). The fraction of ComStock models that include thermostat setbacks is shown in Table 23. Note that the timing of the thermostat setbacks coincides with the assigned hours of operation for a specific model, the methodology for which is described in Section 4.2.

Unoccupied Thermostat Setbacks Informed by Building Automation System Data

The method for determining the magnitude of the temperature setback for buildings with unoccupied temperature setbacks is described in this section. This methodology is used for the following building types: full service restaurant, large office, medium office, primary school, quick service restaurant, retail standalone, retail strip mall, secondary school, small office, and warehouse. In warehouse buildings, this methodology only applies to the office space type within the building.

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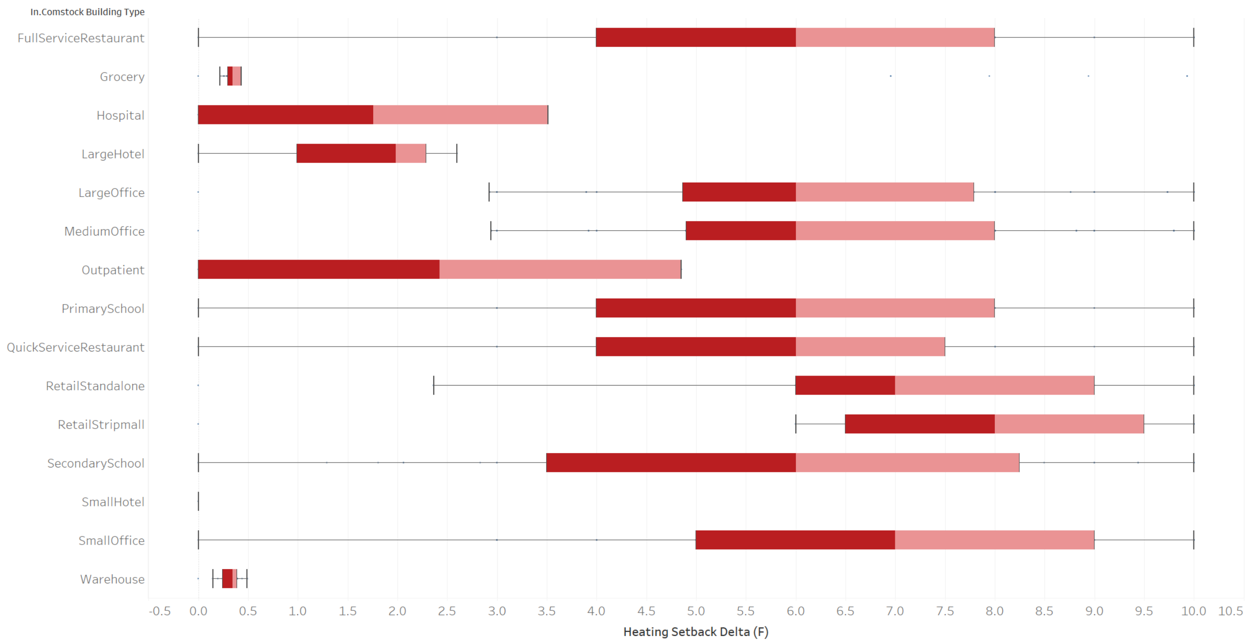

Figure 47. Thermostat heating setback delta temperature probability distributions per building type.

The magnitudes of the temperature setbacks are determined using the same data sets and methods described in Section 4.8.7 for thermostat set points; probability distributions are created for each building type. The relationship between the thermostat set points and the delta setbacks is shown in Figure 101. The resulting heating and cooling thermostat delta setback temperature probability distributions, for each applicable building type, are shown in Figure 47 and Figure 48, respectively.

Thermostat Setpoints Not Informed by Building Automation System Data

The following ComStock building types do not infer thermostat setpoints from the BAS data, and therefore each have there own methodology previously described in this section: Hospitals, Outpatient, Warehouses, Small Hotels, and Large Hotels.

Warehouses

Heating thermostat setpoints for warehouse storage spaces are adjusted from the DOE/DEER prototype model defaults in order to better calibrate warehouse energy consumption to the CBECS truth data set, informed by CBECS 2018 (EIA) responses to the “Percent Heated” and “Percent Cooled” questions as well as engineering judgement. The default DOE prototype setpoint value of 45°F (50°F for buildings built after 2004) was increased, and the default DEER prototype setpoint value of 70°F was decreased, both to a new heating setpoint of 61°F. Cooling thermostat setpoints remained unchanged, except for California (DEER prototype) warehousees, which are modeled as heated-only.

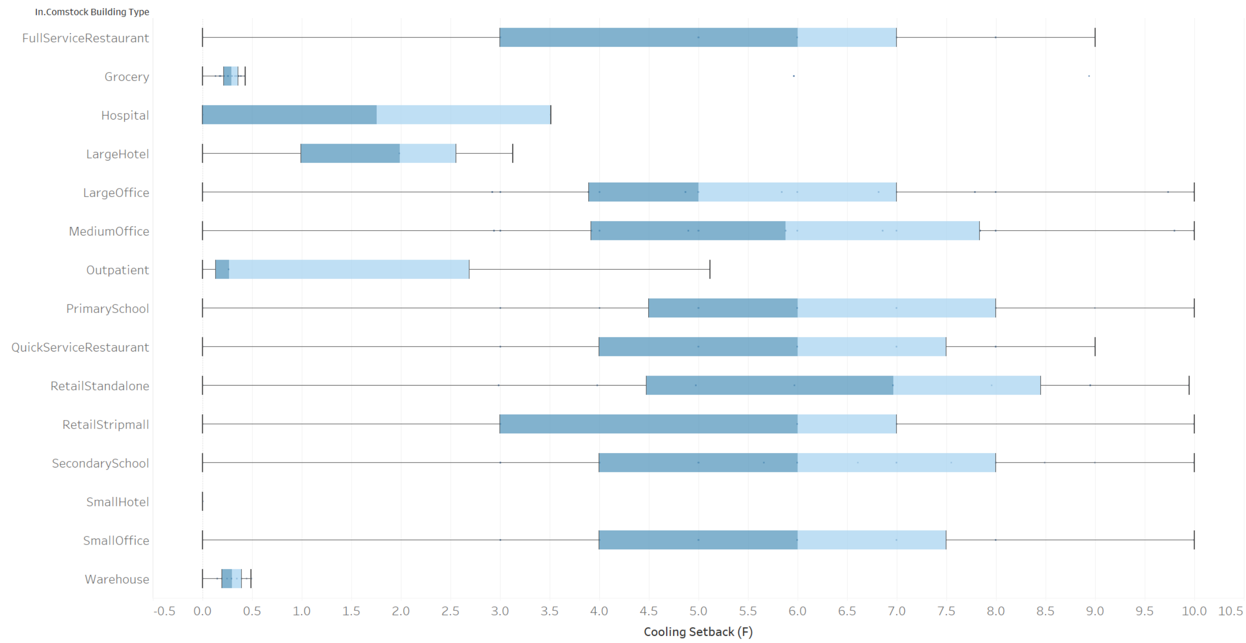

Figure 48. Thermostat cooling setback delta temperature probability distributions per building type.

4.8.8 Unoccupied Air Handling Unit Operation

Commercial buildings require constant design outdoor air ventilation rates when the building is occupied per ASHRAE-90.1. For air handling units (AHUs), the outdoor air is generally mixed with the supply air. This requires constant supply fan operation to maintain the outdoor air requirements established by ASHRAE-62.1 (ASHRAE). However, AHUs do not need to provide outdoor ventilation air when the building is unoccupied. Therefore, ASHRAE-90.1 requires outdoor air dampers to close when the building is unoccupied, and to only cycle on supply fans as needed to maintain thermostat set points. This control scheme can have a large impact on energy usage, and data suggests that not all buildings implement these controls in their AHU systems. This section discusses ComStock's methodology for including the prevalence of different unoccupied AHU control schemes observed in real buildings, which follows the methodology used in CaraDonna and Dombrovski.

An industry-provided BAS data set of over 5,700 AHUs was used to inform the prevalence of three unoccupied AHU operation modes. The data set includes time series (hourly) BAS variables for "Occupied Status" (describes whether the AHU was in an occupied mode for that hour), "Fan Status" (describes whether the fan was used for that hour), and "Ventilation Status" (describes whether outdoor ventilation air was used for that hour). Counts of AHUs and buildings by building type in the data set are shown in Table 24, and the three unoccupied AHU shutdown control schemes are summarized in Table 25.

The data set suggests that 27% of AHUs use scheme 1 (least efficient), 50% of AHUs use scheme 2 (more efficient), and 23% of AHUs use scheme 3 (most efficient; ASHRAE-90.1 required). The prevalence of the AHU unoccupied control schemes by building type is shown in Table 76. These probability distributions are used in ComStock sampling to set the fraction of buildings utilizing the discussed control schemes, by building type, for models that use AHU-based HVAC systems. Non-AHU HVAC system types are not applicable to this methodology, nor are building types not listed in Table 76. Note that building types with less than 25 buildings in the BAS data set (Table 24) use the "All Types" distribution of the data set at large, as fewer than 25 samples cannot reliably be used to represent a population.

The following building types are not included in the unnocupied air handling unit operation workflow, and utilize default scheduling only: small hotels, large hotels, outpatient, hospitals, primary schools, and secondary schools. The building types may be integrated into this workflow in the future as more data becomes available.

Table 24. Site and AHU Counts of Time Series BAS Data per Building Type

Building Type	Site Count	AHU Count
All Types	843	5,706
Retail	541	3,300
Unknown	164	1,391
Office	43	466
Restaurant	39	155
Grocery	35	212
Hotel	6	46
Education	6	29
Warehouse	5	94
Healthcare	4	13

Table 25. AHU Operating Mode Schemes Used During Scheduled Unoccupied Times

Scheme Name	Unoccupied Control Scheme Description	Expected Efficiency	Occupied Status	Fan Status	Ventilation Status
Scheme 1	Scheduled on, running	Least Efficient	Active	Active	Active
Scheme 2	Scheduled off, fan cycles with ventilation to maintain thermostat setpoints	More Efficient	Inactive	Active	Active
Scheme 3	Scheduled off, fan cycles without ventilation to maintain thermostat setpoints	Most Efficient	Inactive	Active	Inactive

4.8.9 Demand Control Ventilation

Demand control ventilation (DCV) acts to reduce outdoor air ventilation during periods of detected low occupancy. Occupancy levels are generally detected through the use of CO_2 sensors located directly in the space or within the HVAC system.

DCV is included in ComStock models when required by the governing ASHRAE-90.1 energy code for the specific spaces/systems in the model. ComStock gathers the necessary criteria for determining DCV requirements and includes DCV functionality only if the space/system requires it. The requirement criteria for DCV include space floor area, space design occupant density, system economizer prevalence, system design outdoor air flow rate, and system energy recovery prevalence. The 90.1 code year for a model is based on the year of the model's last major HVAC replacement. Code year assignment and system turnover assumptions are described further in Section 4.1.5. A summary of the floor area served by a system with DCV is shown in Table 77. Note that DCV is not required by ASHRAE 90.1 when an HVAC system has an ERV. One important observation from these data is that no office buildings include DCV. This is because office buildings are currently modeled using a single, blended space type that is a fractional mix of open offices, enclosed offices, conference rooms, etc. The occupancy density of this blended space does not exceed the DCV thresholds in ASHRAE 90.1. This leads to unrealistically low (0%) DCV in office buildings. Another important observation is that DCV is not modeled in any of the buildings in California (which use the DEER data set), although this does not align with the newer versions of Title 24. DCV is expected to be implemented in California buildings in the near future.

4.8.10 Air-Side Energy Recovery

Energy recovery ventilators (ERVs) in AHUs reduce energy consumption by pre-conditioning the incoming outdoor air using the system exhaust air, which reduces the heating and cooling energy required to condition the air. Energy recovery is especially effective in systems serving spaces with high outdoor air ventilation loads.

ERVs are included in ComStock model HVAC systems only when required by the governing energy code for the specific system. This determination is made using OpenStudio-Standards, where the necessary ComStock model properties are gathered to determine whether an ERV is required for each system. These properties include the

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climate zone, percent outdoor air, and design supply airflow rate, aligning with ASHRAE-90.1 Table 6.5.6.1 for the respective energy code year followed. A summary of the floor area served by systems with energy recovery is shown in Table 26.

Table 26. Fraction of Floor Area Served by HVAC Systems With Energy Recovery by Building Type and Code Year

Building Type	Pre-1980	1980–2004	90.1-2004	90.1-2007	90.1-2010	90.1-2013	DEER All Years
FullServiceRestaurant	0	0	0.051	0.027	0.347	0.392	0
Hospital	0	0	0.457	0.442	0.613	0.871	0
Grocery	0	0	0.0	0.0	0.058	0.199	0
LargeHotel	0	0	0.109	0.09	0.267	0.245	0
LargeOffice	0	0	0.028	0.035	0.139	0.519	0
MediumOffice	0	0	0.007	0.016	0.093	0.306	0
Outpatient	0	0	0.087	0.078	0.095	0.246	0
PrimarySchool	0	0	0.376	0.41	0.597	0.639	0
QuickService-Restaurant	0	0	0	0	0.088	0.063	0
RetailStandalone	0	0	0.027	0.022	0.029	0.306	0
RetailStripmall	0	0	0.115	0.111	0.191	0.435	0
SecondarySchool	0	0	0.540	0.530	0.675	0.725	0
SmallHotel	0	0	0.186	0	0.092	0	0
SmallOffice	0	0	0	0	0.044	0.050	0
Warehouse	0	0	0.065	0.053	0.069	0.083	0

An enthalpy wheel ERV system (rotary) is added to the HVAC systems in ComStock models where an ERV is determined to be required. The effectiveness of the system is 50% for all conditions, aligning with the requirements of ASHRAE-90.1. Economizer lockout and supply air bypass for temperature control are included. The defrost type is exhaust only, which temporarily bypasses the supply side of the heat exchanger to allow warmer exhaust air to remove frost uninhibited when needed.

4.8.11 Air-Side Economizers

Air-side economizers reduce HVAC cooling energy by increasing the amount of outdoor ventilation air during times when the temperature and/or enthalpy are beneficial for cooling. For example, if the outdoor air temperature is 55°F when the building needs cooling, the HVAC system can increase the amount of outdoor ventilation air being delivered to the space to satisfy some or all of the cooling requirement in place of mechanical cooling.

As described in Section 4.1.5, we assume that some building systems, including the HVAC system, are replaced over the lifespan of the building. We re-evaluate the requirement for an air-side economizer based on the energy code in force at the time of the latest HVAC system replacement. For buildings outside of CA, energy code requirements were taken from ASHRAE 90.1. For buildings inside CA, the CA energy code requirements were evaluated taken from the CA DEER MASControl3 models (Hirsch), where the economizer limits and applicability were found as shown in Table 27 and Table 28.

Figure 49 shows the prevalence of economizers (in terms of floor area coverage and contribution to cooling energy) for different subcategories (building type and ventilation system type) of the existing building stock. The percentage of floor area where "economizer availability" is "True" includes the total building area if there is at least one economizer in the building. It does not represent the total floor area served by systems with economizers. While there are buildings that already include economizers in variable air volume (VAV) systems and roof top units (RTU) covering 40% of the total floor area and 28% of total electricity used for cooling, the remaining portion of buildings with those system types do not include economizers.

Based on a large body of anecdotal evidence from conversations with fault-focused field engineers and a brief review of common current (Trane, Carrier, Daikin) rooftop unit product data sheets (Trane), (Carrier), (Daikin), fixed dry bulb controls are a more common choice than differential dry bulb controls, although manufacturers also offer dual enthalpy (fixed dry bulb + fixed enthalpy) options with the addition of an enthalpy sensor. For this reason, fixed dry bulb controls are assumed for almost all building vintages and climate zones, with the exception being ASHRAE 90.1-2010 and 2013, which prohibited fixed dry bulb economizers in the warmer humid climate zones. These restrictions were lifted in ASHRAE 90.1-2016.

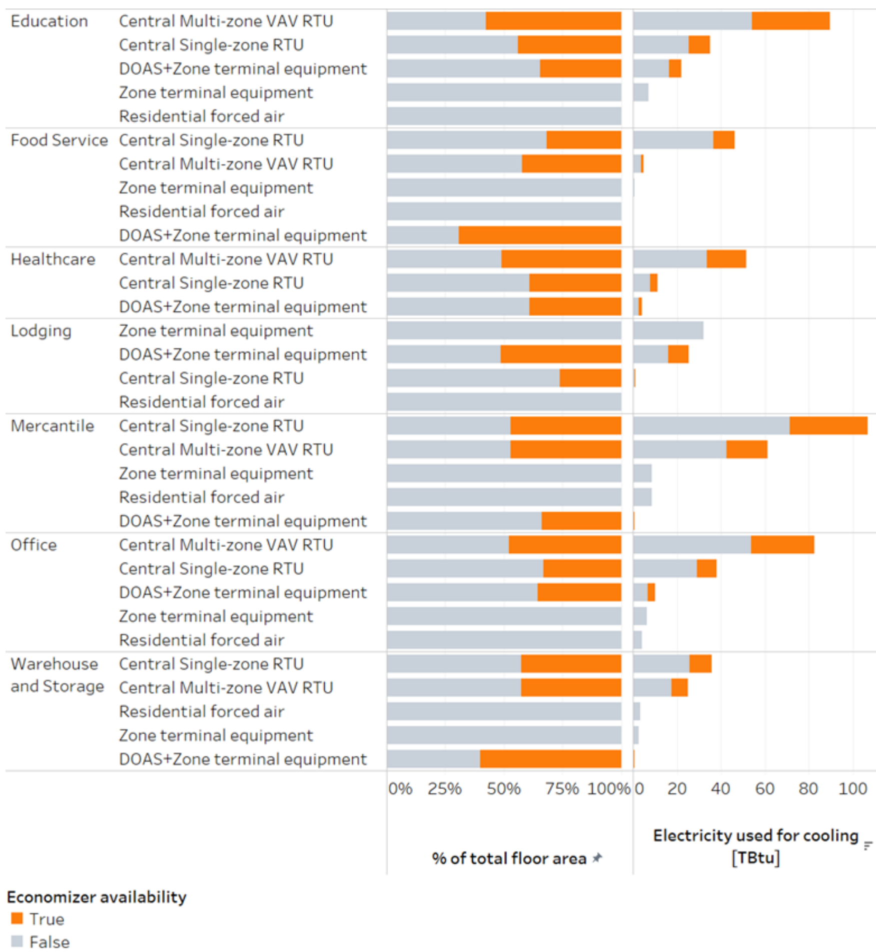

Figure 49. Presence of air-side economizers in the building stock.

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Table 27. Economizer limits from MASControl3

Climate Zone	Drybulb Limit (°F)	Enthalpy Limit (Btu/lb)
CZ01	70	28
CZ02	73	28
CZ03	70	28
CZ04	73	28
CZ05	70	28
CZ06	71	28
CZ07	69	28
CZ08	71	28
CZ09	71	28
CZ10	73	28
CZ11	75	28
CZ12	75	28
CZ13	75	28
CZ14	75	28
CZ15	75	28
CZ16	75	28

Table 28. Economizer applicability from MASControl3

Vintage	Packaged DX	Chilled Water	Water Loop HP
1975	FALSE	TRUE	FALSE
1985	FALSE	TRUE	FALSE
1996	FALSE	TRUE	FALSE
2003	FALSE	TRUE	FALSE
2007	FALSE	TRUE	FALSE
2011	FALSE	TRUE	FALSE
2014	TRUE	TRUE	TRUE
2015	TRUE	TRUE	TRUE
2017	TRUE	TRUE	TRUE
2020	TRUE	TRUE	TRUE

Figure 50 shows the comparison of economizer coverage with respect to building floor area between ComStock and estimation from Commercial Buildings Energy Consumption Survey (EIA). Because of how data is structured in CBECS, the floor area shown in these figures represents the entire floor area of the building if any economizer is present in any of the HVAC systems in the building rather than actual floor area covered by HVAC systems with an economizer. Because CBECS data only shows total building area instead of total area covered by the economizers, this comparison helps give a rough estimate of economizers.

Economizers are well known for frequent faulty operations. There were many efforts in the past to understand fault characteristics in commercial buildings (Kim et al.), (Crowe et al.), (Katipamula et al.), (Frank et al.). While this evidence is insufficient to reflect all aspects (e.g., prevalence, incidence, intensity, and evolution described in (Kim et al.)) of all faults in the commercial building stock across the country, it is possible to make simplifications for modeling certain fault types based on available data.

Figure 51 shows how the first fault is modeled for buildings with economizers. Crowe et al. (Crowe et al.) acquired data from AFDD venders that monitored 3,660 AHUs and 7,974 RTUs and reported 31% of all economizers were experiencing faulty operations. Shoukas et al. (Shoukas, Bianchi, and Deru) received data from a clothing retailer and food chain that monitored 1,416 RTUs and reported 60% of all faults related to economizers were related to economizer not effectively reducing cooling load compared to the theoretical potential. The symptom described as "ineffective economizing" can be due to different faults: damper stuck, damper bias, sensor bias, sensor frozen, inappropriate configuration, etc. A report (Seventhwave and Center for Energy and Environment) published by Minnesota Department of Commerce Division of Energy Resources monitored 41 RTUs in Minnesota that were installed

Figure 50. Economizer floor area coverage comparing ComStock (left) with CBECS 2018 (right).

in many different building types (e.g., office, restaurant, retail, hotel, etc.) and reported the actual changeover temperature setting in the economizer were not configured efficiently (average of 52°F) resulting in missed free cooling opportunity.

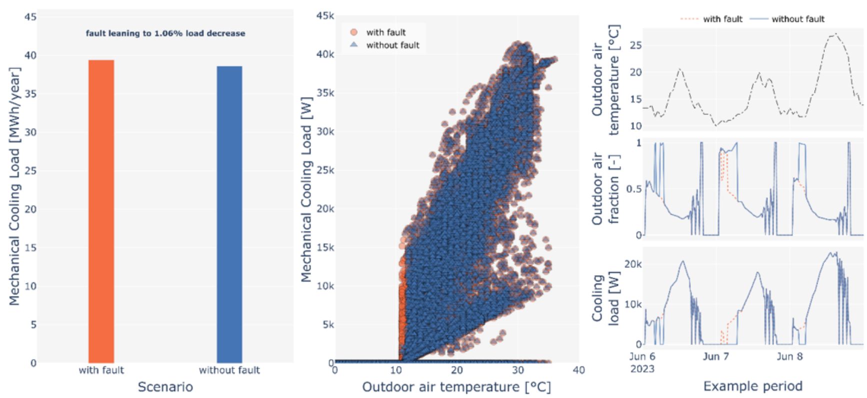
Based on this information focusing on different aspects of the fault, a fault measure was developed as shown in Figure 51. The figure includes a description of the fault as well as four different metrics that define the characteristics of a fault. Fault intensity (or severity) is when a fault can have a severity level. For example, if the sensor is drifting, the intensity is the difference between the true value and the biased measured value. Fault prevalence refers to the portion of systems or components with the fault among all systems or components in the sample space (e.g., 30% of all economizers have the fault). Fault incidence refers to the occurrence rate of a fault for a given system or component over for a given time period (e.g., economizer damper gets stuck once every year). Fault evolution refers to certain faults where the severity naturally changes over time. For example, sensor drift is typically a fault where the severity changes over the course of time. For the incorrect high limit setting described in Figure 51, the fault changes the changeover temperature setting of an economizer to 52°F and applies to 30% of economizers that use fixed dry-bulb control. Fault incidence and fault evolution were not modeled because these aspects are mostly irrelevant for this fault.

Figure 52 shows a comparison of simulated operation with and without the fault. As a result, the fault will reduce the changeover (high limit) temperature of the economizer, disabling the economizer even if the outdoor air temperature is favorable (e.g., 52-72°F), thus, losing opportunities for free cooling. The figure shows how the fault impacts the annual cooling energy, how the changepoint temperature changes with fault, and how the transient response changes.

As reported by Heinemeier (Heinemeier), contractors in California stated that 30-40% of economizers they have worked with were disabled with fully closed dampers. This is often caused by mechanical linkage issues between damper and actuator, where the economizer automatically reverts to the fully closed position as a safety measure. An economizer with a fully closed damper will not draw any fresh outdoor air, causing an air quality issue. Depending on the outdoor air condition (i.e., favorable or not favorable for economizing), it can either reduce or increase energy consumption. Figure 53 shows the description of the fault for the economizer outdoor air damper fully closed and stuck. Unlike the fault described in Figure 51, this fault has a bigger impact on air quality and energy and the incidence of the fault is important.

Evidence data		Fault Characteristic	Definition
From a survey from 20 contractors, **30-40%** of all economizers were disabled with dampers fully closed. From 3,660 AHUs, **30%** of all economizers had outdoor damper issue. And having outdoor air flow issue for **30%** of the time. From 1,416 RTUs (owned by food chain and clothing retailer), economizer damper fully closing happened between **0.2-1** times per year per economizer	translate evidence data to fault	Description	economizer outdoor air damper fully closed during faulted period
		Intensity/severity	damper fully closed
		Prevalence	35% of buildings with economizers
		Incidence	Once per year with the duration of one month
		Evolution	not relevant so not implemented

Figure 51. Economizer incorrect changeover temperature setting fault description.



(a) mechanical cooling load (b) changepoint temperature (c) transient behavior

Figure 52. Economizer incorrect changeover temperature setting fault impact on simulation results.

Evidence data		Fault Characteristic	Definition
From 3,660 AHUs and 7,974 RTUs, Economizer faults occurred in **31%** of all economizers. From 1,416 RTUs (owned by food chain and clothing retailer), **60%** of economizer faults were due to not leveraging 100% colder air properly. From 41 RTUs (across office, restaurant, retail, hotel), average changepoint temperature with RTUs with economizers = **52°F**	translate evidence data to fault	Description	changeover temperature for fixed dry-bulb control incorrectly configured
		Intensity/severity	changeover temperature = 52°F
		Prevalence	30% of buildings with economizers
		Incidence	fault present whenever economizing
		Evolution	not relevant so not implemented

Figure 53. Economizer damper stuck closed fault description.

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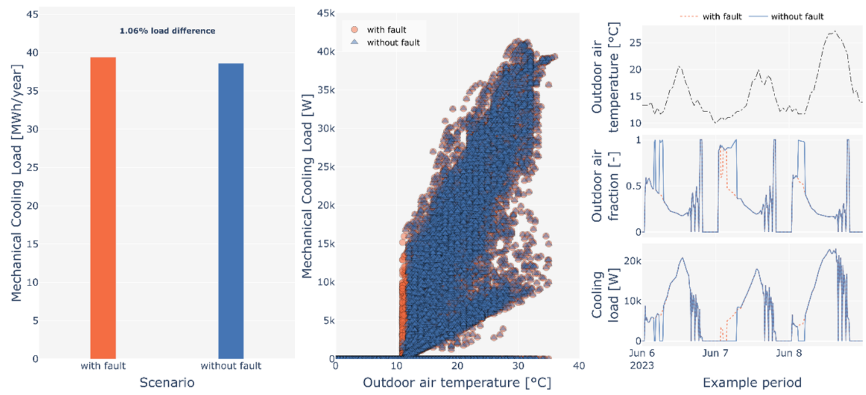

(a) mechanical cooling load (b) changepoint temperature (c) transient behavior

Figure 54. Economizer damper stuck closed fault impact on simulation results.

Figure 54 shows example simulation results for a building with and without the damper fully closed fault. The fault was imposed once during the entire April period resulting in 1.8% mechanical load increase. As mentioned previously, the energy impact of the fault can either be increased or decreased energy consumption, and Figure 54(c) highlights the transition from negative to positive savings when the outdoor air temperature transitions from favorable to unfavorable conditions.

Although faults (e.g., damper fully closed) are implemented with fixed prevalence (e.g., 35%), the actual percentage of economizers being faulted (among applicable economizers) is less than the defined prevalence due to implementation limitations. For example, 35% of randomly selected buildings that include certain HVAC system types (categorized by the air system) are assigned the damper fully closed fault. However, certain portions of these air systems do not have economizers, thus, they cannot have an economizer fault. In other words, the current limitation is that the random selection of faulted economizers is not fully aligned with buildings that actually have economizers. In these cases, we are losing the opportunity for applying faults and decreasing the representation of fault prevalence in final building stock. Newer versions of California's Title 24 energy code requires fault detection and diagnostics (FDD) for economizers which should prevent and mitigate faults. However, ComStock does not reflect the impact of FDD technology, possibly overestimating the impact of faults in buildings with newer HVAC systems in California.

4.8.12 Furnaces

Furnaces are used in a variety of HVAC equipment for space heating through the direct combustion of a fuel. For ComStock models, the fuel type can be natural gas, propane, or fuel oil. The following ComStock system types use furnaces: PSZ-AC with electric coil, PSZ-AC with gas coil, PTAC with electric coil, PTAC with gas coil, residential AC with residential forced air furnace, and residential forced air furnace.

Furnace Efficiencies

Furnaces in ComStock are all assumed to be standard, non-condensing types at this time. Rated efficiency assignments are a function of capacity and in-force HVAC template code. The furnace efficiency assignments are summarized in Table 29.

Furnace Performance Modifiers

Furnaces in ComStock do not use any performance curves, so there is no change in efficiency or capacity as a function of temperature or part load ratio, and therefore no cycling losses. Furthermore, no parasitic fuel losses are included in ComStock furnace models.

4.8.13 Boilers

Boilers create hot water for heating in buildings. The following ComStock HVAC types use boilers for heating: DOAS with fan coil air-cooled chiller with boiler, DOAS with fan coil chiller with boiler, DOAS with water source

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Table 29. Furnace Efficiency by Capacity and Code Year

Template	Minimum Capacity (Btu/hr)	Maximum Capacity (Btu/hr)	Minimum Annual Fuel Utilization Efficiency (AFUE)	Minimum Thermal Efficiency (%)	Minimum Com-bustion Efficiency (%)	Notes
Pre-1980	-	249,999	-	0.8	-	-
Pre-1980	250,000	no max	-	0.8	-	-
Pre-1980	250,000,000	no max	-	0.8	-	-
1980–2004	-	299,999	-	0.8	-	-
1980–2004	300,000	249,999,999	-	0.8	-	-
90.1-2004	-	224,999	0.78	0.8	-	Table 6.8.1E page 49
90.1-2004	225,000	249,999,999	-		0.8	
90.1-2007	-	224,999	0.78	0.8	-	
90.1-2007	225,000	249,999,999	-		0.8	
90.1-2010	-	224,999	0.78	0.8	-	
90.1-2010	225,000	249,999,999	-	0.8	-	
90.1-2013	-	224,999	0.78	0.8	-	
90.1-2013	225,000	249,999,999	-	0.8	-	
90.1-2016	-	224,999	0.78	0.8	-	
90.1-2016	225,000	249,999,999	-	0.8	-	
90.1-2019	-	224,999	-	0.81	-	Table 6.8.1-6 for >225 kBtu/hr; Table F-4 for <225 kBtu/hr
90.1-2019	225,000	249,999,999	-	0.8	-	

heat pumps cooling tower with boiler, PSZ-AC with gas boiler, PTAC with gas boiler, PVAV with gas boiler reheat, VAV air-cooled chiller with gas boiler reheat, and VAV chiller with gas boiler reheat.

Boiler Efficiencies

At this time, boiler systems in ComStock are all gas-fired (or other combustible fuels) storage tank non-condensing units. A single boiler is used to meet the hot water load for the entire building. Rated efficiency assignments are a function of the HVAC code year and boiler capacity, mirroring the requirements of ASHRAE-90.1, and are summarized in Table 30.

Boiler Part Load Efficiencies

Boiler efficiency at different part load conditions is modeled through an assigned efficiency as a function of a part load ratio (PLR) cubic curve. The output of this curve is multiplied by the full load rated efficiency, providing the effective efficiency of the boiler for each time step. The performance curve assignments for different boiler scenarios are summarized in Table 30. The curve features are shown in Table 78, and the curves are illustrated in Figure 102.

Table 30 shows the older DOE reference building templates using a constant efficiency curve for the boiler ("Boiler Constant Efficiency Curve"). Therefore, these boilers do not currently have efficiency modifications at different part load conditions. This likely underestimates cycling losses that boilers experience at lower PLRs, and may underestimate their gas usage. The 90.1 templates for 2004 through 2010 exclusively use a performance curve for boilers with no turndown controls ("Boiler With No Minimum Turndown"). This provides some efficiency loss, as PLR is reduced. For 90.1-2013 and beyond, performance curves for boilers with minimum turndowns ("Boiler With Minimum Turndown") are added for larger boiler systems. This provides a slight performance improvement compared to boilers with no minimum turndown. All three curves are illustrated in Figure 102.

Boiler Controls

ComStock boilers use 180°F hot water loops with flow that leaves the set point modulated, meaning the boiler model internally varies the flow rate so that the temperature leaving the boiler matches a set point. The delta T of the loop is 20°F.

4.8.14 Direct Expansion Cooling

Standard air-cooled direct expansion (DX) cooling is the most prevalent cooling equipment type in commercial buildings. The following ComStock HVAC system types use DX cooling: PSZ-AC with district hot water, PSZ-AC with electric coil, PSZ-AC with gas boiler, PSZ-AC with gas coil, PSZ-HP, PTAC with electric coil, PTAC with gas boiler, PTAC with gas coil, PTHP PVAV with PFP boxes, PVAV with district hot water reheat, PVAV with gas boiler reheat, PVAV with gas heat with electric reheat, residential AC with residential forced air furnace.

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Table 30. Boiler Efficiency and Performance Curve Assignment

Template	Minimum Capacity (Btu/hr)	Maximum Capacity (Btu/hr)	Minimum Annual Fuel Utilization Efficiency (AFUE)	Minimum Thermal Efficiency (%)	Minimum Com-bustion Efficiency (%)	Efficiency Function of Part Load Ratio (EFFFPLR)	Notes
Pre-1980	-	299,999		0.73		Boiler Constant Efficiency Curve	From DOE Reference Buildings
Pre-1980	300,000	no max		0.74			
Pre-1980	250,000,000	249,999,999		0.76			
1980–2004	-	299,999	0.8				From 90.1-1989
1980–2004	300,000	249,999,999			0.8		
90.1-2004	-	299,999	0.8			Boiler with No Minimum Turndown	From 90.1-2004
90.1-2004	300,000	249,999,999		0.75			
90.1-2004	250,000,000	no max			0.8		
90.1-2007	-	299,999	0.8				From 90.1-2007
90.1-2007	300,000	249,999,999		0.8			
90.1-2007	250,000,000	no max			0.82		
90.1-2010	-	299,999	0.8				From 90.1-2010
90.1-2010	300,000	249,999,999		0.8			
90.1-2010	250,000,000	no max			0.82		
90.1-2013	-	299,999	0.82				From 90.1-2013 From 90.1-2016
90.1-2013	300,000	999,999		0.8			
90.1-2013	1,000,000	249,999,999		0.8		Boiler with Minimum Turndown	
90.1-2013	250,000,000	no max			0.82		
90.1-2016	-	299,999	0.82			Boiler with No Minimum Turndown	
90.1-2016	300,000	999,999		0.8			
90.1-2016	1,000,000	249,999,999		0.8		Boiler with Minimum Turndown	
90.1-2016	250,000,000	no max			0.82		
90.1-2019	-	299,999	0.84			Boiler with No Minimum Turndown	From 90.1-2019
90.1-2019	300,000	999,999		0.8			
90.1-2019	1,000,000	249,999,999		0.8		Boiler with Minimum Turndown	
90.1-2019	250,000,000	no max			0.82		

DX Cooling Rated Performance

DX cooling systems are assigned full load and part load efficiencies based on the HVAC code template for the model and the capacity. These assignments are summarized in Table73 (unitary DX) and Table74 (PTAC). These values mirror those found in ASHRAE-90.1 (or those used in the DOE reference buildings for the pre-1980 template).

DX Cooling Performance Modifiers

The performance of DX cooling equipment changes based on operating conditions. ComStock DX cooling equipment uses five performance modifier curves to model this behavior. Energy input ratio (EIR) as a function of part load ratio (PLR) describes how the equipment efficiency varies at different load fractions, accounting for equipment cycling (Figure 103). EIR as a function of temperature describes how the equipment efficiency varies based on both the outdoor air dry bulb temperature and the wet bulb temperature of the air entering the cooling coil (Figure 106). EIR as a function of airflow describes how the equipment efficiency varies as a function of the supply airflow fraction (Figure 105). Capacity as a function of temperature describes how the equipment available capacity varies as a function of both the outdoor air dry bulb temperature and the wet bulb temperature of the air entering the cooling coil (Figure 107). Lastly, capacity as a function of airflow describes how the equipment available capacity varies as a function of the supply airflow fraction (Figure 104). The outputs of the EIR modifiers are multiplied against the nominal EIR at every time step (except for the PLR modifier, which is divided), which provides the effective EIR at each time step. Meanwhile, the outputs of the two capacity modifiers are multiplied against the nominal capacity at every time step, yielding the effective available capacity for the time step.

4.8.15 Air-Source Heat Pumps

Air-source heat pumps (ASHPs) provide electric heating using a reverse vapor compression cycle. This generally provides a higher COP option for electric heating compared to standard electric resistance electric heating. In most cases, ASHPs use the same air-cooled DX system for both DX heating and DX cooling. ASHPs can be split system, packaged units, or through-the-wall packaged terminal heat pumps (PTHP). The following ComStock HVAC systems types use ASHPs: packaged single zone heat pump (PSZ-HP) and PTHP.

ASHP sizing is often based on the design cooling requirements. Because the DX cooling and heating use the same compressor system, the capacities for each are coupled. ASHPs generally have a minimum operating temperature, below which the DX heating is disabled due to lack of capacity and efficiency. To remedy this, backup heating is often included in colder climates, and for any system where the design heating load is higher than the design cooling load. ComStock ASHP sizing follows this methodology: ASHPs are sized to meet the design cooling load, and backup electric heating is added to the system to meet the design heating load when the available DX heating capacity is unavailable or insufficient. The minimum temperature for compressor operation for ComStock heat pump systems is 17°F PTHP and 10°F for PSZ-HP.

Table 31. Air-Source Heat Pump Efficiency and Performance Curve Assignment

Template	Cooling Type	Subcategory	Minimum Capacity (Btu/hr)	Maximum Capacity (Btu/hr)	HSPF	Min COP	PTHP_-COP_-Coefficient_1	PTHP_-COP_-Coefficient_2
Pre-1980 Through 1980–2004	AirCooled, Through-Wall	Split System	0	64,999	6.8			
	AirCooled	Single Package	0	64,999	6.6			
	AirCooled	Single Package	65,000	134,999		3.2		
	AirCooled	Single Package	135,000	no max		3.1		
	AirCooled	PTHP	0	no max			2.9	0.026
90.1-2004	AirCooled, Through-Wall	Split System	0	64,999	6.8			
	AirCooled, Through-Wall	Single Package	0	64,999	6.6			
	AirCooled	Single Package	65,000	134,999		3.2		
	AirCooled	Single Package	135,000	no max		3.1		
	AirCooled	PTHP	0	no max			3.2	0.026
90.1-2007	ThroughWall	Split System	0	29,999	7.1			
	AirCooled	Split System, Single Package	0	64,999	7.7			
	ThroughWall	Single Package	0	29,999	7			
	AirCooled	Single Package	65,000	134,999		3.2		
	AirCooled	Single Package	135,000	no max		3.1		
	AirCooled	PTHP	0	no max			3.2	0.026
90.1-2010	ThroughWall	Split System, Single Package	0	29,999	7.4			
	AirCooled	Split System, Single Package	0	64,999	7.7			
	AirCooled	Single Package	65,000	134,999		3.3		
	AirCooled	Single Package	135,000	no max		3.2		
	AirCooled	PTHP	0	no max			3.2	0.026
90.1-2013	ThroughWall	Split System, Single Package	0	29,999	7.4			
	AirCooled	Split System	0	64,999	8.2			
	AirCooled	Single Package	0	64,999	8			
	AirCooled	Single Package	65,000	134,999		3.3		
	AirCooled	Single Package	135,000	no max		3.2		
	AirCooled	PTHP	0	no max			3.7	0.052
90.1-2016	ThroughWall	Split System, Single Package	0	29,999	7.4			
	AirCooled	Split System	0	64,999	8.2			
	AirCooled	Single Package	0	64,999	8			
	AirCooled	Single Package	65,000	134,999		3.3		
	AirCooled	Single Package	135,000	no max		3.2		
	AirCooled	PTHP	0	no max			3.7	0.052
90.1-2019	ThroughWall	Split System, Single Package	0	29,999	7.4			
	AirCooled	Split System	0	64,999	8.2			
	AirCooled	Single Package	0	64,999	8			
	AirCooled	Single Package	65,000	134,999		3.3		
	AirCooled	Single Package	135,000	no max		3.2		
	AirCooled	PTHP	0	6,999		3.3		
	AirCooled	PTHP	6,999	14,999			3.7	0.052
	AirCooled	PTHP	14,999	no max		2.9		

ASHP Rated Performance

ASHPs in ComStock are assigned efficiencies based on ASHRAE-90.1. The assigned efficiencies are based on the template code year, the unit capacity, and the unit type. These assignments are summarized in Table 31.

Table 32. Air-Cooled Chiller Efficiency and Performance Curve Assignment

Model Template	Minimum Capacity (Tons)	Maximum Capacity (Tons)	Minimum Full Load Efficiency (kW/ton)	Minimum Integrated Part Load Value (kW/ton)	Capacity Function of Temperature (Schedule Name)	EIR Function of Temperature (Schedule Name)	EIR Function of PLR (Schedule Name)	Notes
Pre-1980	0	149.99	1.303	-	ChlrAir_RecipQRatio_fTchwsToadbSI	ChlrAir_RecipEIRRatio_fTchwsToadbSI	ChlrAir_RecipEIRRatio_fQRatio	From 90.1-1989
Pre-1980	150	299.99	1.332	-				From DOE Reference Buildings
Pre-1980	300	no max	1.332	-				
1980-2004	150	no max	1.407	1.407				
90.1-2004	0	no max	1.256	1.153	AirCooled_Chiller_2010_PathA_CAPFT	AirCooled_Chiller_2010_PathA_EIRFT	AirCooled_Chiller_AllCapacities_2004_2010_EIRFPLR	From 90.1-2004 Table 6.8.1A
90.1-2007	0	no max	1.29	1.164				
90.1-2010	0	149.99	1.255	0.941				
90.1-2010	150	no max	1.255	0.941				
90.1-2013	0	149.99	1.25	0.96	ChlrAir_ScrollQRatio_fTchwsToadbSI	ChlrAir_ScrollEIRRatio_fTchwsToadbSI	ChlrAir_ScrollEIRRatio_fQRatio	Path A Efficiencies
90.1-2013	150	no max	1.25	0.94				
90.1-2013	0	149.99	1.188	0.876				
90.1-2013	150	no max	1.188	0.857				
90.1-2016	0	149.99	1.188	0.876				
90.1-2016	150	no max	1.188	0.857				
90.1-2019	0	149.99	1.188	0.876				
90.1-2019	150	no max	1.188	0.857				

ASHP Performance Modifiers

Similar to DX cooling equipment, the performance of ASHP equipment changes based on different operating conditions. The curve assignments are shown in Table 79. ComStock ASHP equipment uses five performance modifier curves to model this behavior. Energy input ratio (EIR) as a function of part load ratio (PLR) describes how the equipment efficiency varies at different load fractions, where the nominal EIR is divided by the output of this curve to account for equipment cycling losses (Figure 109). EIR as a function of temperature describes how the equipment efficiency varies based on outdoor air dry bulb temperature (Figure 108). Figure 108 illustrates the capacity loss of ASHPs at lower outdoor air temperatures. EIR as a function of airflow describes how the equipment efficiency varies as a function of the supply airflow fraction (Figure 110). Capacity as a function of temperature describes how the equipment available capacity varies as a function of outdoor air dry bulb temperature (Figure 112). Lastly, capacity as a function of airflow describes how the equipment EIR ratio varies as a function of the supply airflow fraction (Figure 112). The outputs of the EIR modifiers are multiplied against the nominal EIR at every time step (except for the PLR curve output, which is divided), which provides the effective EIR at each time step. Meanwhile, the outputs of the two capacity modifiers are multiplied against the nominal capacity at every time step, yielding the effective available capacity for the time step. The curves described here are primarily derived from the DOE prototype/reference building models.

4.8.16 Air-Cooled Chillers

Air-cooled chillers (ACCs) provide chilled water for building cooling systems and use an air-cooled condenser for heat rejection. Therefore, no condenser water loop is required for ACCs. The following ComStock HVAC types use ACCs: DOAS with fan coil air-cooled chiller with boiler, VAV air-cooled chiller with PFP boxes, VAV air-cooled chiller with district hot water reheat, and VAV air-cooled chiller with gas boiler reheat.

Air-Cooled Chiller Rated Performance

ACCs are assigned full load and part load efficiencies based on the HVAC code template for the model and the capacity. These assignments are summarized in Table 32. These values mirror those found in ASHRAE-90.1 (or those used in the DOE reference buildings for the pre-1980 template).

Air-Cooled Chiller Performance Modifiers

ACCs vary in capacity and efficiency under different operating conditions. ComStock uses three curve types to model the variation in performance: capacity as a function of temperature (CAPFT) modifier, EIR as a function of temperature (EIRFT) modifier, and EIR as a function of part load ratio (EIRFPLR) modifier. For each time step, the EIR modifier function outputs are multiplied by the ACC's rated EIR (except for the PLR curve output, which is divided). This provides the realized EIR for the time step. Similarly, the CAPFT modifier function output is

Table 33. Water-Cooled Chiller Efficiency and Performance Curve Assignment

Model Template	Compressor Type	Minimum Capacity (Tons)	Maximum Capacity (Tons)	Minimum Full Load Efficiency (kW/ton)	Minimum Integrated Part Load Value (kW/ton)	Capacity Function of Temperature (Schedule Name)	EIR Function of Temperature (Schedule Name)	EIR Function of PLR (Schedule Name)	Notes
Pre-1980	Rotary Screw	0	149.99	0.852	-	ChlrWtr-PosDispPath-AAll-QRatio-fTchws-TcwsSI	ChlrWtr-PosDispPath-AAll-EIRRatio_fTchw-sTcwsSI	ChlrWtr-PosDispPath-AAll-EIRRatio_fQRatio	From DOE Reference Buildings
Pre-1980		150	299.99	0.782	-				
Pre-1980		300	no max	0.688	-				
1980–2004		0	149.99	0.926	0.902				From 90.1-1989
1980–2004		150	299.99	0.837	0.782				
1980–2004		300	no max	0.676	0.664				
90.1-2004		0	149.99	0.79	0.676				Path A Efficiencies
90.1-2004		150	299.99	0.718	0.628				
90.1-2004		300	no max	0.639	0.572				
90.1-2007		0	74.99	0.78	0.63	WaterCooled_PositiveDisplacement_Chiller_LT150_2010_PathA_CAPFT	WaterCooled_PositiveDisplacement_Chiller_LT150_2010_PathA_EIRFT		Path A Minimum Efficiencies
90.1-2007		75	149.99	0.775	0.615				
90.1-2007		150	299.99	0.68	0.58				
90.1-2007		300	no max	0.62	0.54				
90.1-2010		0	74.99	0.78	0.63				
90.1-2010		75	149.99	0.775	0.615				
90.1-2010		150	299.99	0.68	0.58				
90.1-2010		300	no max	0.62	0.54				
90.1-2013		0	74.99	0.75	0.6	ChlrWtr-PosDisp-PathAAll-QRatio-fTchws-TcwsSI	ChlrWtr-PosDisp-PathAAll-EIRRatio-fTchws-TcwsSI		Path A Efficiencies
90.1-2013		75	149.99	0.72	0.56				
90.1-2013		150	299.99	0.66	0.54				
90.1-2013		300	599.99	0.61	0.52				
90.1-2013		600	no max	0.56	0.5				
90.1-2016		0	74.99	0.75	0.6				
90.1-2016		75	149.99	0.72	0.56				
90.1-2016		150	299.99	0.66	0.54				
90.1-2016		300	599.99	0.61	0.52				
90.1-2016		600	no max	0.56	0.5				
90.1-2019		0	74.99	0.75	0.6				
90.1-2019		75	149.99	0.72	0.56				
90.1-2019		150	299.99	0.66	0.54				
90.1-2019		300	599.99	0.61	0.52				
90.1-2019		600	no max	0.56	0.5				

multiplied by the ACC's nominal capacity every time step to get the actual available capacity for that time step. The curve assignments are summarized in Table 32, and the curve parameters are specified in Table 80. The curves are also illustrated in Figure 113, Figure 114, and Figure 115.

4.8.17 Water-Cooled Chillers

Water-cooled chillers (WCCs) provide chilled water for building cooling systems and use a water-cooled condenser for heat rejection. Therefore, a condenser water loop is required for WCCs, generally conditioned by a boiler and cooling tower. The following ComStock HVAC types use WCCs: DOAS with fan coil chiller with baseboard electric, DOAS with fan coil chiller with boiler, DOAS with fan coil chiller with district hot water, VAV chiller with PFP boxes, VAV chiller with district hot water reheat, and VAV chiller with gas boiler reheat.

Water-Cooled Chiller Rated Performance

WCCs are assigned full load and part load efficiencies based on the HVAC code template for the model and the capacity. These assignments are summarized in Table 33. These values mirror those found in ASHRAE-90.1 (or those used in the DOE reference buildings for the pre-1980 template).

Water-Cooled Chiller Performance Modifiers

WCCs have been shown to vary capacity and efficiency at different operating conditions. ComStock uses three curve types to model the variation in performance: capacity as a function of temperature (CAPFT) modifier, EIR as a function of temperature (EIRFT) modifier, and EIR as a function of part load ratio (EIRFPLR) modifier. For each time step, the EIR modifier function outputs are multiplied by the WCC's rated EIR (except for the PLR curve output, which is divided). This provides the realized EIR for the time step. Similarly, the CAPFT modifier function output is multiplied by the WCC's nominal capacity every time step to get the actual available capacity for that time

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Table 34. Cooling Tower Efficiency

Model Template	Equipment Type	Fan Type	Fan Type	Minimum Air Flow Rate Ratio	Design Inlet Wet Bulb Temperature (°F)	Design Entering Water Temperature (°F)	Design Leaving Water Temperature (°F)	Minimum Performance (gpm/hp)	Notes
Pre-1980	Open Cooling Tower	Propeller or Axial	VFD	0.2	76	95	85	38.2	From 90.1-2004 Table 6.8.1G
1980–2004									From 90.1-2004 Table 6.8.1G
90.1-2004									From 90.1-2004 Table 6.8.1G
90.1-2007									From 90.1-2007 Table 6.8.1G
90.1-2010									From 90.1-2010 Table 6.8.1 G
90.1-2013								40.2	From 90.1-2013 Table 6.8.1-7
90.1-2016									From 90.1-2016 Table 6.8.1-7
90.1-2019									From 90.1-2019 Table 6.8.1-7

step. The curve assignments are summarized in Table33, and the coefficients are shown in Table 81. Furthermore, the performance curves are illustrated in Figure 116 (EIRFPLR for all chillers), Figure117, and Figure115.

4.8.18 Cooling Towers

Cooling towers are an HVAC component used to reject heat from a condenser water loop. The following ComStock HVAC system types use cooling towers: DOAS with fan coil chiller with baseboard electric, DOAS with fan coil chiller with boiler, DOAS with fan coil chiller with district hot water, DOAS with water source heat pumps cooling tower with boiler, VAV chiller with PFP boxes, VAV chiller with district hot water reheat, and VAV chiller with gas boiler reheat.

The cooling tower assumptions used in ComStock are primarily code-driven and are summarized in Table 34.

4.8.19 Water-Source Heat Pumps

Water-source heat pumps (WSHPs) are an HVAC system type that uses water-to-air heat pumps for space conditioning. These differ from ASHPs in that the condenser side of the heat pumps use water from a condenser water loop as the heat source/sink instead of air. The following ComStock HVAC system type(s) use WSHPs: DOAS with water source heat pumps cooling tower with boiler.

4.8.20 Ground-Source Heat Pumps

Ground-source heat pumps (GSHPs) are WSHP systems that use the ground as the heat sink for the condenser water loop. The temperature of the ground is fairly constant throughout the year, which makes the ground an effective heat sink for the refrigeration cycle. The following ComStock HVAC system type uses GSHPs: DOAS with water source heat pumps with ground source heat pump.

The GSHP model in ComStock uses the “Plant Component Temperature Source” with energy management system (EMS) controls to represent the temperature behavior of the ground condenser water loop. The EMS predicts the exit temperature of the ground loop based on the inlet temperature of the loop, where the exit temperature will directly impact the efficiency and capacity of the heat pump system. A warmer exit temperature will generally be beneficial for heating, whereas a colder exit temperature will generally be beneficial for cooling. The exit temperature in ComStock is predicted by a linear interpolation that assumes a +12°F delta temperature at the lowest expected inlet loop temperature of 30°F (42°F loop exit temperature), and a -12°F delta temperature at the highest expected inlet loop temperature of 90°F (78°F loop exit temperature), while ramping linearly in between. The relationship between the inlet loop temperature and the outlet loop temperature is illustrated in Figure 119. Note that there is no change in the loop temperature at 60°F, as this approach results in a constant ground temperature assumption of 60°F.

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4.8.21 Refrigeration

In ComStock, refrigeration systems refer to the refrigerated cases and walk-ins found in commercial kitchens, grocery stores, and other food service spaces. Small plug-in refrigerators are included in plug and process loads, as described in Section 4.6. Refrigeration is modeled in building types where it is a major end use (primary and secondary schools, restaurants, hotels, hospitals, and grocery stores).

Walk-ins and Case Scaling

Earlier versions of ComStock used fixed-size walk-in coolers and freezers for each building kitchen zone. This has been replaced with a scaling approach: refrigeration equipment is now sized according to the floor area of the associated space type (such as kitchens, stock rooms, or grocery sales areas). Rather than applying fixed case or walk-in sizes, ComStock uses reference space types to establish a ratio of refrigerated area or case length to total floor area. For example, a reference space type might assume 20,000 ft^2 of grocery sales area with 400 ft of refrigerated cases; this ratio of case type to floor area is then scaled to the actual space type floor area in the model. This scaling approach is consistent with the best available data sources and has been validated through in-person site visits performed by NREL staff, providing confidence that modeled refrigeration capacities align with real-world practice.

Technology Level Assignment

Refrigeration systems are now characterized by probabilistic assignment of technology levels: *old*, *new*, and *advanced*. These levels represent distributions of baseline efficiency as a function of both building vintage and building size. Technology levels influence compressor efficiency, case lighting, fan motors, and defrost cycles. This approach allows ComStock to capture variability in stock performance, from legacy systems to modern ENERGY STAR®-like equipment (DOE; EPA).

The assignment of technology levels draws from three TSVs:

- *include_refrigeration_technology_level.tsv* flags buildings with refrigeration.
- *year_bin_of_last_refrigeration_replacement.tsv* assigns the year range of the last major equipment replacement, based on survival curves (see Section 4.1.6).
- *refrigeration_technology_level.tsv* probabilistically assigns equipment efficiency distributions based on year built, replacement year, and building size.

Figure 55 illustrates the resulting distribution of refrigeration technology levels by building size and year of last replacement.

Efficiency Distributions

Efficiency distributions for refrigeration equipment are derived from DOE Technical Support Documents, ENERGY STAR® archives, ASHRAE research, and utility/laboratory studies (DOE; Fricke and Becker; CEC). Historical data show a clear trend of improvement:

- Pre-1990 equipment had very high energy intensities (e.g., 0.3–0.4 kWh/ft^3/day for reach-in refrigerators, 2.5–3.0 kWh/ft/day for open vertical cases).
- 1990s equipment introduced modest improvements (better insulation, new refrigerants), but performance was still poor by modern standards.
- Early 2000s saw the introduction of ENERGY STAR® criteria and California Title 20 standards, driving significant efficiency gains in reach-ins, freezers, and merchandisers.
- By the late 2000s, most new commercial refrigeration equipment met or exceeded federal standards, with widespread adoption of LED case lighting, ECM fan motors, anti-sweat heater controls, and night covers.

These historical shipment distributions were mapped to *old*, *new*, and *advanced* efficiency levels using Oak Ridge National Laboratory (ORNL) performance data embedded in OpenStudio Standards. In practice, ComStock samples from these distributions to assign performance characteristics to each refrigeration system. Approximate efficiency values by technology level are summarized in Table 35. This ensures the resulting stock reflects both legacy equipment and the adoption of modern efficiency measures over time.

Table 35. Approximate efficiency levels for refrigeration equipment categories (illustrative ranges).

Equipment Category	Old (Legacy / Pre-Standard)	New (Standard-Era Baseline)	Advanced (High Efficiency / ENERGY STAR)
Reach-in Refrigerators (solid/-glass door)	0.30–0.40 $kWh/ft^3/day$	0.20–0.30 $kWh/ft^3/day$	0.15–0.20 $kWh/ft^3/day$
Reach-in Freezers	0.50–0.60 $kWh/ft^3/day$	0.40–0.50 $kWh/ft^3/day$	0.30–0.40 $kWh/ft^3/day$
Vertical Open Display Cases (medium-temp)	2.3–3.0 kWh/ft/day	1.8–2.3 kWh/ft/day	1.2–1.6 kWh/ft/day
Horizontal/Coffin Freezers (low-temp)	2.0–2.5 kWh/ft/day	1.5–2.0 kWh/ft/day	1.0–1.4 kWh/ft/day
Walk-in Coolers (8×8 typical)	0.07–0.09 $kWh/ft^3/day$	0.05–0.07 $kWh/ft^3/day$	0.03–0.05 $kWh/ft^3/day$
Walk-in Freezers (8×8 typical)	0.14–0.18 $kWh/ft^3/day$	0.11–0.14 $kWh/ft^3/day$	0.08–0.11 $kWh/ft^3/day$

Values represent typical daily energy use intensities under standard test conditions, used to define the "Old," "New," and "Advanced" technology levels applied in ComStock. Ranges are derived from DOE Technical Support Documents, ENERGY STAR® criteria, and ASHRAE/utility research studies, and mapped to OpenStudio Standards performance data.

System Types and Controls

Refrigeration configurations also vary by building type and size. Large grocery stores almost universally use centralized compressor rack systems serving dozens of cases and walk-ins, while small-format stores rely on self-contained units (EIA). Efficiency technologies such as floating head pressure control, variable-speed compressors, adaptive defrost, and LED case lighting are incorporated in proportion to their historical and present-day adoption levels. For example:

- Floating head pressure control was common by the late 1990s and is standard in modern racks.
- Variable-speed compressors and VFD-controlled condenser fans are now standard in new systems.
- Adaptive defrost and anti-sweat heater controls are widely adopted in newer or retrofitted equipment.
- Medium-temperature case doors, once rare, are now installed in roughly half of all modern supermarkets, reflecting a major retrofit trend.

Summary

In summary, ComStock's refrigeration modeling now:

- Scales walk-in and case sizes based on space type floor area, validated against site visits and data sources;
- Applies survival-based replacement schedules to reflect realistic equipment lifetimes (Section 4.1.6);
- Assigns technology levels probabilistically, capturing distributions of baseline efficiency by vintage and size, based on DOE shipment data mapped to OpenStudio Standards performance levels;
- Incorporates adoption of modern refrigeration efficiency measures and retrofit trends.

This methodology ensures that ComStock refrigeration energy use better reflects the diversity of U.S. commercial building stock, including both legacy equipment and advanced technologies.

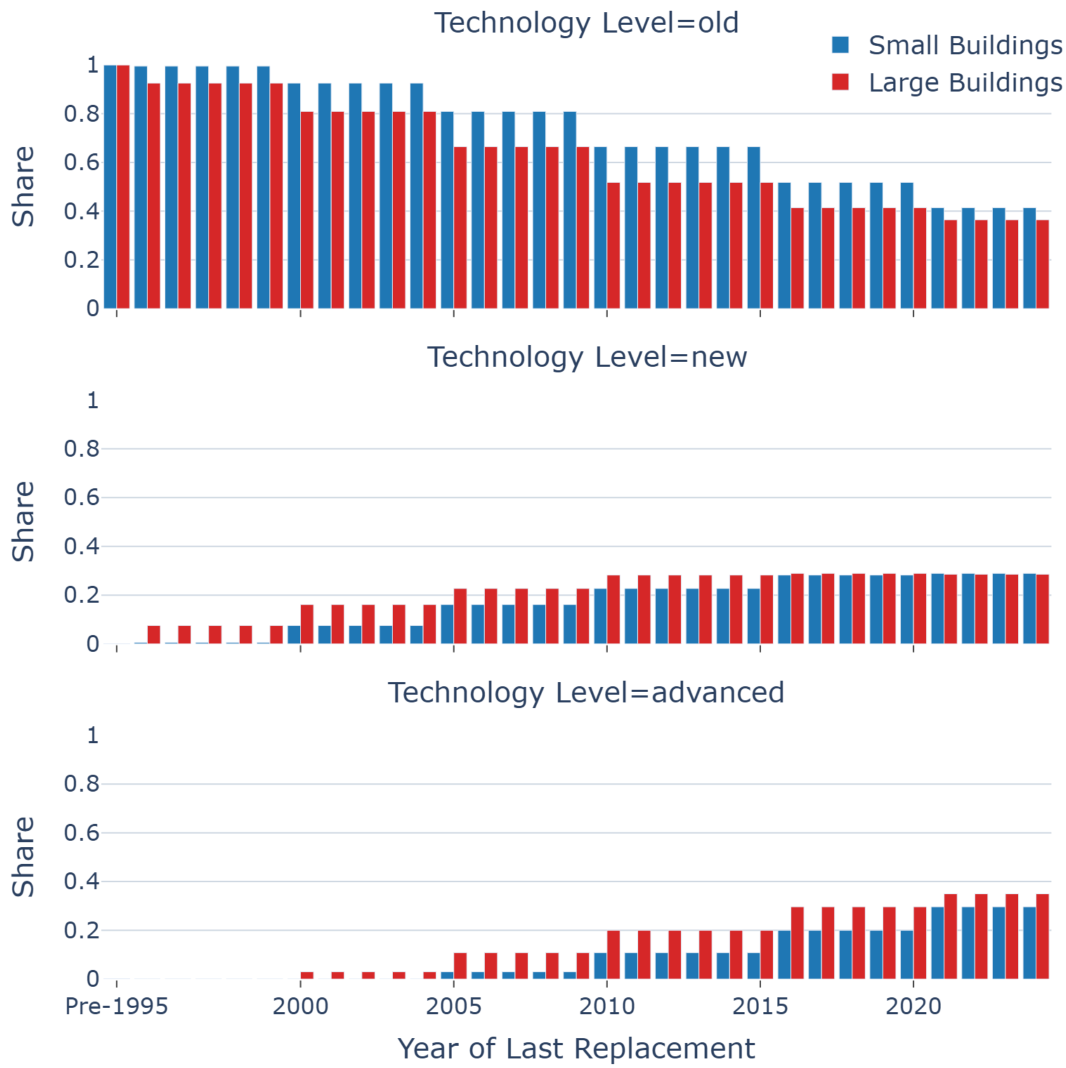

Figure 55. Distribution of refrigeration technology levels (old, new, advanced) by building size and year of last replacement. Based on DOE shipment data mapped to OpenStudio Standards performance levels.

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4.9 Simulation Settings

4.9.1 EnergyPlus Simulation Settings

The EnergyPlus simulation settings are a crucial part of any run because they set the length of the run, the calendar year, the number of time steps, and a number of other inputs. A list of all the simulation settings used in ComStock and their descriptions is shown in Table 36.

Table 36. EnergyPlus Simulation Settings

Simulation Setting	Input	Input Explanation
Number of time steps per hour used by EnergyPlus for heat transfer and load calculations	4	ComStock uses four time steps per hour for all EnergyPlus simulations, unless otherwise specified. This creates a 15-minute time step.
Enable daylight saving time	TRUE	EnergyPlus automatically interprets schedules as being in local time, and therefore shifts with daylight saving time. In the individual model output time series data, the timestamp is reported out in local time, Daylight Standard Time, and Coordinated Universal Time (UTC). In ComStock, the time series results for all buildings are all converted to Eastern Standard Time (EST) for publication. For buildings whose local time is not EST, the last few hours of the data set are moved to the beginning of the time series to ensure a full year of data.
Start of daylight saving time End of daylight saving time	Second Sunday in March First Sunday in November	Daylight saving time (DST) in the United States starts on the second Sunday in March and ends on the first Sunday in November. The current schedule was introduced in 2007 and follows the Energy Policy Act of 2005.
Calendar year of simulation	Varies	The calendar year varies based on the year intended to be simulated. The calendar year should match the year of the weather file being used for simulation.
January 1 day of week	Varies	The day of the week on January 1 for the calendar year being simulated.
Beginning month of simulation Beginning day of simulation End month of simulation End day of simulation	1 1 12 31	These four parameters specify the length of the simulation. The default is a one-year, 8,760-hour simulation, starting on January 1 and ending on December 31. If the calendar year of simulation is a leap year, the end of the simulation period will be input as December 30 instead of December 31 to ensure 8,760 hours of simulation results. In years with February 29, December 31 will not be included in the simulation. These settings can also be adjusted if only a partial year simulation is necessary.

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5 ComStock Outputs

ComStock creates a wide array of data that can be analyzed and aggregated to draw conclusions. While it is common to look at how results vary by building type and climate zone, ComStock provides a wide range of outputs not traditionally provided in large-scale analyses, with the hope of providing maximum utility.

Sections 2.6 and 2.7 describe how to access ComStock outputs. Additionally, the sample building energy models are available at https://data.openei.org/ in the nrel-pds-building-stock data lake. See the README.md file for details.

5.1 Energy Consumption by Fuel and End Use

ComStock provides energy consumption by fuel and end use at both an annual and time-series (typically 15-minute time steps for one year) resolution. Not all combinations of fuels and end uses are found in ComStock. The definitions below describe the fuels and end uses in detail.

ComStock provides modeled energy consumption for the following **fuels**:

- **Electricity**: This represents the electricity that is delivered to the building through the power grid and consumed on-site. How this electricity is generated depends on the generation mix found on the power grid in the region serving the building. This does not include electricity that is generated through a backup generator.
- **Natural Gas**: This represents the natural gas that is delivered to the building through the natural gas pipeline system and consumed on-site.
- **Propane**: This represents the propane that is delivered to the building in tanks and consumed on-site.
- **Fuel Oil**: This represents the liquid fuel oil that is delivered to the building, stored in tanks, and consumed on-site.
- **Other Fuel**: In some ComStock outputs, propane and fuel oil are combined and reported together as "other fuel" due to reporting limitations in the simulation engine. Where this is the case, propane and fuel oil are not reported separately to avoid double-counting.
- **District Heating**: This represents the hot water or steam that is delivered to the building through a district heating piping system and consumed on-site. The quantity of energy consumed represents only the energy extracted from the district heating system by the building; it does not represent the consumption of electricity or natural gas at the district heating plant required to provide heat to the building. In order to capture the energy consumption of the district heating plant, assumptions about distribution heat losses, pumping power, and district heating plant equipment efficiency and controls may be made.
- **District Cooling**: This represents the chilled water that is delivered to the building through a district cooling piping system and consumed on-site. The quantity of energy consumed represents only the energy extracted from the district cooling system by the building; it does not represent the consumption of electricity or natural gas at the district cooling plant required to provide chilled water to the building. In order to capture the energy consumption of the district cooling plant, assumptions about distribution heat gains, pumping power, and district cooling plant equipment efficiency and controls may be made.

ComStock provides modeled energy consumption for the following **end uses** for each applicable fuel:

- **Cooling**: This includes all energy consumed by primary cooling equipment such as chillers, direct expansion air conditioners (includes condenser fan energy), and direct expansion heat pumps in cooling mode (includes condenser fan energy). This also includes parasitic energy consumption of the equipment, such as pan heaters, defrost energy, and any energy needed to overcome modeled pipe losses.
- **Heating**: This represents all energy consumed by primary heating equipment such as boilers, furnaces, natural gas heating coils, electric resistance strip heating coils, and direct expansion heat pumps in heating mode

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(includes evaporator fan energy). This also includes parasitic energy consumption of the equipment, such as pilot lights, standby losses, defrost energy, and any energy needed to overcome modeled pipe losses.

- **Fans**: This includes all energy consumed by supply fans, return fans, exhaust fans, and kitchen hoods in the building. It excludes the condenser fan energy from direct expansion coils, which is captured in cooling and heating, as described above.

- **Pumps**: This includes all energy consumed by pumps for the purpose of moving hot water for heating and service water heating, chilled water for cooling, and condenser water for heat rejection.

- **Heat Recovery**: This includes the energy used to turn heat or enthalpy wheels, plus the increased fan energy associated with the increased pressure rise caused by the heat recovery wheels.

- **Heat Rejection**: This includes the energy used to run cooling towers and fluid coolers to reject heat from the condenser water loop to the air. As previously noted, condenser fans on direct expansion cooling and heating coils are included in heating and cooling.

- **Humidification**: This includes all energy used to purposely increase humidity in the building. Most buildings are assumed not to use humidification.

- **Water Systems**: This includes all energy consumed by the primary service hot water supply equipment, such as boilers and water heaters. This also includes parasitic energy consumption of the equipment, such as pilot lights, standby losses, and any energy needed to overcome modeled pipe losses.

- **Refrigeration**: This includes all energy used by large refrigeration cases and walk-ins such as those commonly found in grocery stores and large commercial kitchens. Plug-in refrigerators, such as those commonly found in the checkout areas of retail stores, are included in interior equipment.

- **Interior Lighting**: This includes all energy used to light the interior of the building, including general lighting, task lighting, accent lighting, and exit lighting.

- **Exterior Lighting**: This includes all energy used to light the exterior of the building and the surrounding area, including parking lot lighting, entryway illumination, and wall washing.

- **Interior Equipment**: This includes all energy used in the building that was not included in one of the other categories. This covers miscellaneous electric loads such as computers and monitors, large equipment such as elevators, and special-purpose equipment such as data center and IT-closet servers. This is a large and coarse bin, largely because the variety of energy-consuming devices found in buildings is large and little comprehensive data are available.

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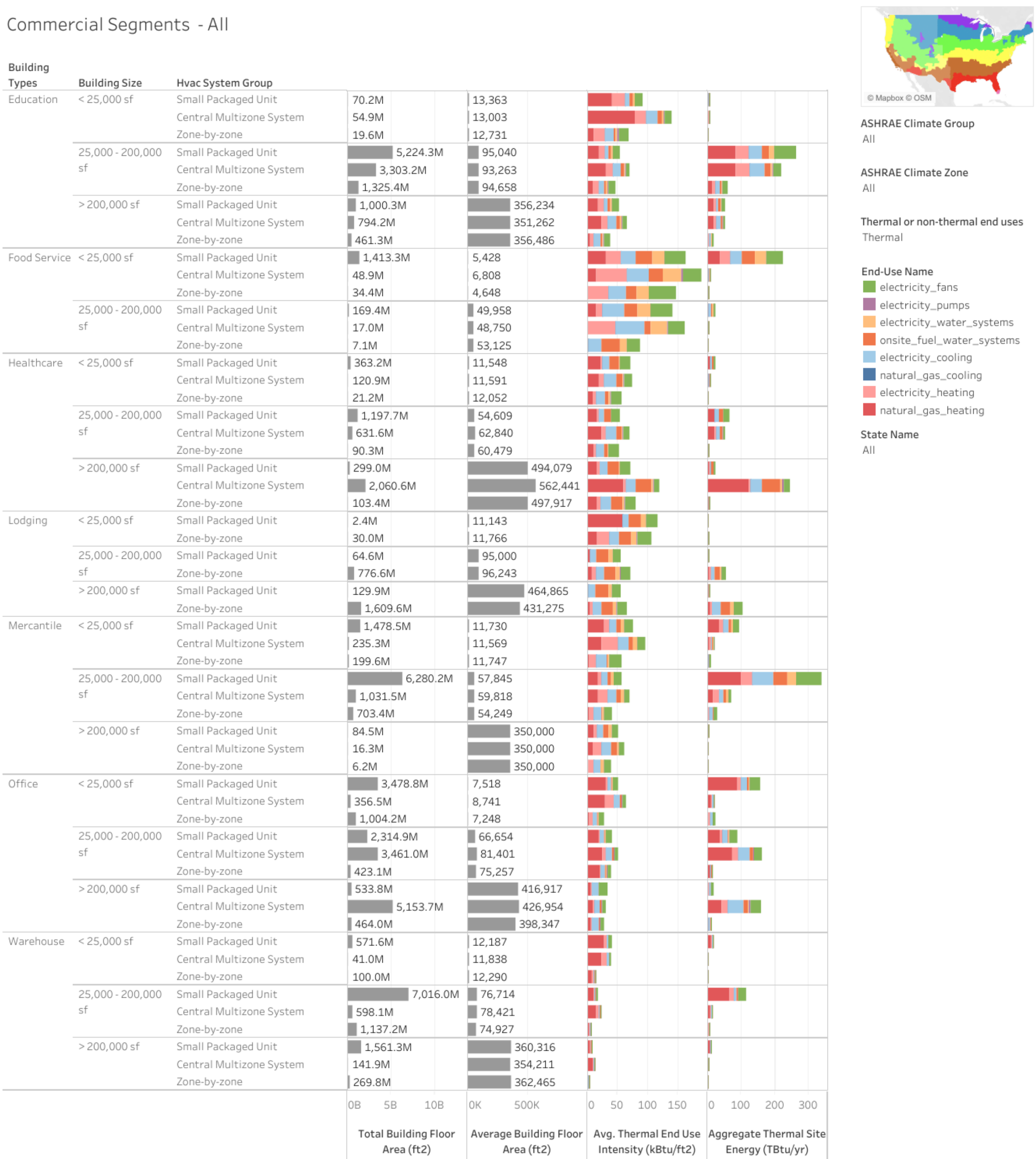

Figure 56. Example ComStock Results

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5.2 Building Characteristics

In addition to energy consumption data, ComStock outputs include a variety of building input characteristics. Most of these are either direct or indirect inputs to the building model generation workflow. Units for these characteristics are described in the files that accompany the ComStock data sets. Names and descriptions for these characteristics are included in Table 37.

Table 37. Building Input Characteristics

Building Input Characteristic	Description
in.year_built	Year of original building construction
in.building_id	ID number for model
in.upgrade_id	ID of upgrade, including 00 for baseline
in.upgrade_name	Name of upgrade (if an upgrade was run)
in.tstat_clg_delta_f	Cooling thermostat unoccupied set point temperature delta from primary occupied cooling set point. A value of 999 indicates that default values were used for the model
in.tstat_clg_sp_f	Cooling thermostat occupied set point. A value of 999 indicates that default values were used for the model
in.tstat_htg_delta_f	Heating thermostat unoccupied set point temperature delta from primary occupied heating set point. A value of 999 indicates that default values were used for the model
in.tstat_htg_sp_f	Heating thermostat occupied set point. A value of 999 indicates that default values were used for the model
in.aspect_ratio	Aspect ratio of building geometry, which is the ratio of the north/south facade length relative to the east/west facade length
in.window_type	Type of windows in the model
in.building_subtype	Building subtype of the model
in.county	County ID of the building model
in.comstock_building_type	Primary building type of the model
in.rotation	Building rotation off of north axis (positive value is clockwise)
in.number_of_stories	Building number of stories above grade
in.floor_area	Building total floor area
in.hvac_system_type	Building primary HVAC system type
in.wall_construction_type	Type of construction used for exterior walls
in.weekday_operating_hours	Building duration of weekday hours of operation, which influences the duration of schedules
in.weekday_opening_time	Building weekday start hour, which impacts the start time of schedules
in.weekend_operating_hours	Building duration of weekend hours of operation, which influences the duration of schedules
in.weekend_opening_time	Building weekend start hour, which impacts the start time of schedules
in.energy_code_followed_during_last_exterior_lighting_replacement	Specifies the energy code used to determine exterior lighting power and controls
in.energy_code_followed_during_last_hvac_replacement	Specifies the energy code used to determine HVAC system types, efficiencies, and controls
in.energy_code_followed_during_last_interior_equipment_replacement	Specifies the energy code used to determine interior equipment loads
in.energy_code_followed_during_last_roof_replacement	Specifies the energy code used to determine roof insulation values
in.energy_code_followed_during_last_service_water_heating_replacement	Specifies the energy code used to determine service water heating efficiencies
in.energy_code_followed_during_last_walls_replacement	Specifies the energy code used to determine wall insulation values

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Building Input Characteristic	Description
in.energy_code_followed_during_original_building_-construction	Specifies the date of construction of the modeled building, which impacts the assumed energy code year of building subsystems
in.heating_fuel	Building primary HVAC heating fuel source
in.hvac_night_variability	Specifies the nighttime HVAC operation used in the model, which impacts fan and ventilation behavior during unoccupied times
in.interior_lighting_generation	The technology used for interior lighting in the building
in.number_stories	Specifies the number of stories of the building
in.floor_area_category	Specifies the rentable area range of the building
in.service_water_heating_fuel	Building primary service water heating fuel source
in.nhgis_tract_gisjoin	Census tract identifier in National Historical Geographic Information System (NHGIS) format
in.nhgis_county_gisjoin	County identified in NHGIS format
in.state_name	Full name of state
in.state_abbreviation	Postal abbreviation of state
in.census_division_name	Census division name
in.census_region_name	Census region name
in.weather_file_2018	Weather file used for the 2018 AMY simulations
in.weather_file_TMY3	Weather file used for the TMY3 simulations
in.climate_zone_building_america	DOE Building America climate zone
in.climate_zone_ashrae_2006	ASHRAE Standard 169–2006
in.iso_region	Electric system independent system operator/regional transmission organization (ISO/RTO) region
in.reeds_balancing_area	Balancing area ID for the NREL Regional Energy Deployment System (ReEDS) modeling tool
in.resstock_county_id	State abbreviation and county name
in.nhgis_puma_gisjoin	Census PUMA identifier in NHGIS format
in.ejscreen_census_tract_percentile_for_people_of_color	Percentile for % people of color in building's census tract. See U.S. Environmental Protection Agency (EPA) Environmental Justice Screening and Mapping Tool (EJSCREEN) documentation for details
in.ejscreen_census_tract_percentile_for_low_income	Percentile for % low-income in building's census tract. See EPA EJSCREEN documentation for details
in.ejscreen_census_tract_percentile_for_less_than_high_-school_education	Percentile for % less than high school in building's census tract. See EPA EJSCREEN documentation for details
in.ejscreen_census_tract_percentile_for_people_in_-linguistic_isolation	Percentile for % of individuals in linguistic isolation in building's census tract. See EPA EJSCREEN documentation for details.
in.ejscreen_census_tract_percentile_percent_people_-under_5	Percentile for % under age 5 in building's census tract. See EPA EJSCREEN documentation for details
in.ejscreen_census_tract_percentile_for_people_over_64	Percentile for % over age 64 in building's census tract. See EPA EJSCREEN documentation for details
in.ejscreen_census_tract_percentile_for_demographic_-index	Percentile for demographic index in building's census tract. See EPA EJSCREEN documentation for details
in.cejst_is_disadvantaged	Whether the building's census tract is identified as a disadvantaged community in the EPA Climate and Economic Justice Screening Tool (CEJST). See CEJST documentation for more details
in.include_refrigeration_technology_level	Flags buildings that should receive a refrigeration technology level assignment (e.g., grocery stores, restaurants, hospitals with kitchens). Restricts refrigeration modeling to relevant building types.

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Building Input Characteristic	Description
in.year_bin_of_last_refrigeration_replacement	Year bin of last refrigeration system replacement. Based on building year_built, size_bin, and year_of_simulation using DOE survival curves. Larger buildings are assumed to replace more frequently.
in.refrigeration_technology_level	Assigned refrigeration technology level (old, new, or advanced). Based on include_refrigeration_technology_-level, year_bin_of_last_refrigeration_replacement, and size_bin. Derived from DOE shipment data and ORNL performance curves.

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5.3 Building Summary Statistics

In addition to the building input characteristics, ComStock outputs include a variety of summary statistic information about the building. These statistics captures building characteristics that result from the complex rules that are applied to HVAC systems after sizing routines and are therefore not easy to discern from the building input characteristics. Units for these outputs are described in the files that accompany the ComStock data sets. Names and descriptions for these summary statistics are included in Table 84

5.4 Greenhouse Gas Emissions Reporting

ComStock calculates the greenhouse gas emissions from the building stock and savings from measures using both historical and projected emissions data.

5.4.1 Electricity Emissions

eGRID Historical Emissions

Historical emissions use the CO_2-equivalent total output emission rate from EPA's Emissions and Generation Resource Integrated Database (eGRID)(EPA). ComStock results include the historical emissions for 2018, 2019, 2020, and 2021 using eGRID U.S. state and eGRID subregion emissions factors. eGRID regions are similar to Cambium grid regions but not identical. Notably, eGrid separates out New York into upstate, New York City, and Long Island. Cambium uses a whole-state average, and historical emissions use the New York state average instead of the grid region for New York buildings. Historical eGrid emissions rates are an *annual* average multiplied by the total annual electricity use.

Cambium Projected Emissions

Projected emissions use data from NREL's Cambium 2022 data set (Gagnon, Cowiestoll, and Schwarz). Projected emissions consider both the average emissions rate (AER) and the long-run marginal emission rate (LRMER). LRMER, described in Gagnon and Cole, is an estimate of the rate of emissions that would be either induced or avoided by a long-term (i.e., more than several years) change in electrical demand. LRMER data is levelized over 15 and 30 years(Gagnon, Cowiestoll, and Schwarz). ComStock results including End Use Savings Shapes round 1 results and earlier projects used emissions factors from the Cambium 2021 data (Gagnon et al.),(Gagnon, Hale, and Cole).

5.4.2 On Site Fossil Fuel Emissions

Natural gas, propane, and fuel oil emissions use the emission factors in *Table 7.1.2(1) of draft National Average Emission Factors for Household Combustion Fuels* defined in *ANSI/RESNET/ICCC 301-2022 Addendum B-2022 Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index*. Natural gas emissions include both combustion and pre-combustion emissions (e.g., methane leakage for natural gas).

On-Site Fossil Fuel Emissions Factors:
Natural gas: 147.3 lb/MMBtu (228.0 kg/MWh)
Propane: 177.8 lb/MMBtu (275.7 kg/MWh)
Fuel oil: 195.9 lb/MMBtu (303.2 kg/MWh)

5.4.3 District Energy Emissions

District heating and cooling emissions use the emissions factors defined in the August 2024 version of the *Energy Star Portfolio Manager Technical Reference* available at https://portfoliomanager.energystar.gov/pdf/reference/Emissions.pdf. The district heating emissions factor is the same for both steam and hot water. The district cooling emissions factor assumes district chilled water served by electric driver chillers. The emissions factors were originally sourced from EIA data for district chilled water and the EPA voluntary reporting program for district steam and hot water. These district emissions factors do not include upstream methane leakage. There is considerable variation by location and type of district system, so you may need to scale the results by factors specific to your region or system.

On-Site Fossil Fuel Emissions Factors:

District Cooling: 52.70 kg/MMBtu
District Heating: 66.40 kg/MMBtu

5.4.4 Air Pollution from On Site Fossil Fuel Combustion

ComStock reports annual pollution emissions for NOx, CO, PM, SO2 from on-site combustion of natural gas, propane, and fuel oil. Emission factors are from U.S. EPA *AP-42: Compilation of Air Emissions Factors from Stationary Sources*(EPA). Natural gas emissions use emissions factors from AP-42 Table 1.4-2 and particulate emissions are reported as *total* PM. Propane emissions use emissions factors from AP-42 Table 1.5-1 and particulate emissions are reported as *total* PM. Fuel oil emissions use emissions factors for No.2 fuel oil from AP-42 Table 1.3-1 and particulate emissions are reported as *filterable* PM. ComStock does not report air pollution from electricity generation, because grid emissions vary considerably by grid region and are typically located far away from the building site.

5.5 Utility Bills

ComStock estimates utility bills for several of the primary fuels consumed in buildings. Although the rest of ComStock represents the building stock circa 2018, the utility bill estimates reflect utility rates circa 2022, which was the most recent year of data available from EIA at the time of implementation. We made this choice because most users of the data were assumed to prefer bills that most closely reflect the present for decision making.

5.5.1 Electric Bills

The primary resource for the electric utility rates is the Utility Rate Database (URDB) (Ong and McKeel). This database contains machine-readable descriptions of electric rate structures which have been compiled by manually processing utility rate documentation published by utilities.

Rate Selection

URDB contains electric rates that span all sectors (residential, commercial, industrial, etc.), so we limited the rates to those applicable to commercial buildings. First, we filtered down to rates identified as serving the commercial sector and not supplied at transmission voltage. Second, we processed the utility rate names to eliminate rates serving non-building loads based on certain keywords. The list of keywords included Agriculture, Irrigation, Farming, Pump, Snow, Vehicle, Oil, Cotton Gin, Outdoor Light, Security Light, Street, Wholesale, Recreation, Heating (typically found in names of heating-only rates), Substation, and Electric Motor Standby. We downloaded the detailed rate structure data in JSON format for the selected 13,923 rates.

Next, we fed each utility rate and an 8,760-hour electric consumption profile from a Small Hotel building energy model to NREL PySAM (NREL) to calculate an annual electric bill. We eliminated rates with an annual average blended price below \$0.01/kWh. Upon reading the names and comments included with these rates, we found that they were mostly fixed rates for individual pieces of equipment such as cable or internet infrastructure that are not metered. We also eliminated rates with an annual average blended price above \$0.45/kWh, except in the case of AK or HI, which legitimately have high rates. Some of the high rates appeared to be data entry errors. We also removed rates where PySam could not calculate an annual bill based on the rate data. Overall, this process resulted in 10,623 remaining rates spread across 2,658 utilities. 90% of the utilities have 8 or fewer rates. The remainder have more rates, with the most (200) belonging to Southern California Edison. These rates cover 85% of the buildings and 85% of the floor area in ComStock. Rates are stored in machine-readable JSON format and organized by EIA Utility Identifier.

A distribution of blended rates calculated using URDB was compared to a distribution of the blended rates calculated using data from EIA (EIA). The median blended price in the URDB rates was about \$0.08/kWh, while the median blended price reported to EIA in 2022 was \$0.12/kWh, which is about 50% higher than URDB. An analysis of the start date fields for the rates selected from URDB showed a median start date of 2013, which is more than ten years old at the time of writing.

In order to understand the change in rates between 2013 and 2022, a pairwise analysis of the utilities reporting to EIA (EIA) in both years was performed, and a state-wide average annual change was calculated. The median

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increase was 1-3% per year. Thus in many cases the rates have increased by (2%/yr * (2022-2013)) = 18% or more between 2013 and 2022.

Electric Utility Assignment

To assign an electric rate to a building in ComStock, we need to know which electric utility serves it. We joined the U.S. DOE Electric Utility Companies and Rates Look-up by Zipcode (Huggins) with the U.S. HUD USPS ZIP Code Crosswalk Files (HUD PD&R) to create a mapping between census tracts and utilities. This was done using both 2010 and 2020 census tracts, because ComStock uses a mix of both. As previously described, rates are assigned to 85% of the buildings in ComStock, and cover 85% of the weighted floor area. There are approximately 37,734 ZIP Codes in the United States. The dataset does not have an electric utility assignment for 738 of these ZIP Codes, which are spread across many states. There are 3,946 census tracts covered by these ZIP Codes which therefore do not have an electric utility assigned. Manually filling these missing mappings could be done in future work.

Bill Calculation

At runtime, an 8,670-hour electric load profile is extracted from the building energy model. The annual min and max demand (kW) and annual energy consumption (kWh) are calculated. The final census tract to which the simulation's results will be allocated is not known at simulation time, but the range of possible tracts is known based on the sampling region. For all possible census tracts, the electric utility EIA identifier is looked up. If rates are found for this utility, the rates are downselected based on the observed load profile any min/max demand or energy consumption qualifiers the rate may have. For example, some rates only apply to buildings with a minimum annual peak demand of 500 kW. For each of the remaining applicable rates, the annual bill is calculated using the 8,760 load profile and the PySAM utility rate calculation engine. This engine accounts for complex rate structures with demand charges, lookback periods, time-of-use rates, etc. To adjust for the lag in the rates on the URDB, the start date for rate is collected and the number of years between the start date and 2022 is calculated. The average annual price increase for the state where the building is located, which was calculated from Form EIA861 data as previously described, is looked up. The annual bill is multiplied by this increase to estimate an adjustment to current 2022 rates.

A median bill cost is calculated from the set of all costs from all applicable rates. Any bill that is lower than 25% of the median or higher than 200% of the median is eliminated to avoid extreme bills. Although uncommon, in testing these extreme bills were found to be associated with rates whose names indicate they are likely not applicable to the building. For example, a "large secondary general" rate which has a high minimum demand charge is not likely applicable to a small retail customer. This step typically only affects the mean bill for a building +/- 10%, so the other applicability criteria appear to be downselecting appropriate rates effectively. The minimum, maximum, and mean bills area reported along with the URDB rate label for the applicable rate, which can be used to locate details of the rate with the URDB API or via a URL, e.g.: "https://apps.openei.org/USURDB/rate/view/[rate_label]". If the number of applicable rates is even, a single median bill will not have a specific applicable rate (being the average of the middle two values). Thus in all cases, a 'median_low' and 'median_high' bill and applicable rate label are reported, representing the two central values in the bill results if the total number is even, or the duplicated true median value if the total number is odd. For tracts where no electric utility assigned, or for buildings where none of the stored rates for the utility are applicable, the annual bill is estimated using the 2022 EIA Form861 (EIA) average prices based on the state the building is located in. While this method does not reflect the detailed rate structures and demand charges, it is a fallback for the 15% of buildings in ComStock with no utility assigned.

After simulation, when individual results are allocated to tracts and weights computed, the applicable bills are weighted accordingly. The weighted bills are summed when the tract results area aggregated by geographies (e.g. by PUMA, County or State), and aggregate bill savings are calculated.

5.5.2 Natural Gas Bills

Natural gas bills are calculated using state-level, volumetric rates due to a lack of detailed public databases of natural gas rates. 2022 U.S. EIA Natural Gas Prices Commercial Price and U.S. EIA Heat Content of Natural Gas Delivered to Consumers (EIA) were used to create an energy price in dollars per kBtu. State-level prices range from \$0.007/kBtu in ID to \$0.048/kBtu in HI, with a mean of \$0.012/kBtu nationally.

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5.5.3 Propane and Fuel Oil Bills

Propane and fuel oil bills are calculated using volumetric rates due to a lack of detailed public databases of rates. Rates are state-level where this data is available, and use national average pricing where not. These fuels are typically delivered in batches, so in any given year the number of deliveries could vary. Minimum charges per delivery are assumed to be included in the volumetric price. 2022 U.S. EIA residential No. 2 Distillate Prices by Sales Type and U.S. EIA residential Weekly Heating Oil and Propane Prices (October March) (EIA) were downloaded, along with the EIA assumed heat content for these fuels. Residential prices were used because commercial prices are only available at the national scale. Additionally, most commercial buildings using these fuels are assumed to be smaller buildings where a residential rate is likely realistic. These data were used to create an energy price in dollars per kBtu for both fuels.

For states where state-level pricing was available, these prices are used directly. For other states, Petroleum Administration for Defense District (PADD)-average pricing was used. For states where PADD-level pricing was not available, national average pricing was used. For propane, prices ranged from $0.022/kBtu in ND to $0.052 in FL, with a mean of $0.032/kBtu nationally. For fuel oil, prices ranged from $0.027/kBtu in NE to $0.036 in DE, with a mean of $0.033/kBtu nationally. The mean national price for both fuels is roughly three times the mean national price of natural gas.

5.5.4 District Heating and District Cooling Bills

No resources with utility rates for district heating and cooling were identified. Because there are several hundred district systems across the U.S., many of which are university or healthcare campuses, gathering individual rates manually was deemed impractical. Therefore, utility bills for these fuels are not calculated.

5.6 Commercial Gap Model

The Commercial Gap Model estimates the national energy consumption by commercial buildings that are not explicitly modeled in the ComStock building stock model, as well as non-building energy use reported by utilities as part of the commercial sector. The Commercial Gap Model uses publicly available data to develop an electrical load model at hourly time scales and county-level geographic resolution.

5.6.1 Commercial Gap Model Formulation

ComStock is a highly granular, bottom-up model of the United State commercial building sector that uses advanced whole-building simulation models to estimate the annual sub-hourly energy consumption of buildings. The model derives characteristics important to the energy dynamics of buildings from a wide range of data sources, such as buildings surveys and real estate data. The scope of this data is limited, however, and as such ComStock is unable to model building typologies where the uses and energy characteristics are too variable or not sufficiently described in the available data. An estimate of the total building uses not covered in ComStock based on CBECS data shows that approximately 37% of the commercial building total annual site energy consumption is missing from the ComStock data (Figure 57).

Estimating the energy use of the buildings not covered in ComStock is important to put the ComStock data, and energy savings from building stock improvements, in context of the entire buildings sector. The Commercial Gap model attempts to fill in the missing energy by taking a data-driven, rather than bottom-up, approach to modeling building energy consumption. ComStock users could take the Commercial Gap profiles calculated from a ComStock baseline run, add them onto the profiles of a ComStock-modeled upgrade measure of interest, and see the expected result of that upgrade applied to buildings modeled in ComStock on the entire commercial sector.

The remainder of this section describes the available truth data sources and general formulation used to generate the Commercial Gap Model.

Total Balancing Authority Demand

Balancing Authorities (BAs) are entities in the United States electrical system that balance electrical supply and demand in a geographical area and manage interchange of power with other balancing authorities. They are either Regional Transmission Organizations (RTOs) or electric utilities that have also taken on balancing responsibilities.

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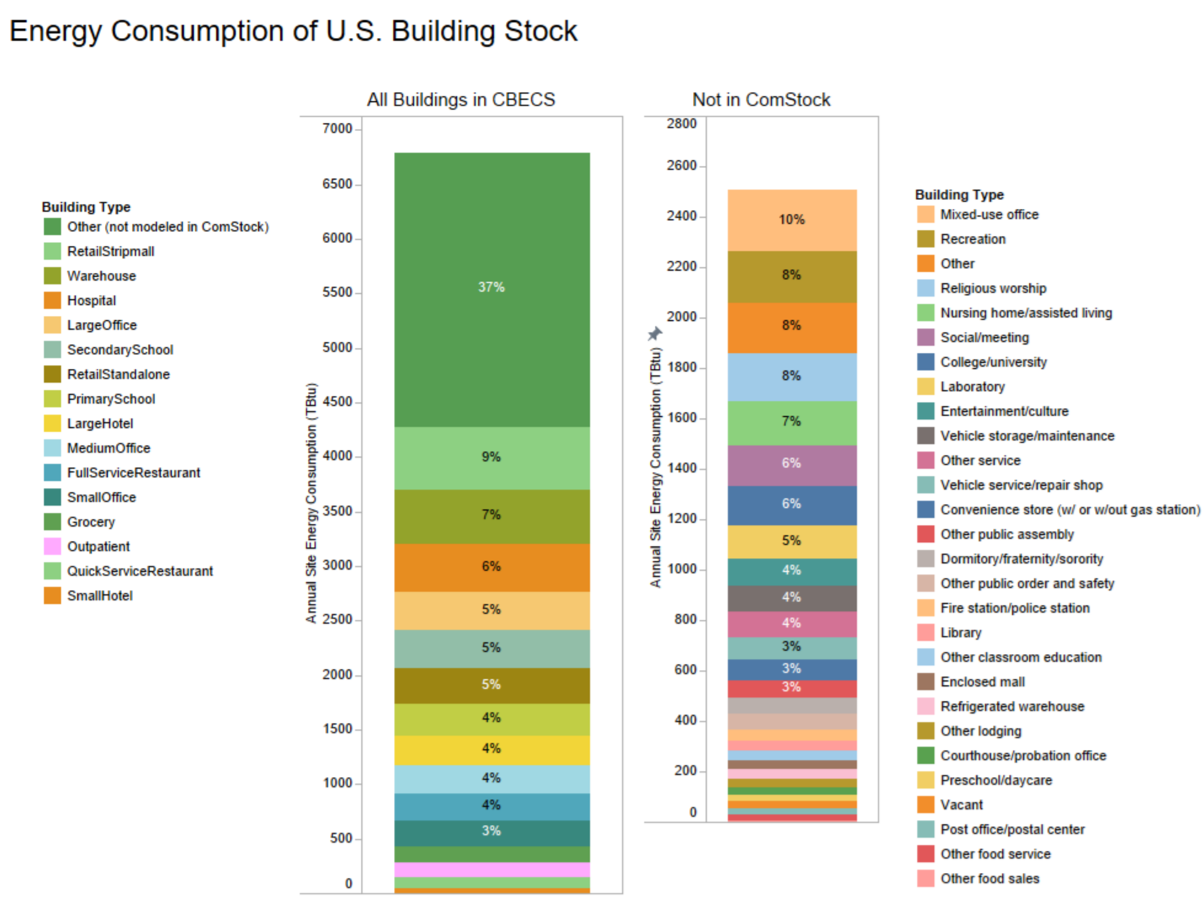

Figure 57. CBECS Principal Buildings Activity Plus building types not covered by ComStock on an energy use basis.

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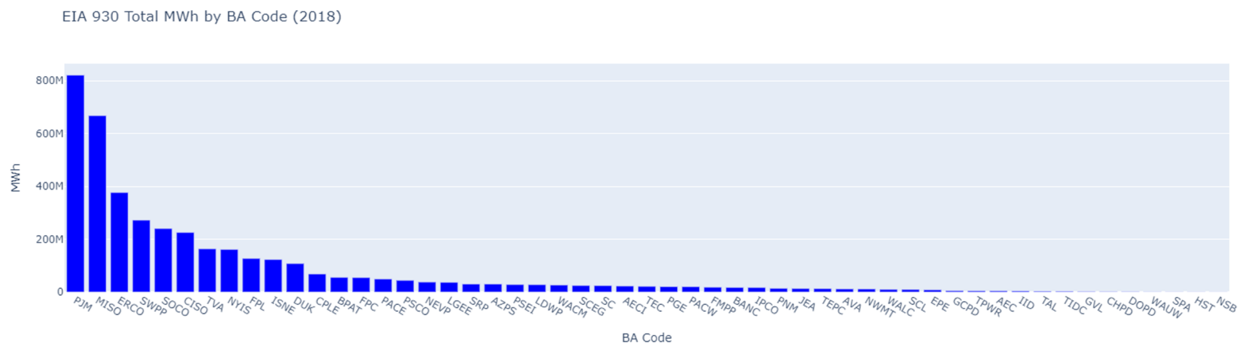

Figure 58. Total 2018 Demand by Balancing Authority

The US Energy Information Administration (EIA) collects hourly data on generation, interchange, and demand from BAs with form EIA-930 (US Energy Information Agency (EIA)). Demand values in the EIA-930 data are calculated from the difference between metered generation within the BA and net interchange between BAs, and represent the total electric load within the BA, including from all sectors, power plant consumption and transmission and distribution losses. Of the 78 total balancing authorities that report data to EIA, 53 that are active, US-based (covering the continental United States) and not generation-only were used to establish demand profiles for this analysis. The total reported megawatt hours for these BAs are shown below in Figure 58.

Annual Electric Power Industry Report

EIA collects total annual electricity sales and customer counts by major sectors (i.e., Commercial, Industrial, Residential and Transportation), state and BA from distribution utilities and power marketers of electricity using form EIA-861 (US Energy Information Agency (EIA)) and its monthly counterpart EIA-861M (US Energy Information Agency (EIA)), which are published in the Sales to Ultimate Consumers dataset. Approximately 2,300 utilities submit data for EIA-861, and an additional 1,100 small utilities report aggregate sales and customer counts at state and balancing authority levels using form EIA-861S (the short form). EIA-861 defines the ‘commercial sector’ as including non-manufacturing business establishments such as:

- Hotels
- Motels
- Restaurants
- Wholesale businesses
- Retail stores
- Health, social and educational institutions
- Public street and highway lighting
- Municipalities
- Divisions or agencies of states and federal governments under special contracts or agreements, and other utility departments, as defined by the pertinent regulatory agency and/or electric utility (US Energy Information Agency (EIA)).

Gap Model Formula

For electricity consumption, the Commercial Gap Model uses the hourly data of total electrical demand from EIA-930 for the ComStock simulation year, subtracts hourly profiles generated for the Industrial and Residential sectors to determine what the total Commercial sector load profile should be. The Commercial Gap profile is then calculated by subtracting the ComStock modeled baseline hourly profiles from the calculated Commercial sector total. Thus,

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Figure 59. Annual industrial electrical profiles for Met Ed (blue), Penelc (red), Penn Power (green), and West Penn Power (purple).

for each Balancing Authority, the Commercial Gap is calculated from the following:

$$G_C = D_T - (I + R + C) \tag{5.1}$$

where:

- G_C: Commercial Gap, hourly by BA
- D_T: hourly Total Demand by BA, from EIA-930
- I: hourly Industrial load, estimated
- R: hourly Residential load, derived from ResStock simulation
- C: hourly modeled ComStock load

Details of how the Industrial profile is estimated, the modeled ResStock results are adjusted, the ResStock and ComStock results are aggregated to the BA level, and how the BA-level Commercial Gap profiles distributed back to the county level, are described in the following sections.

5.6.2 Industrial Sector Demand Profile

According to data in form EIA-861, the Industrial sector makes up about a third of the national electricity demand, and includes uses for the purposes of manufacturing, construction, mining, agriculture (irrigation), fishing, and forestry establishments. Efforts to characterize industrial consumption to the county level are available for prior years than the ComStock simulation year (2018), but at the time of Commercial Gap model development, no national hourly industrial-sector power profiles exist.

Electric utilities conduct load research to facilitate cost-of-service and rate design, as well as demand-side management and load settlement. In many states where electric utilities are deregulated, utilities will publish expected load profiles so that suppliers can anticipate and prepare generation capacity. This load research data can take many forms, such as typical or average customer profiles by rate class, "unitized" load (i.e. hourly fraction of total annual consumption), or sector total demand. The utilities owned by First Energy Pennsylvania (Met-Ed, Penelec, Penn Power, West Penn Power), serving the majority of central Pennsylvania, publish total hourly Commercial, Industrial and Residential load profiles for their service territories. For 2018, these utilities delivered more than 22,000 GWh to over 3,000 industrial customers. Plotting the hourly load data from these utilities for the year showed very little seasonal variation, with most of the profile variation corresponding to time of day and day of week (Figure 59).

Using the First Energy PA utility profiles as a stand-in for the industrial sector nationwide, a regression model was developed that attempted to fit the average load fraction of the four utilities' demand with a model whose parameters depended only on the hour of day, day of week, and whether the day was a major holiday. For a dataset of this size, a Histogram-based Gradient Boosting Regression Tree model was used due to the advantages of faster training time, and improved fit over other regression techniques. The model achieved a coefficient of determination (R^2) of 0.85 for the First Energy PA dataset.

The model output was compared to unitized load profiles available for other utilities: AES Ohio (also known as Dayton Power & Light), which achieved an R^2 of 0.76, and the average unitized customer profile for two rate classes

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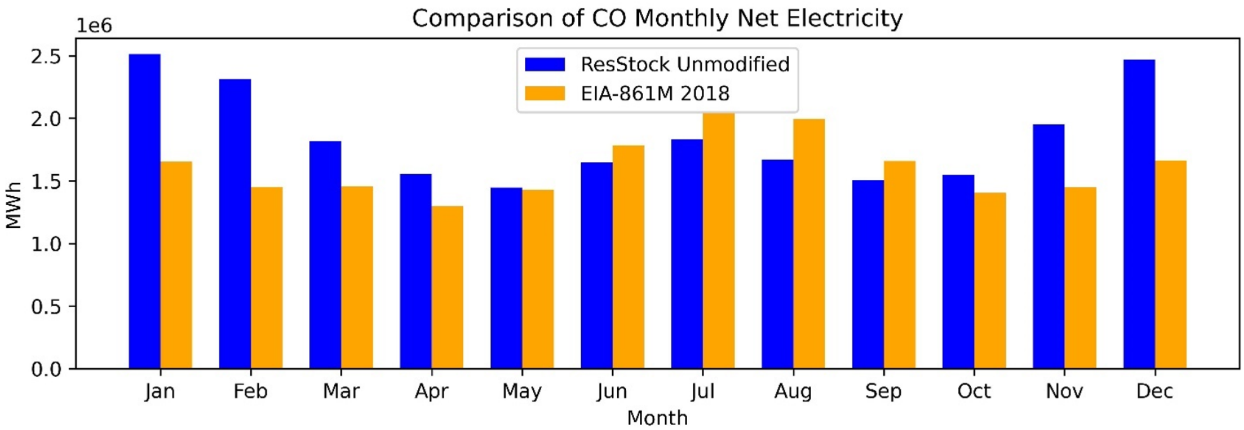

Figure 60. Original ResStock monthly total new electricity consumption for Colorado vs. EIA-861M residential sales.

from Pacific Gas & Electric – Large (>1000 kW) Primary Voltage and Large Secondary Voltage, with an R^2 of 0.62. The comparison with AES Ohio showed roughly the same magnitude of daily peak and diurnal variation in the regression model output and the load data, although the variation is greater in the PG&E data, indicating some fundamental differences in the industrial loads in California compared to Pennsylvania and Ohio. The model does capture the load drop-off during weekends and major holidays seen in the available load data.

With the regression model, estimated BA-level industrial profiles were created by multiplying the sum of Industrial sales by BA from EIA-861 by the hourly load fraction values output from the regression model. While the method of using a time-based regression model to generate the sector profile for all BAs benefits from simplicity, it does not account for differences in type of industrial loads in different parts of the country that may have different operating profiles. For example, industrial load in agriculture-heavy areas may have more seasonal and diurnal dependence, and less day-of-week dependence, than areas with more manufacturing load. Capturing these differences was deemed out of scope for this initial analysis and is a potential future refinement of the modeling approach.

5.6.3 Residential Sector Demand Profile

ResStock, the residential equivalent of ComStock, models the entire residential sector; there is no missing 'gap' as in ComStock. Therefore, obtaining BA-level residential profiles for the Commercial Gap calculation should be a simple matter of obtaining the profiles directly from ResStock results. However, comparing ResStock net electricity (excluding consumption provided from on-site generation) to total monthly sales as reported from EIA-861M shows that ResStock overestimates electricity consumption in winter months in colder states, sometimes by as much as 50% (Figure 60).

Note that while the ResStock results align exactly to the calendar months, since they are summed directly from timeseries simulation results, the reported EIA data does not necessarily algin exactly to calendar months. The utilities surveyed have different ways of aggregating when sales occur, and what is reported for a particular month may be all customers for which the billing period ends within that month. Thus, the reported consumption may be some combination consumption from that and the previous calendar months. However, the magnitude of the error seen in the winter months likely exceeds what can be attributed to the reporting difference.

The ResStock hourly results were adjusted to better match monthly electricity consumption totals reported in EIA-861M. Hourly profiles were aggregated by county and scaled using state-level residential customer counts from EIA-861 (2018) to estimate average daily demand per customer. These were compared with population-weighted temperature data to identify seasonal consumption patterns (CPC). To align the ResStock data with observed trends, temperature-sensitive relationships between demand and temperature were compared to those derived from EIA-861M data for each state. Adjustment factors were developed based on these comparisons to correct daily demand in the ResStock results, ensuring that the modeled data more closely reflected reported state-level consumption patterns. Aggregating the adjusted ResStock data to monthly totals and comparing against the EIA-861M data for 2018 shows the adjustments resulted in better alignment with reported truth data than the unmodified results (Figure 61).

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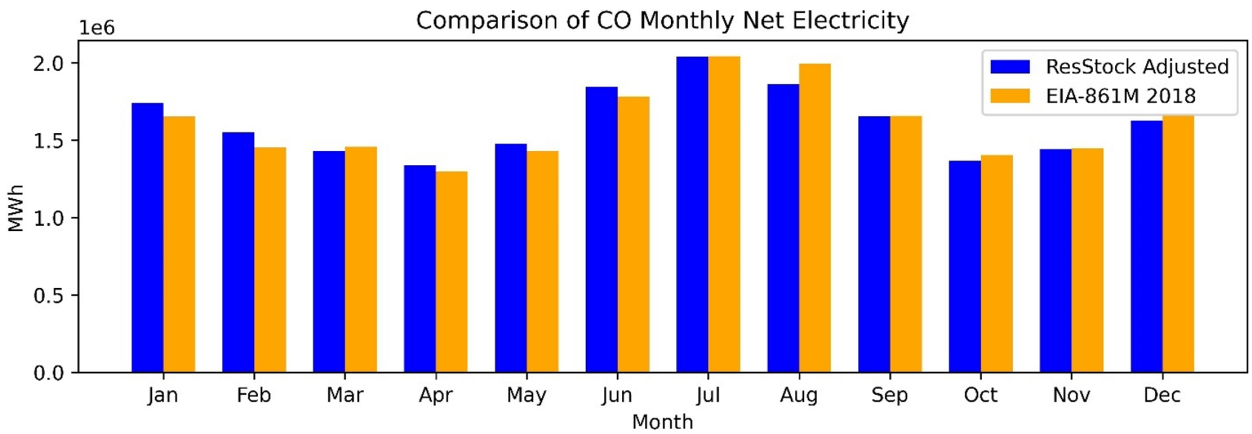

Figure 61. Modified ResStock monthly total net electricity consumption for Colorado vs EIA-861M Residential sales.

5.6.4 Geographic Apportionment

The primary Commercial Gap calculation is done at the BA level, which covers specific geographic extents that are not easily mappable to the state and sub-state geographic levels of the ComStock and ResStock data, i.e. census tracts and counties. While the Industrial profile was calculated solely at the BA level, a method was needed to apportion the ResStock and ComStock state-level profiles to BAs, and then distribute the calculated BA commercial gap down to the county level to provide maximum utility for performing analyses with ComStock. Several methods were considered to accomplish this apportionment and distribution, and ultimately the method described below was used.

EIA/CBECS Apportionment

With this apportionment method, two similar approaches were taken for aggregating state consumption to BA-level (for ResStock and ComStock) and disaggregating the Commercial Gap back down to county-level. For ResStock aggregation, EIA-861 sales data was grouped by state and BA code to determine the power sold to each BA by State. ComStock results were aggregated from tract to BA using the census tract to utility ID mapping developed for the ComStock Utility Bills measure, which derived from the U.S. Electric Utility Companies and Rates: Look-up by Zipcode data (Huggins). With the Utility ID, the BA was found from EIA-861 reporting, allowing the tract-level ComStock profiles to be summed by BA.

After the Commercial Gap BA profiles were calculated, they needed to be disaggregated down to the county level. This was done by leveraging the commercial real estate dataset used to generate the building type and size distributions for ComStock (Section 3.1.1), known as the 'StockE' data, which includes information on all commercial buildings in the country (particularly size, type, and census tract) including those not modeled in ComStock. The non-ComStock StockE building types were paired to Principal Building Activity types from CBECS, and the electrical EUI from those CBECS buildings applied to the sum of areas of the non-ComStock StockE buildings by type and census division. This provided an estimate of the total annual consumption of non-ComStock buildings found in the StockE data. The utility ID could then be joined to the StockE data by census tract, and the estimated consumption summed by BA and county, and the county proportion of the BA Commercial Gap profiles determined. This process is illustrated in Figure 62.

This apportionment/distribution method has some drawbacks, mainly in the mapping of StockE building types to CBECS Principal Building Activities, and the assumption that CBECS reported EUIs are representative of those buildings (and non-building commercial demand) on average across a census division. Of the several apportionment methods considered, comparing the apportioned Commercial Gap by county showed that the method resulted in the fewest counties with a negative total gap, which was interpreted as being best at allocating the gap in a realistic way. Most of the variation in apportionment methods was seen in very small rural counties, with minor differences in the apportioned Commercial Gap in larger counties. In counties with larger populations and numbers of buildings, the error in BA assignment would be smaller, since the utilities serving larger populations are more likely to be well represented in the truth data, and the building counts from CBECS more likely to be representative of 'average' building size and energy consumption.

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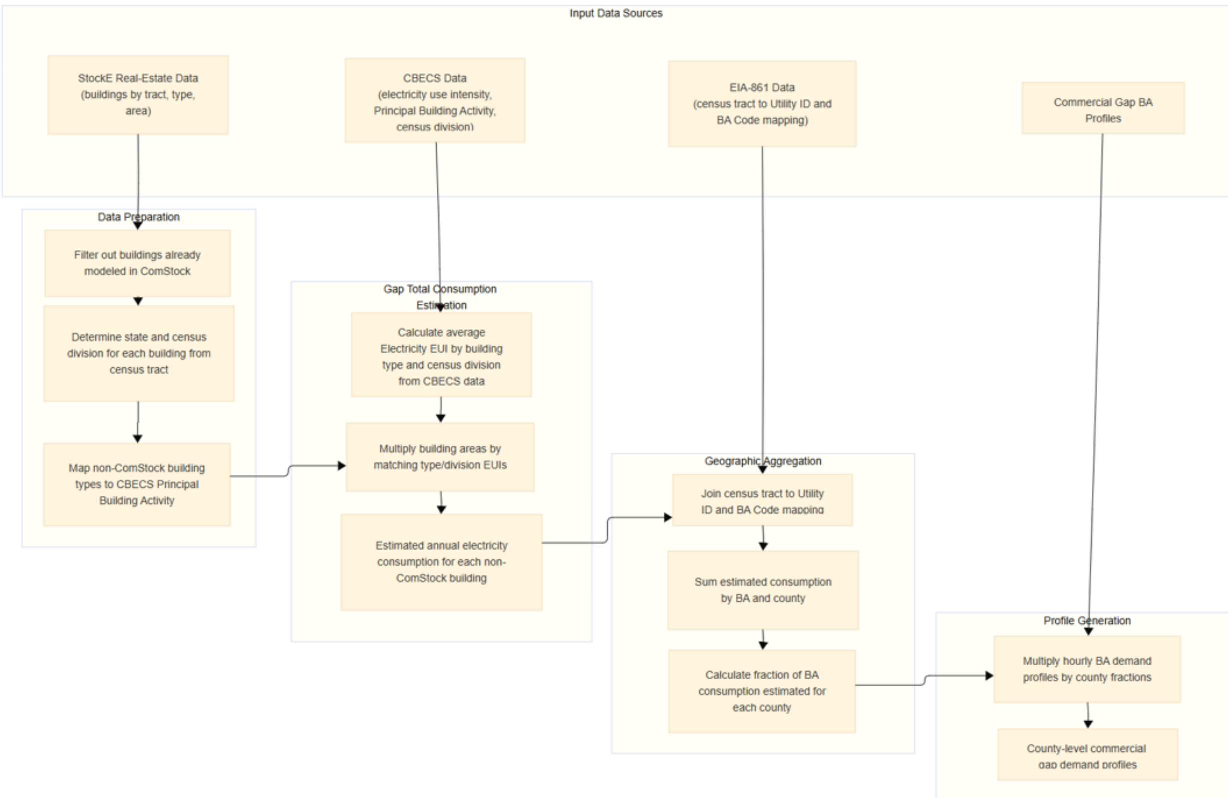

Figure 62. EIA/CBECS method for county-level gap profile allocation process.

5.6.5 Commercial Gap Results

Hourly electric Commercial Gap profiles were calculated for each BA and apportioned down to the county level using the process described above. Total Demand, Industrial, ResStock adjusted, ComStock modeled, and computed Commercial Gap profiles are shown in Figure 63 and Figure 64 for the PJM (Pennsylvania-New Jersey-Maryland Interconnection). Profiles are shown stacked and as individual lines, to illustrate both the component-level contribution to the total as well as the independent profile shape. Note that all times are plotted in Eastern Standard Time.

Summing the modeled profiles for all BAs by month and comparing them against the reported monthly total sales by sector from EIA-861 (Figure 65) reveals some notable features of the modeled gap, as well as the truth data. On the truth data side, there is a 'Reported Gap', which is the difference between the total demand as reported by EIA-930 and the sum of the Industrial, Commercial and Residential sales from EIA-861. While some of this reported gap includes the Transportation sector not included in this analysis, that sector's sales are smaller than what is shown. Since the EIA-930 data is calculated as the difference between generation and net interchange, it is likely that the remainder of the gap between 'Demand' and 'Sales' is from transmission and distribution losses, or consumption at the utility side (for plant operation, etc.) that would not be reported as sales.

The total of the calculated profiles by component closely matches the reported EIA sector sales, which is expected since the reported data directly informed the Industrial profile and ResStock adjustment. The difference between the modeled ComStock totals and the EIA-861 Commercial sales constitutes the Commercial Gap -— the building types and non-building commercial uses (such as street and highway lighting) not directly modeled in ComStock. The 'Uncategorized Gap' is remaining demand that cannot be allocated to a specific use, and just like the 'Reported Gap' likely includes system losses and reporting discrepancies.

Annually, the 'Reported Gap' amounts to approximately 10% of the total reported demand, and about a third of the difference between the modeled sector totals and the EIA-930 total demand. The remaining commercial gap accounts for about 39% of the total reported commercial sector electricity sales, slightly higher than the 36% of missing total site energy as found in the CBECS analysis shown in Figure 66.

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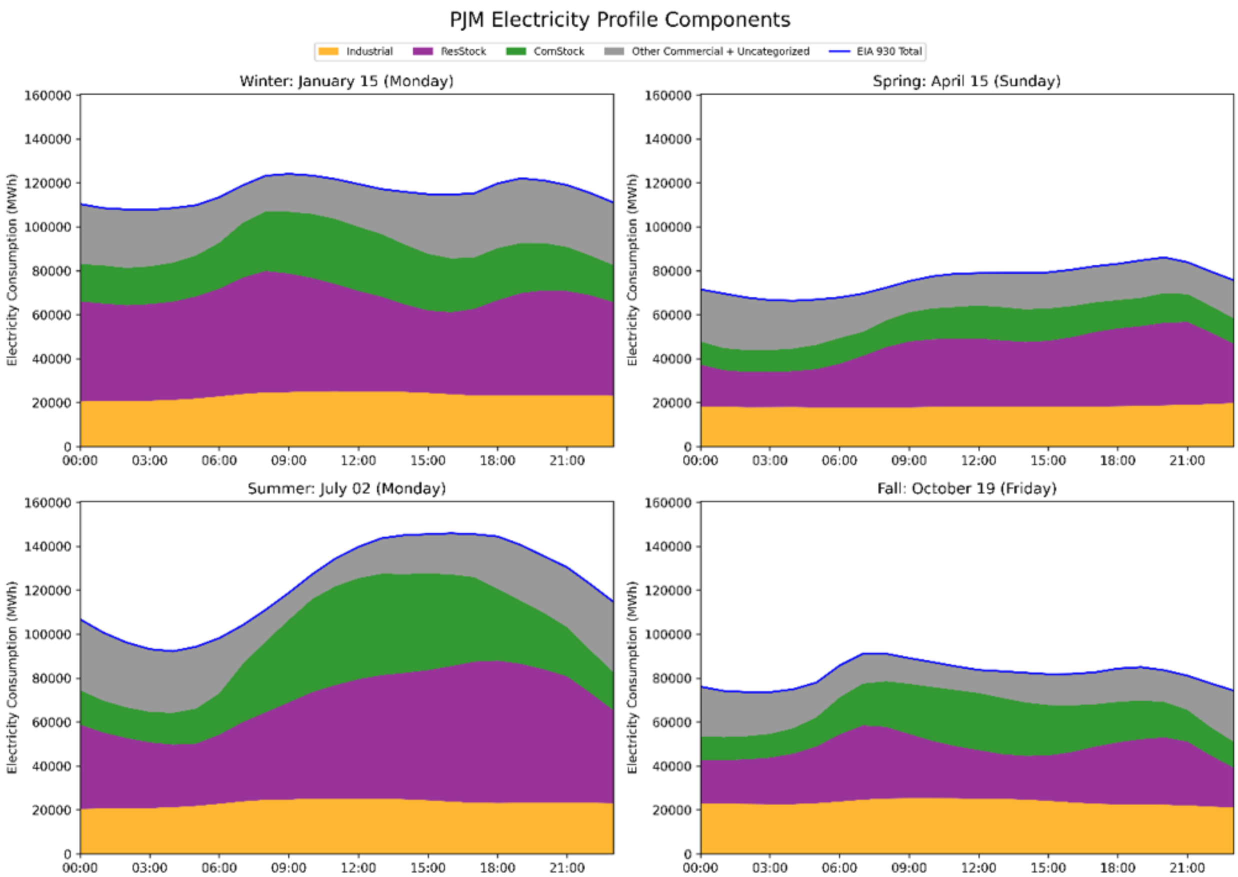

Figure 63. PJM Electricity Profile Components

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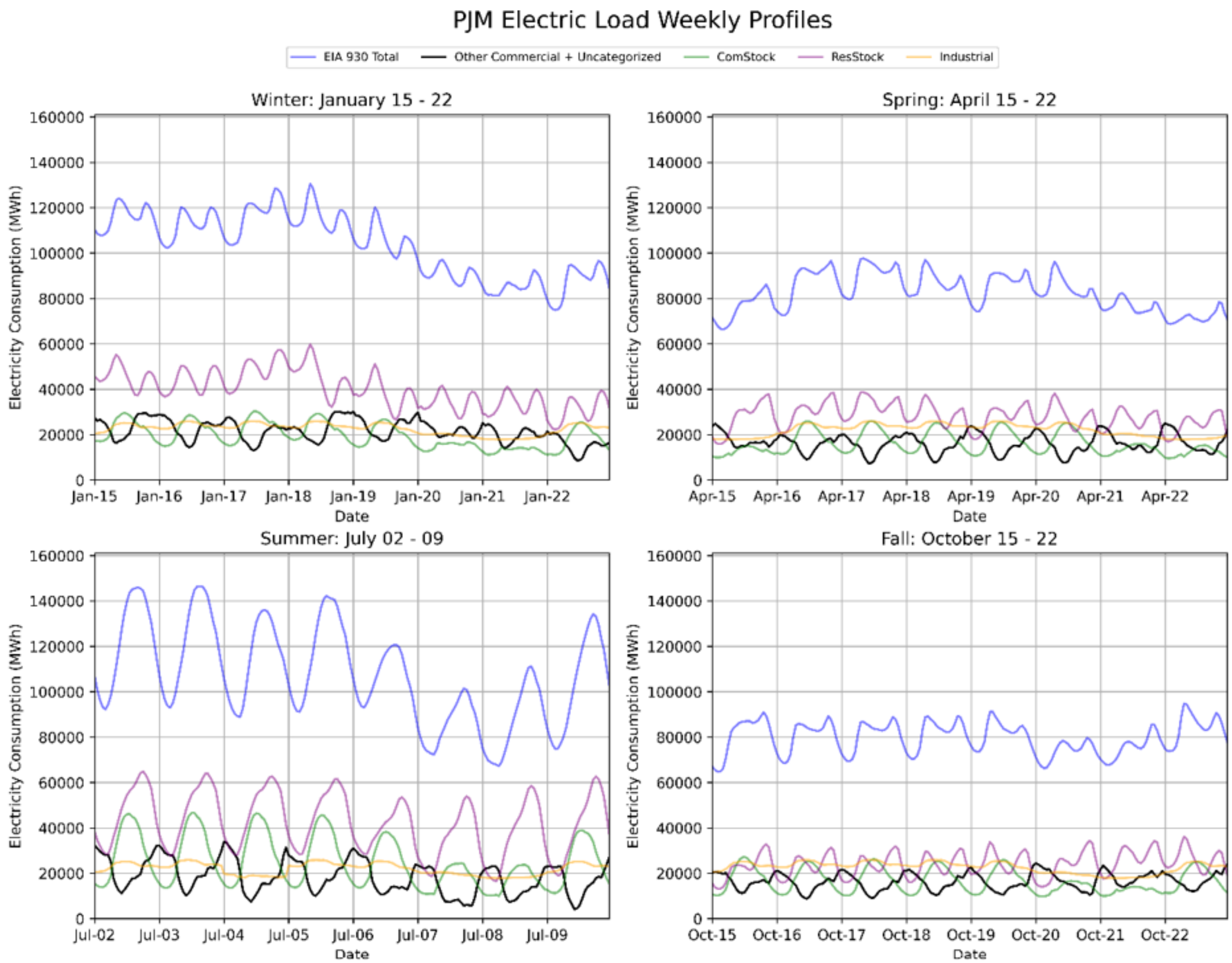

Figure 64. PJM Electric Load Weekly Profiles

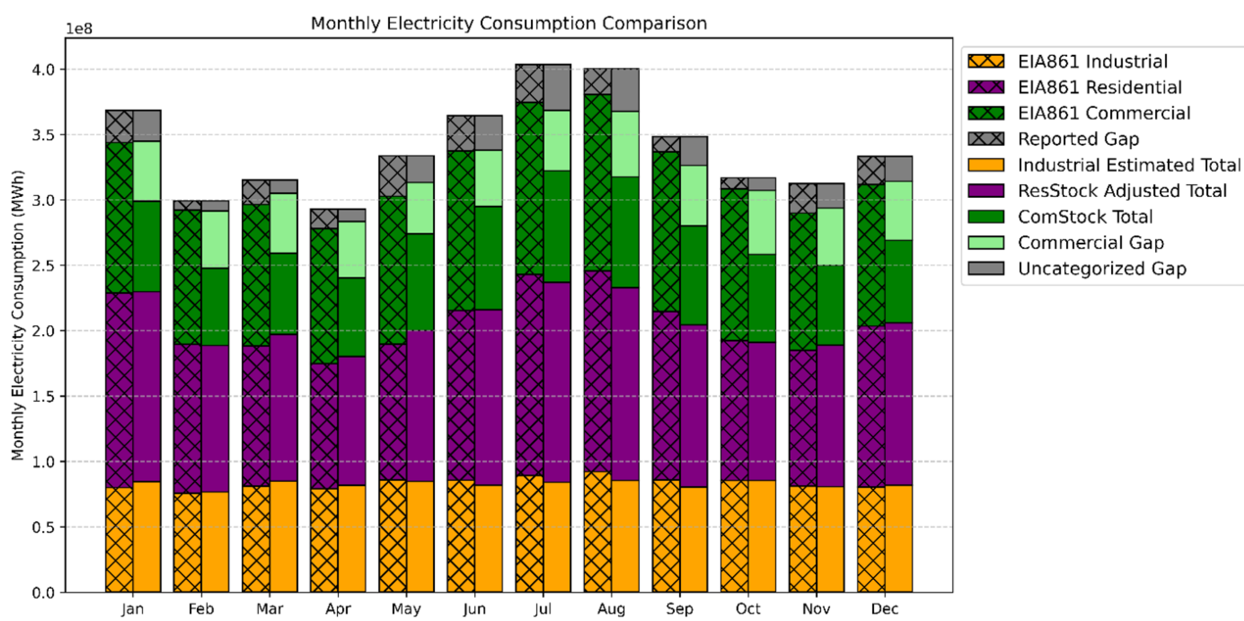

Figure 65. Monthly modeled sector totals and reported EIA totals.

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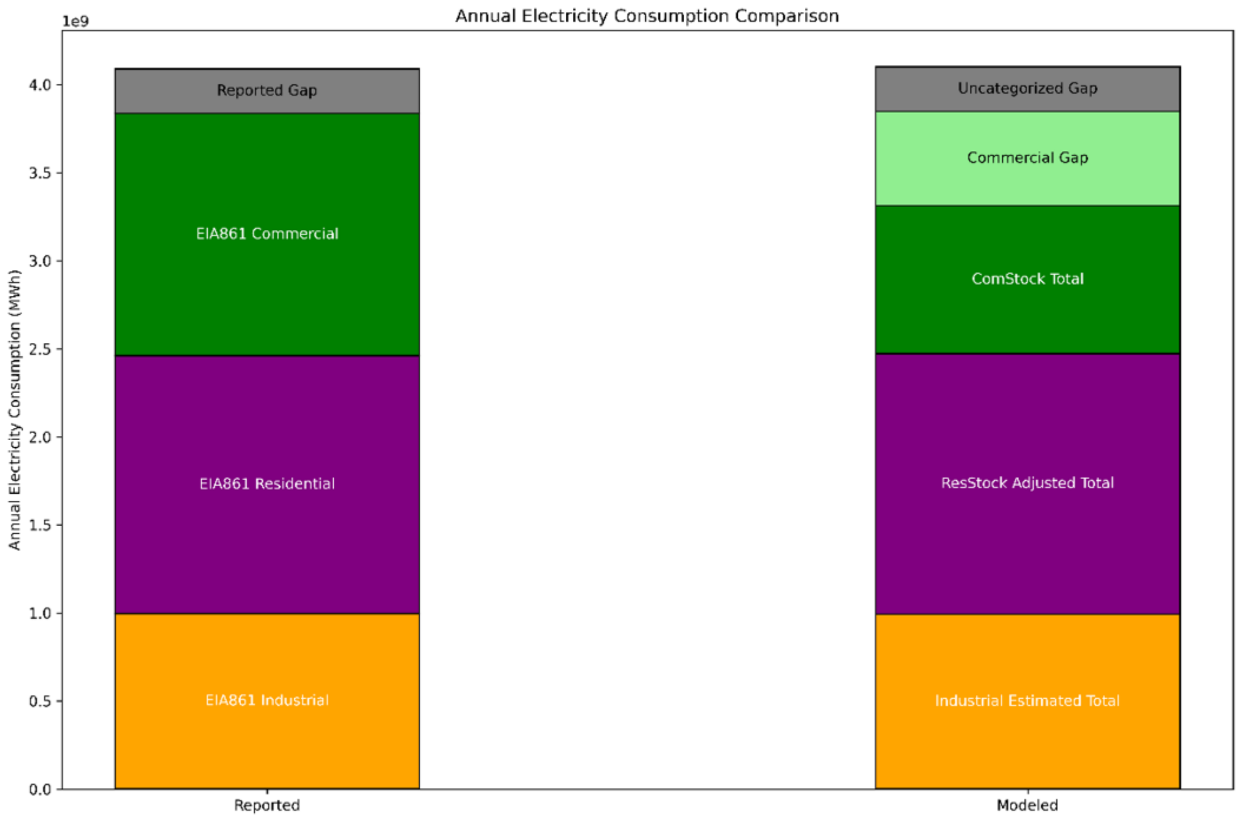

Figure 66. Annual modeled sector totals and reported sector totals.

5.6.6 Limitations and Future Work

As described above, Industrial sector load profiles used in the Commercial Gap model calculations are derived from a simple time-based regression model from only three similarly located electric utilities' load research data. This approach misses any location-based or seasonal variation in industrial load, and would be improved with a more detailed load profile model that considers the different industry makeup across the county. Additionally, by subtracting the estimated industrial load from the total demand at the Balancing Authority level and then disaggregating the remainder to the county-level might skew the gap apportionment at the county level for counties with different amounts of industrial load. Ideally, the BA-level profiles would be disaggregated to county-level total profiles, and the Commercial gap profile calculated at the individual county level, which would require better modeling of county-level industrial profiles than was available for this work.

Similarly, the adjustments to ResStock simulation results used for the Residential profiles could be improved by adjusting the monthly EIA consumption data to account for the difference between reporting and billing months implicit in that data, which could potentially improve the degree-day correlation models. Alternatively, the underlying source of the heating overestimation in the ResStock simulations could be identified and rectified, allowing ResStock results to be used without alteration.

Finally, the county-level commercial gap profiles could be validated against commercial sector total load profiles available from the load research data from utilities that publish to that granularity, which could perhaps shed some light on the shape of the 'uncategorized gap' profile.

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References

Abramson, B., L.-S. Wong, and D. L. Herman. "Service Life Data from an Interactive Web-Based Owning and Operating Cost Database". *ASHRAE Transactions* 112, no. 1 (Jan. 2006): 81–92.

American Society of Heating, R., and I. Air-Conditioning Engineers. *ASHRAE Handbook - Fundamentals*. Atlanta: American Society of Heating, Refrigerating, / Air-Conditioning Engineers, Inc., 2017.

ASHRAE. *Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings*. https://ashrae.iwrapper.com/ASHRAE_PREVIEW_ONLY_STANDARDS/STD_90.1_1989, 1989.

– . *Ventilation for Acceptable Indoor Air Quality*. https://ashrae.iwrapper.com/ASHRAE_PREVIEW_ONLY_STANDARDS/STD_62.1_2019, 2004.

– . *Standard 90.1-2010 (I-P Edition) Energy Standard for Buildings Except Low-Rise Residential Buildings*. Tech. rep. ASHRAE, 2010.

– . *ASHRAE Owning and Operating Cost Database*. http://weblegacy.ashrae.org/publicdatabase/summary.asp. Accessed: 2021-09-05, 2021.

– . *Standard 90.1-2022 (I-P Edition) Energy Standard for Buildings Except Low-Rise Residential Buildings*. Tech. rep. ASHRAE, 2022.

Bianchi, C., L. Zhang, D. Goldwasser, A. Parker, and H. Horsey. "Modeling occupancy-driven building loads for large and diversified building stocks through the use of parametric schedules". *Applied Energy* 276 (2020): 115470.

Bonnema, B., I. Doebber, S. Pless, and P. Torcellini. *Technical Support Document: Development of the Advanced Energy Design Guide for Small Hospitals and Healthcasre-30% Energy Savings*. Tech. rep. NREL/TP-550-46314. National Renewable Energy Laboratory, Mar. 2010. https://www.nrel.gov/docs/fy10osti/46314.pdf.

Bourgeois, D., and D. Macumber. *Thermal Bridging and Derating, Version 3.4.2*, 2024. https://github.com/rd2/tbd.

Briggs, R. S., D. B. Belzer, and D. B. Crawley. *Analysis and categorization of the office building stock. Topical report, February-September 1987*. Tech. rep. Pacific Northwest Lab, Oct. 1987. https://www.osti.gov/biblio/6795134.

Buccitelli, N., C. Elliott, S. Schober, and M. Yamada. *2015 U.S. Lighting Market Characterization*. Tech. rep. U.S. Department of Energy, Nov. 2017.

Building Codes Assistance Project. *Code Status Maps: Commercial Energy Code Adoption*. http://bcapcodes.org/code-status/, 2021.

Cadmus Group. *Commercial Building Stock Assessment 4 (2019) Final Report*. Tech. rep. Northwest Energy Efficiency Alliance, 2019.

California Energy Commission. *Appliance Efficiency Regulations (Title 20)*. Tech. rep. California Energy Commission, 2006. https://www.energy.ca.gov/rules-and-regulations/appliance-efficiency-regulations.

California Public Utilities Commission. *Energy Efficiency Policy Manual Version 6 For Post-2018 Programs*. Tech. rep. California Public Utilities Commission, 2020. https://www.cpuc.ca.gov/-/media/cpuc-website/files/legacyfiles/e/6442465683-eepolicymanualrevised-march-20-2020-b.pdf.

– . *Database for Energy Efficient Resources*. http://deeresources.com/. Accessed: 2021-09-05, 2021.

CaraDonna, C., and K. Dombrovski. "Air Handling Unit Shutdowns During Scheduled Unoccupied Hours: US Commercial Building Stock Prevalence and Energy Impact". 041001, *ASME Journal of Engineering for Sustainable Buildings and Cities* 3, no. 4 (Oct. 2022). ISSN: 2642-6641. https://doi.org/10.1115/1.4055887. eprint: https://asmedigitalcollection.asme.org/sustainablebuildings/article/3/3/031003/1147306/Air-Handling-Unit-Shutdowns-During-Scheduled. https://doi.org/10.1115/1.4055887.

Carrier. *Carrier Economizer*, 2023.

Ciraulo, R., V. Nubbe, S. Wedekind, C. Jean-Michel, and J. Stanley. *Commercial Fenestration Market Study*. Tech. rep. Guidehouse Inc., 2021.

CoStar. *CoStar Property - Commercial Property Research and Information*. http://www.costar.com/products/costar-property-professional, 2018.

– . *Annual Report on Form 10-K*. https://s22.q4cdn.com/578731016/files/doc_financials/2020/ar/2020-Annual-Report-on-Form-10-K.pdf, 2020.

Crowe, E., Y. Chen, J. Granderson, H. Reeve, L. Troup, D. Yuill, and Y. Chen. "What We Learned From Analyzing 18 Million Rows of Commercial Buildings' HVAC Fault Data". In *2022 Summer Study on Energy Efficiency in Buildings*. Aug. 2022. https://www.osti.gov/biblio/1889192.

Daikin. *Rebel Commercial Packaged Rooftop Systems*, 2023.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

Dedman College of Humanities and Sciences; Roy M Huffington Department of Earth Sciences. “SMU Geothermal Lab | Data and Maps | Temperature Maps”. Accessed: 15 December 2023, 2023. https://www.smu.edu/dedman/academics/departments/earth-sciences/research/geothermallab/datamaps/temperaturemaps.

Deru, M., et al. *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*. Tech. rep. National Renewable Energy Laboratory, Feb. 2011. https://doi.org/10.2172/1009264. https://www.osti.gov/biblio/1009264.

– . *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock*. Tech. rep. NREL/TP-5500-46861. National Renewable Energy Laboratory, Feb. 2011. https://www.nrel.gov/docs/fy11osti/46861.pdf.

Emmerich, S. J., and A. K. Persily. “Analysis of U.S. Commercial Building Envelope Air Leakage Database to Support Sustainable Building Design”. *International Journal of Ventilation* 12, no. 4 (2014): 331–344. https://doi.org/10.1080/14733315.2014.11684027. eprint: https://doi.org/10.1080/14733315.2014.11684027. https://doi.org/10.1080/14733315.2014.11684027.

EnergyPlus, Version 00, Sept. 2017. https://www.osti.gov/biblio/1395882.

Fisher, D., and C. Chantrasrisalai. *Lighting Heat Gain Distribution in Buildings*. Tech. rep. ASHRAE, Sept. 2006.

Frank, S. M., J. Kim, J. Cai, and J. E. Braun. *Common Faults and Their Prioritization in Small Commercial Buildings: February 2017 - December 2017*. Tech. rep. National Renewable Energy Laboratory, June 2018. https://doi.org/10.2172/1457127. https://www.osti.gov/biblio/1457127.

Fricke, B., and B. Becker. “Energy Use of Doored and Open Vertical Refrigerated Display Cases”. *ASHRAE Journal* (2010): 44–52.

Gagnon, P., and W. Cole. “Planning for the evolution of the electric grid with a long-run marginal emission rate”. *iScience* 25, no. 3 (2022): 103915. ISSN: 2589-0042. https://doi.org/10.1016/j.isci.2022.103915. https://www.sciencedirect.com/science/article/pii/S2589004222001857.

Gagnon, P., B. Cowiestoll, and M. Schwarz. *Cambium 2022 Scenario Descriptions and Documentation*. Tech. rep. NREL/TP-6A40-84916. Golden, CO: National Renewable Energy Laboratory, 2023. https://www.nrel.gov/docs/fy23osti/84916.pdf.

Gagnon, P., W. Frazier, W. Cole, and E. Hale. *Cambium Documentation: Version 2021*. Tech. rep. NREL/TP-6A40-81611. Golden, CO: National Renewable Energy Laboratory, 2021. https://www.nrel.gov/docs/fy22osti/81611.pdf.

Gagnon, P., E. Hale, and W. Cole. *Long-run Marginal Emission Rates for Electricity - Workbooks for 2021 Cambium Data*. Tech. rep. National Renewable Energy Laboratory, Jan. 2022. https://doi.org/10.7799/1838370. https://www.osti.gov/biblio/1838370.

Goel, S., R. A. Athalye, W. Wang, J. Zhang, M. I. Rosenberg, Y. Xie, P. R. Hart, and V. V. Mendon. *Enhancements to ASHRAE Standard 90.1 Prototype Building Models*. Tech. rep. Pacific Northwest National Laboratory, Apr. 2014. https://doi.org/10.2172/1129366. https://www.osti.gov/biblio/1129366.

Goetzler, W., M. Guernsey, K. Foley, J. Young, and G. Chung. *Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances (2015 Update)*. Tech. rep. U.S. Department of Energy, 2016. https://www.energy.gov/sites/prod/files/2016/06/f32/DOE-BTO%20Comml%20Appl%20Report%20-%20Full%20Report_0.pdf.

Healthcare, G. G. for. *Green Guide for Healthcare: Best Practices for Creating High Performance Healing Environments*. http://www.gghc.org, 2007.

Heinemeier, K. “Free cooling: At what cost?” *ACEEE Summer Study Energy Efficiency Build* (2014).

Hiller, C. “Determining equipment service life”. *ASHRAE Journal* 42 (Aug. 2000): 48–50+52.

Hirsch, J. J. *MasControl 3*, May 2021. https://cedars.sound-data.com/deer-resources/tools/mas-control/.

HUD PD&R. *HUD USPS ZIP CODE CROSSWALK FILES*. Accessed: 2024-01-08. U.S. Department of Housing, Urban Development Office of Policy Development, and Research, 2023. https://www.huduser.gov/portal/datasets/usps_crosswalk.html.

Huggins, J. *U.S. Electric Utility Companies and Rates: Look-up by Zipcode (2021)*. Accessed: 2024-01-08. National Renewable Energy Laboratory, 2021. https://catalog.data.gov/dataset/u-s-electric-utility-companies-and-rates-look-up-by-zipcode-2021.

International Code Council. *2003 International Building Code*. https://codes.iccsafe.org/content/IBC2018?site_type=public, 2003.

Jiang, W., R. E. Jarnagin, K. Gowri, M. McBride, and B. Liu. *Technical Support Document: The Development of the Advanced Energy Design Guide for Highway Lodging Buildings*. Tech. rep. PNNL-17875. Pacific Northwest

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

National Laboratory, Sept. 2008. https://www.pnnl.gov/main/publications/external/technical_reports/pnnl-17875.pdf.

Katipamula, S., R. M. Underhill, N. E. Fernandez, W. Kim, R. G. Lutes, and D. J. Taasevigen. "Prevalence of typical operational problems and energy savings opportunities in U.S. commercial buildings". *Energy and Buildings* 253 (Dec. 2021). https://doi.org/10.1016/j.enbuild.2021.111544. https://www.osti.gov/biblio/1829706.

Kim, J., T. Kim, J. Granderson, Y. Chen, E. Crowe, H. Reeve, S. Newman, and P. Ehrlich. "Research challenges and directions in HVAC fault prevalence". *Science and Technology for the Built Environment* 27, no. 5 (2021): 624–640. https://doi.org/10.1080/23744731.2021.1898243. eprint: https://doi.org/10.1080/23744731.2021.1898243. https://doi.org/10.1080/23744731.2021.1898243.

LightBox. *SmartParcels database*. Tech. rep. LightBox, 2021.

Liu, B., R. Jarnagin, W. Jiang, and K. Gowri. *Technical Support Document The Development of the Advanced Energy Design Guide for Small Warehouse and Self-Storage Buildings*. Tech. rep. PNNL-17056. Pacific Northwest National Laboratory, Dec. 2007. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-17056.pdf.

Liu, R., X. Zhou, S. Lochhead, Z. Zhong, and C. Van Huynh. *Low Energy LED LIghting Heat Distribution in Buildings*. Tech. rep. ASHRAE, Sept. 2016.

National Oceanic and Atmospheric Administration; Climate Prediction Center. *Degree Days Statistics*, 2018. https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/.

Navigant Consulting. *2014 Commercial Building Stock Assessment: Final Report*. https://neea.org/resources/2014-cbsa-final-report. Prepared by Navigant Consulting for the Northwest Energy Efficiency Alliance, 2014.

Ng, L. C., W. S. Dols, and S. J. Emmerich. "Evaluating potential benefits of air barriers in commercial buildings using NIST infiltration correlations in EnergyPlus". *Building and Environment* 196 (2021): 107783. ISSN: 0360-1323. https://doi.org/https://doi.org/10.1016/j.buildenv.2021.107783. https://www.sciencedirect.com/science/article/pii/S0360132321001906.

NREL. *NREL-PySAM Documentation*, 2023. https://nrel-pysam.readthedocs.io/en/main/.

Ong, S., and R. McKeel. *National Utility Rate Database: Preprint*. Tech. rep. National Renewable Energy Laboratory, Jan. 2012. https://doi.org/10.2172/1050105. https://www.osti.gov/biblio/1050105.

Pless, S., P. Torcellini, and N. Long. *Technical Support Document: Development of the Advanced Energy Design Guide for K-12 Schools-30% Energy Savings*. Tech. rep. NREL/TP-550-42114. National Renewable Energy Laboratory, Sept. 2007. https://www.nrel.gov/docs/fy07osti/42114.pdf.

Praprost, M. *End-Use Savings Shapes Measure Documentation: Electric Cooking Equipment*. Technical Report 89130. National Renewable Energy Laboratory, 2024. https://www.nrel.gov/docs/fy24osti/89130.pdf.

Rahbar, S., S. Krsikapa, D. Fisher, J. Nickel, S. Ardley, and D. Zabrowski. *Technology Review of Commercial Food Service Equipment*. Tech. rep. Natural Resources Canada, 1996. https://www.osti.gov/etdeweb/servlets/purl/404139.

Reid, M. *MatthewReid854/reliability: v0.5.1*. Version v0.5.1, July 2020. https://doi.org/10.5281/zenodo.3938000. https://doi.org/10.5281/zenodo.3938000.

Seventhwave and Center for Energy and Environment. *Commercial Roof-top Units in Minnesota: Characteristics and Energy Performance*. Tech. rep. Minnesota Department of Commerce Division of Energy Resources, 2016. https://slipstreaminc.org/research/commercial-roof-top-units-minnesota-characteristics-and-energy-performance.

Shoukas, G., M. Bianchi, and M. Deru. *Analysis of Fault Data Collected from Automated Fault Detection and Diagnostic Products for Packaged Rooftop Units*. Tech. rep. National Renewable Energy Laboratory, Sept. 2020. https://doi.org/10.2172/1665808. https://www.osti.gov/biblio/1665808.

Skumatz, L. A. "What Makes a Good EUL? Analysis of Existing Estimates and Implications for New Protocols for Estimated Useful Lifetimes (EULs)". In *2012 International Energy Program Evaluation Conference, Rome, Italy*. 2012. https://energy-evaluation.org/wp-content/uploads/2019/06/2012-iepec-skumatz-eul-v5-revised.pdf.

Texas Instruments. *Reliability terminology*. Accessed: 2021-09-05, 2021. https://www.ti.com/support-quality/reliability/reliability-terminology.html.

Thornton, B. A., M. I. Rosenberg, E. E. Richman, W. Wang, Y. Xie, J. Zhang, H. Cho, V. V. Mendon, R. A. Athalye, and B. Liu. *Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010*. Tech. rep. Pacific Northwest National Laboratory, May 2011. https://doi.org/10.2172/1015277. https://www.osti.gov/biblio/1015277.

Trane. *Packaged Rooftop Air Conditioners Foundation*, 2023.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

U.S. Bureau of Labor Statistics (BLS). *American Time Use Survey (ATUS), 2018*. https://www.bls.gov/tus/. Accessed: 2023-11-27, 2018.

U.S. Department of Energy. *Energy Conservation Standards for Refrigerated Beverage Vending Machines: Technical Support Document*. Tech. rep. U.S. Department of Energy, 2009. https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program.

–. *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Commercial Refrigeration Equipment*. Tech. rep. EERE-2017-BT-STD-0007, prepared by Guidehouse Consulting, Inc. and Lawrence Berkeley National Laboratory. Office of Energy Efficiency and Renewable Energy, Building Technologies Program, Dec. 2024. https://www.regulations.gov/document/EERE-2017-BT-STD-0007-0118.

U.S. Department of Homeland Security. *Homeland Security Infrastructure Program*. https://hifld-geoplatform.hub.arcgis.com/, 2012.

U.S. Energy Information Administration. *2012 Commercial Building Energy Consumption Survey (CBECS)*. http://www.eia.doe.gov/emeu/cbecs/. Accessed: 2021-09-08, 2012.

–. *Commercial Demand Module of the National Energy Modeling System: Model Documentation*. Tech. rep. U.S. Energy Information Administration, 2017. https://www.eia.gov/outlooks/aeo/nems/documentation/commercial/pdf/m066(2017).pdf.

–. *Residential and Commercial Sector Energy Code Adoption and Compliance Rates*. Tech. rep. Prepared by ICF International L.L.C for the U.S. Energy Information Administration. U.S. Energy Information Administration, 2017. https://www.eia.gov/analysis/studies/rescomm/adoptcomprates/pdf/adoption_compliance.pdf.

–. *2018 Commercial Building Energy Consumption Survey (CBECS)*. https://www.eia.gov/consumption/commercial/data/2018/. Accessed: 2023-03-20, Table C1. Total energy consumption by major fuel, 2018.

–. *Commercial Buildings Energy Consumption Survey (CBECS): Food Sales*. U.S. Energy Information Administration, 2018. https://www.eia.gov/consumption/commercial.

–. *U.S. CO2 emissions from energy consumption by source and sector, 2021*. Tech. rep. U.S. Energy Information Administration, 2021.

–. *Monthly Energy Review*. Accessed: 2022-08-02, 2022. https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T07.06#/?f=A.

–. *Natural Gas Explained*. Accessed: 2022-08-02, 2022. https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php.

–. *Petroleum and Other Liquids*. Accessed: 2023-12-20, 2023. https://www.eia.gov/dnav/pet/pet_pri_dist_a_epd2_prt_dpgal_a.htm.

U.S. Environmental Protection Agency. *ENERGY STAR Program Requirements for Commercial Refrigerators and Freezers*. U.S. Environmental Protection Agency and U.S. Department of Energy, 2001. https://www.energystar.gov.

U.S. Environmental Protection Agency (EPA). *Emissions and Generation Resource Integrated Database (eGRID), 2020*. https://www.epa.gov/egrid. Accessed: 2022-06-23, 2022.

–. *AP-42: Compilation of Air Emissions Factors from Stationary Sources, 2024*. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors-stationary-sources. Accessed: 2025-03-18, 2024.

US Energy Information Agency (EIA). *Form 861 Annual Electric Power Industry Report Instructions*, 2017. https://www.eia.gov/survey/form/eia_861/proposed/instructions.pdf.

–. *Annual Electric Power Industry Report, Form 861*. Webpage, 2025. https://www.eia.gov/electricity/data/eia861.

–. *Hourly and Daily Balancing Authority Operations Report, Form 930*. Webpage, 2025. https://www.eia.gov/electricity/gridmonitor/about.

–. *Monthly Electric Power Industry Report, Form 861M*. Webpage, 2025. https://www.eia.gov/electricity/data/eia861m.

Wilson, E. J., C. B. Christensen, S. G. Horowitz, J. J. Robertson, and J. B. Maguire. *Energy Efficiency Potential in the U.S. Single-Family Housing Stock*. Tech. rep. National Renewable Energy Laboratory, Dec. 2017. https://doi.org/10.2172/1414819. https://www.osti.gov/biblio/1414819.

Wilson, E. J. H., et al. *End-Use Load Profiles for the U.S. Building Stock: Methodology and Results of Model Calibration, Validation, and Uncertainty Quantification*. Tech. rep. National Renewable Energy Laboratory, Mar. 2022. https://doi.org/10.2172/1854582. https://www.osti.gov/biblio/1854582.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications

Xing, L. "Estimations of Undisturbed Ground Temperatures Using Numerical and Analytical Modeling". PhD thesis, Oklahoma State University, 2014.

Yamada, M., J. Penning, S. Schober, K. Lee, and C. Elliott. *Energy Savings Forecast of Solid-State Lighting in General Illumination Applications*. Tech. rep. U.S. Department of Energy, Dec. 2019.

Zhang, J., D. Schrock, D. Fisher, A. Livchak, D. Zabrowski, M. Lane, R. Athalye, and B. Liu. *Technical Support Document: 50% Energy Savings for Quick-Service Restaurants*. Tech. rep. Pacific Northwest National Laboratory, 2010. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-19809.pdf.

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Appendix A Tables

Table 47. Space Type Ratios

Building Type	Building Subtype	Space Type	Fraction of Floor Area
Secondary School	NA	Auditorium	0.0504
Secondary School	NA	Cafeteria	0.0319
Secondary School	NA	Classroom	0.3041
Secondary School	NA	ComputerRoom	0.0487
Secondary School	NA	Corridor	0.2144
Secondary School	NA	Gym	0.1646
Secondary School	NA	Kitchen	0.011
Secondary School	NA	Library	0.0429
Secondary School	NA	Lobby	0.0214
Secondary School	NA	Mechanical	0.0349
Secondary School	NA	Office	0.0543
Secondary School	NA	Restroom	0.0214
Primary School	NA	Cafeteria	0.0458
Primary School	NA	Classroom	0.04793
Primary School	NA	ComputerRoom	0.0236
Primary School	NA	Corridor	0.1633
Primary School	NA	Gym	0.052
Primary School	NA	Kitchen	0.0244
Primary School	NA	Library	0.0581
Primary School	NA	Lobby	0.0249
Primary School	NA	Mechanical	0.0367
Primary School	NA	Office	0.0642
Primary School	NA	Restroom	0.0277
Small Office	NA	WholeBuilding - Sm Office	1
Medium Office	mediumoffice_default	WholeBuilding - Md Office	1
Medium Office	mediumoffice_nodatacenter	WholeBuilding - Md Office	1
Medium Office	mediumoffice_datacenter	WholeBuilding - Md Office	0.98
Medium Office	mediumoffice_datacenter	OfficeLarge Data Center	0.02
Large Office	largeoffice_default	WholeBuilding - Lg Office	0.09737
Large Office	largeoffice_default	OfficeLarge Data Center	0.0094
Large Office	largeoffice_default	OfficeLarge Main Data Center	0.0169
Large Office	largeoffice_datacenter	WholeBuilding - Lg Office	0.09737
Large Office	largeoffice_datacenter	OfficeLarge Data Center	0.0094
Large Office	largeoffice_datacenter	OfficeLarge Main Data Center	0.0169
Large Office	largeoffice_nodatacenter	WholeBuilding - Lg Office	1
Large Office	largeoffice_datacenteronly	OfficeLarge Data Center	1
Small Hotel	NA	Corridor	0.1313
Small Hotel	NA	Elec/MechRoom	0.0038
Small Hotel	NA	ElevatorCore	0.0113
Small Hotel	NA	Exercise	0.0081
Small Hotel	NA	GuestLounge	0.0406
Small Hotel	NA	GuestRoom123Occ	0.4081
Small Hotel	NA	GuestRoom123Vac	0.2231
Small Hotel	NA	Laundry	0.0244
Small Hotel	NA	Mechanical	0.0081
Small Hotel	NA	Meeting	0.02
Small Hotel	NA	Office	0.0325
Small Hotel	NA	PublicRestroom	0.0081
Small Hotel	NA	StaffLounge	0.0081
Small Hotel	NA	Stair	0.04
Small Hotel	NA	Storage	0.0325
Large Hotel	NA	Banquet	0.0585
Large Hotel	NA	Basement	0.1744
Large Hotel	NA	Cafe	0.0166
Large Hotel	NA	Corridor	0.1736
Large Hotel	NA	GuestRoom	0.4099
Large Hotel	NA	Kitchen	0.0091
Large Hotel	NA	Laundry	0.0069
Large Hotel	NA	Lobby	0.1153
Large Hotel	NA	Mechanical	0.0145
Large Hotel	NA	Retail	0.0128
Large Hotel	NA	Storage	0.0084
Warehouse	NA	Bulk	0.6628
Warehouse	NA	Fine	0.2882
Warehouse	NA	Office	0.049
Retail Standalone	NA	Back_Space	0.1656
Retail Standalone	NA	Entry	0.0052
Retail Standalone	NA	Point_of_Sale	0.0657
Retail Standalone	NA	Retail	0.7635
Retail Stripmall	strip_mall_default	Strip mall - type 1	0.25
Retail Stripmall	strip_mall_default	Strip mall - type 2	0.25
Retail Stripmall	strip_mall_default	Strip mall - type 3	0.5

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Continued from previous page

Building Type	Building Subtype	Space Type	Fraction of Floor Area
Retail Stripmall	strip_mall_restaurant0	Strip mall - type 1	0.25
Retail Stripmall	strip_mall_restaurant0	Strip mall - type 2	0.25
Retail Stripmall	strip_mall_restaurant0	Strip mall - type 3	0.5
Retail Stripmall	strip_mall_restaurant10	Strip mall - type 1	0.225
Retail Stripmall	strip_mall_restaurant10	Strip mall - type 2	0.225
Retail Stripmall	strip_mall_restaurant10	Strip mall - type 3	0.45
Retail Stripmall	strip_mall_restaurant10	Dining	0.07272
Retail Stripmall	strip_mall_restaurant10	Kitchen	0.02728
Retail Stripmall	strip_mall_restaurant20	Strip mall - type 1	0.2
Retail Stripmall	strip_mall_restaurant20	Strip mall - type 2	0.2
Retail Stripmall	strip_mall_restaurant20	Strip mall - type 3	0.4
Retail Stripmall	strip_mall_restaurant20	Dining	0.14544
Retail Stripmall	strip_mall_restaurant20	Kitchen	0.05456
Retail Stripmall	strip_mall_restaurant30	Strip mall - type 1	0.175
Retail Stripmall	strip_mall_restaurant30	Strip mall - type 2	0.175
Retail Stripmall	strip_mall_restaurant30	Strip mall - type 3	0.35
Retail Stripmall	strip_mall_restaurant30	Dining	0.2182
Retail Stripmall	strip_mall_restaurant30	Kitchen	0.8184
Retail Stripmall	strip_mall_restaurant40	Strip mall - type 1	0.15
Retail Stripmall	strip_mall_restaurant40	Strip mall - type 2	0.15
Retail Stripmall	strip_mall_restaurant40	Strip mall - type 3	0.3
Retail Stripmall	strip_mall_restaurant40	Dining	0.29088
Retail Stripmall	strip_mall_restaurant40	Kitchen	0.10912
Quick Service Restaurant	NA	Dining	0.5
Quick Service Restaurant	NA	Kitchen	0.5
Full Service Restaurant	NA	Dining	0.7272
Full Service Restaurant	NA	Kitchen	0.2728
Hospital	NA	Basement	0.1667
Hospital	NA	Corridor	0.1741
Hospital	NA	Dining	0.0311
Hospital	NA	ER_Exam	0.0099
Hospital	NA	ER_NurseStn	0.0551
Hospital	NA	ER_Trauma	0.0025
Hospital	NA	ER_Triage	0.005
Hospital	NA	ICU_NurseStn	0.0298
Hospital	NA	ICU_Open	0.0275
Hospital	NA	ICU_PatRm	0.0115
Hospital	NA	Kitchen	0.0414
Hospital	NA	Lab	0.0236
Hospital	NA	Lobby	0.0657
Hospital	NA	NurseStn	0.1723
Hospital	NA	Office	0.0286
Hospital	NA	OR	0.0273
Hospital	NA	PatCorridor	0
Hospital	NA	PatRoom	0.0845
Hospital	NA	PhysTherapy	0.0217
Hospital	NA	Radiology	0.0217
Outpatient	NA	Anesthesia	0.0026
Outpatient	NA	BioHazard	0.0014
Outpatient	NA	Cafe	0.0103
Outpatient	NA	CleanWork	0.0071
Outpatient	NA	Conference	0.0082
Outpatient	NA	DressingRoom	0.0021
Outpatient	NA	Elec/MechRoom	0.0109
Outpatient	NA	ElevatorPumpRoom	0.0022
Outpatient	NA	Exam	0.1029
Outpatient	NA	Hall	0.1924
Outpatient	NA	IT_Room	0.0027
Outpatient	NA	Janitor	0.0672
Outpatient	NA	Lobby	0.0152
Outpatient	NA	LockerRoom	0.019
Outpatient	NA	Lounge	0.0293
Outpatient	NA	MedGas	0.0014
Outpatient	NA	MRI	0.0107
Outpatient	NA	MRI_Control	0.0041
Outpatient	NA	NurseStation	0.0189
Outpatient	NA	Office	0.1828
Outpatient	NA	OR	0.0346
Outpatient	NA	PACU	0.0232
Outpatient	NA	PhysicalTherapy	0.0462
Outpatient	NA	PreOp	0.0129
Outpatient	NA	ProcedureRoom	0.007
Outpatient	NA	Reception	0.0365
Outpatient	NA	Soil Work	0.0088
Outpatient	NA	Stair	0.0146
Outpatient	NA	Toilet	0.0193

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Continued from previous page

Building Type	Building Subtype	Space Type	Fraction of Floor Area
Outpatient	NA	Undeveloped	0.0835
Outpatient	NA	Xray	0.022
DEER Education Primary School	NA	Classroom	0.53
DEER Education Primary School	NA	CorridorStairway	0.1
DEER Education Primary School	NA	Dining	0.15
DEER Education Primary School	NA	Gymnasium	0.15
DEER Education Primary School	NA	Kitchen	0.07
DEER Education Secondary School	NA	Classroom	0.488
DEER Education Secondary School	NA	CompRoomClassRm	0.021
DEER Education Secondary School	NA	CorridorStairway	0.1
DEER Education Secondary School	NA	Dining	0.15
DEER Education Secondary School	NA	Gymnasium	0.15
DEER Education Secondary School	NA	Kitchen	0.07
DEER Education Secondary School	NA	OfficeGeneral	0.021
DEER Hospital	NA	DEER HospitalSurgOutptLab	0.2317
DEER Hospital	NA	Dining	0.0172
DEER Hospital	NA	Kitchen	0.0075
DEER Hospital	NA	OfficeGeneral	0.3636
DEER Hospital	NA	PatientRoom	0.38
DEER Hotel	NA	Dining	0.004
DEER Hotel	NA	BarCasino	0.005
DEER Hotel	NA	HotelLobby	0.0411
DEER Hotel	NA	OfficeGeneral	0.0205
DEER Hotel	NA	GuestRmCorrid	0.1011
DEER Hotel	NA	Laundry	0.0205
DEER Hotel	NA	GuestRmOcc	0.64224
DEER Hotel	NA	GuestRmUnOcc	0.16056
DEER Hotel	NA	Kitchen	0.005
DEER Motel	NA	OfficeGeneral	0.02
DEER Motel	NA	GuestRmCorrid	0.649
DEER Motel	NA	Laundry	0.016
DEER Motel	NA	GuestRmOcc	0.25208
DEER Motel	NA	GuestRmUnOcc	0.06302
DEER Office Large	NA	LobbyWaiting	0.0412
DEER Office Large	NA	OfficeSmall	0.3704
DEER Office Large	NA	OfficeOpen	0.5296
DEER Office Large	NA	MechElecRoom	0.0588
DEER Office Small	NA	Hall	0.3141
DEER Office Small	NA	OfficeSmall	0.6859
DEER Restaurant Fast Food	NA	Dining	0.3997
DEER Restaurant Fast Food	NA	Kitchen	0.4
DEER Restaurant Fast Food	NA	LobbyWaiting	0.1501
DEER Restaurant Fast Food	NA	Restroom	0.0501
DEER Restaurant Sit Down	NA	Restroom	0.0357
DEER Restaurant Sit Down	NA	Dining	0.5353
DEER Restaurant Sit Down	NA	LobbyWaiting	0.1429
DEER Restaurant Sit Down	NA	Kitchen	0.2861
DEER Retail Three Story	NA	RetailSales	1
DEER Retail Large	NA	OfficeGeneral	0.0359
DEER Retail Large	NA	Work	0.04
DEER Retail Large	NA	StockRoom	0.091
DEER Retail Large	NA	RetailSales	0.8219
DEER Retail Large	NA	Kitchen	0.0113
DEER Retail Small	NA	RetailSales	0.8
DEER Retail Small	NA	StockRoom	0.2
DEER Storage Conditioned	NA	WarehouseCond	1
DEER Storage Unconditioned	NA	WarehouseUnCond	1
Grocery	NA	Bakery	0.05
Grocery	NA	Deli	0.0537
Grocery	NA	DryStorage	0.1010
Grocery	NA	Office	0.0067
Grocery	NA	Produce	0.1701
Grocery	NA	Sales	0.5495
Grocery	NA	Corridor	0.0118

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Continued from previous page

Building Type	Building Subtype	Space Type	Fraction of Floor Area
Grocery	NA	Dining	0.0111
Grocery	NA	Elec/MechRoom	0.0133
Grocery	NA	Meeting	0.0111
Grocery	NA	Restroom	0.0150
Grocery	NA	Vestibule	0.0067
DEER Grocery	NA	GrocSales	0.800
DEER Grocery	NA	OfficeGeneral	0.070
DEER Grocery	NA	RefFoodPrep	0.073
DEER Grocery	NA	IndLoadDock	0.057

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Table 38. Food Service (Full Service Restaurant and Quick Service Restaurant) Occupant Density Values by Space Type

Building Type	DOE Space Type	DOE Occupancy per Area (people/1000 ft^2)	DEER Space Type	DEER Occupancy per Area (people/1000 ft^2)
QuickServiceRestaurant	Dining	70	Dining	44.4
QuickServiceRestaurant	Kitchen	5	Kitchen	3.3
QuickServiceRestaurant	Attic	0	StockRoom	2.2
QuickServiceRestaurant	–	–	CorridorStairway	6.7
QuickServiceRestaurant	–	–	LobbyWaiting	6.7
QuickServiceRestaurant	–	–	OfficeGeneral	4.4
QuickServiceRestaurant	–	–	Restroom	19
FullServiceRestaurant	Dining	70	Dining	44.4
FullServiceRestaurant	Kitchen	5	Kitchen	3.3
FullServiceRestaurant	Attic	0	StockRoom	2.2
FullServiceRestaurant	–	–	CorridorStairway	6.7
FullServiceRestaurant	–	–	LobbyWaiting	6.7
FullServiceRestaurant	–	–	OfficeGeneral	4.4
FullServiceRestaurant	–	–	Restroom	19

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Table 39. Healthcare (Hospital and Outpatient) Occupant Density Values by Space Type

Building Type	DOE Space Type	DOE Occupancy per Area (people/1000 ft^2)	DEER Space Type	DEER Occupancy per Area (people/1000 ft^2)
Hospital	Dining	10	Dining	44.4
Hospital	Basement	2.5	FacMaint	2.2
Hospital	Corridor	1	Hall	6.7
Hospital	PatCorridor	1		
Hospital	NurseStn	1.333	HspNursing	6.7
Hospital	Kitchen	5	Kitchen	3.3
Hospital	Lobby	7.14	LobbyWaiting	6.7
Hospital	Office	6.99	OfficeGeneral	4.4
Hospital	PatRoom	5	PatientRoom	6.7
Hospital	ER_Exam	20	–	–
Hospital	ER_NurseStn	1.333	–	–
Hospital	ER_Trauma	20	–	–
Hospital	ER_Triage	20	–	–
Hospital	ICU_NurseStn	1.333	–	–
Hospital	ICU_Open	5	–	–
Hospital	ICU_PatRm	5	–	–
Hospital	OR	5	–	–
Hospital	PhysTherapy	5	–	–
Hospital	Radiology	5	–	–
Hospital	Lab	5	–	–
Hospital	–	–	HspSurgOutptLab	6.7
Hospital	–	–	Restroom	19
Hospital	–	–	RetailSales	22.2
Hospital	–	–	StockRoom	2.2
Hospital	–	–	Break	6.7
Outpatient	Conference	49.95	Conference	44.4
Outpatient	Hall	0	CorridorStairway	6.7
Outpatient	Stair	0		
Outpatient	Lobby	10	LobbyWaiting	6.7
Outpatient	Elec/MechRoom	0	MechElecRoom	2.2
Outpatient	Office	5	OfficeOpen	6.7
Outpatient			OfficeSmall	4.4
Outpatient	Toilet	0	Restroom	19
Outpatient	Anesthesia	20.02	–	–
Outpatient	BioHazard	0	–	–
Outpatient	Cafe	99.89	–	–
Outpatient	CleanWork	20.02	–	–
Outpatient	DressingRoom	5	–	–
Outpatient	ElevatorPumpRoom	0	–	–
Outpatient	Exam	20.02	–	–
Outpatient	IT_Room	5	–	–
Outpatient	Janitor	0	–	–
Outpatient	LockerRoom	15.01	–	–
Outpatient	Lounge	15.01	–	–
Outpatient	MedGas	0	–	–
Outpatient	MRI	20.02	–	–
Outpatient	MRI_Control	20.02	–	–
Outpatient	NurseStation	20.02	–	–
Outpatient	OR	20.02	–	–
Outpatient	PACU	20.02	–	–
Outpatient	PhysicalTherapy	20.02	–	–
Outpatient	PreOp	10	–	–
Outpatient	ProcedureRoom	20.02	–	–
Outpatient	Reception	29.97	–	–
Outpatient	Soil Work	20.02	–	–
Outpatient	Undeveloped	0	–	–
Outpatient	Xray	20.02	–	–
Outpatient	–	–	HspSurgOutptLab	6.7
Outpatient	–	–	Restroom	19
Outpatient	–	–	RetailSales	22.2
Outpatient	–	–	StockRoom	2.2
Outpatient	–	–	Break	6.7
Outpatient	–	–	CopyRoom	5.3

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Table 40. Hotel (Large Hotel and Small Hotel) Occupant Density Values by Space Type

Building Type	DOE Space Type	DOE Occupancy per Area (people/1000 ft^2)	DEER Space Type	DEER Occupancy per Area (people/1000 ft^2)
LargeHotel	Cafe	67	Dining	44.4
LargeHotel	Corridor	1	GuestRmCorrid	6.7
LargeHotel	Corridor2	0		
LargeHotel	GuestRoom	3.57	GuestRmOcc	3.3
LargeHotel	GuestRoom2	5.68		
LargeHotel	GuestRoom3	3.57		
LargeHotel	GuestRoom4	5.68		
LargeHotel	Lobby	30	HotelLobby	6.7
LargeHotel	Kitchen	5	Kitchen	3.3
LargeHotel	Laundry	4	Laundry	6.7
LargeHotel	Banquet	67	–	–
LargeHotel	Basement	5	–	–
LargeHotel	Mechanical	0	–	–
LargeHotel	Retail	15	–	–
LargeHotel	Retail2	15	–	–
LargeHotel	Storage	2	–	–
LargeHotel	–	–	BarCasino	44.4
LargeHotel	–	–	GuestRmUnOcc	3.3
LargeHotel	–	–	OfficeGeneral	4.4
LargeHotel	–	–	Restroom	19
LargeHotel	–	–	StockRoom	2.2
SmallHotel	StaffLounge	51.28	Break	6.7
SmallHotel	Corridor	0	GuestRmCorrid	6.7
SmallHotel	Corridor4	0		
SmallHotel	Stair	0	CorridorStairway	6.7
SmallHotel	Stair4	0		
SmallHotel	GuestRoom123Occ	4.27	GuestRmOcc	3.3
SmallHotel	GuestRoom4Occ	4.27		
SmallHotel	GuestRoom123Vac	4.27	GuestRmUnOcc	3.3
SmallHotel	GuestRoom4Vac	4.27		
SmallHotel	Laundry	10	Laundry	6.7
SmallHotel	Elec/MechRoom	0	MechElecRoom	2.2
SmallHotel	Mechanical	0		
SmallHotel	Office	7.14	OfficeGeneral	4.4
SmallHotel	Meeting	50	–	–
SmallHotel	PublicRestroom	2.85	Restroom	19
SmallHotel	Storage	0	StorageSmlCond	2.2
SmallHotel	GuestLounge	30	–	–
SmallHotel	ElevatorCore	0	–	–
SmallHotel	ElevatorCore4	0	–	–
SmallHotel	Exercise	19.94	–	–

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Table 41. Office (Small Office, Medium Office, and Large Office) Occupant Density Values by Space Type

Building Type	DOE Space Type	DOE Occupancy per Area (people/1000 ft^2)	DEER Space Type	DEER Occupancy per Area (people/1000 ft^2)
LargeOffice	BreakRoom	50	Break	6.7
LargeOffice	Conference	50	Conference	44.4
LargeOffice	PrintRoom	10	CopyRoom	5.3
LargeOffice	Stair	0	CorridorStairway	6.7
LargeOffice	Corridor	1		
LargeOffice	Lobby	10	LobbyWaiting	6.7
LargeOffice	Elec/MechRoom	0	MechElecRoom	2.2
LargeOffice	OpenOffice	5.25	OfficeOpen	6.7
LargeOffice	ClosedOffice	4.75	OfficeSmall	4.4
LargeOffice	Restroom	10	Restroom	19
LargeOffice	Storage	0	StorageSmlCond	2.2
LargeOffice	WholeBuilding - Lg Office	5	–	–
LargeOffice	Vending	1	–	–
LargeOffice	IT_Room	5	–	–
LargeOffice	Dining	10	–	–
LargeOffice	Classroom	35	–	–
MediumOffice	MediumOffice - Breakroom	50	Break	6.7
MediumOffice	MediumOffice - Conference	50	Conference	44.4
MediumOffice	MediumOffice - Stair	0	CorridorStairway	6.7
MediumOffice	MediumOffice - Corridor	0		
MediumOffice	MediumOffice - Lobby	10	LobbyWaiting	6.7
MediumOffice	MediumOffice - Elec/MechRoom	0	MechElecRoom	2.2
MediumOffice	MediumOffice - OpenOffice	5.25	OfficeOpen	6.7
MediumOffice	MediumOffice - ClosedOffice	4.75	OfficeSmall	4.4
MediumOffice	MediumOffice - Restroom	0	Restroom	19
MediumOffice	MediumOffice - Storage	0	StorageSmlCond	2.2
MediumOffice	MediumOffice - Dining	10	–	–
MediumOffice	MediumOffice - Classroom	35	–	–
MediumOffice	WholeBuilding - Md Office	5	–	–
MediumOffice	–	–	CopyRoom	5.3
SmallOffice	SmallOffice - Breakroom	50	Break	6.7
SmallOffice	SmallOffice - Conference	50	Conference	44.4
SmallOffice	SmallOffice - Stair	0	Hall	6.7
SmallOffice	SmallOffice - Corridor	0		
SmallOffice	SmallOffice - Lobby	10	LobbyWaiting	6.7
SmallOffice	SmallOffice - Elec/MechRoom	0	MechElecRoom	2.2
SmallOffice	SmallOffice - OpenOffice	5.25	OfficeOpen	6.7
SmallOffice	SmallOffice - ClosedOffice	4.75	OfficeSmall	4.4
SmallOffice	SmallOffice - Restroom	0	Restroom	19
SmallOffice	SmallOffice - Storage	0	StorageSmlCond	2.2
SmallOffice	SmallOffice - Dining	10	–	–
SmallOffice	SmallOffice - Classroom	35	–	–
SmallOffice	WholeBuilding - Sm Office	5.6	–	–
SmallOffice	–	–	CompRoomData	6.7
SmallOffice	–	–	CopyRoom	5.3

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Table 42. School (Primary School and Secondary School) Occupant Density Values by Space Type

Building Type	DOE Space Type	DOE Occupancy per Area (people/1000 ft^2)	DEER Space Type	DEER Occupancy per Area (people/1000 ft^2)
SecondarySchool	Classroom	35	Classroom	33.3
SecondarySchool	ComputerRoom	35	CompRoomClassRm	13.3
SecondarySchool	Auditorium	150	Conference	44.4
SecondarySchool	Corridor	0	CorridorStairway	6.7
SecondarySchool	Cafeteria	100	Dining	44.4
SecondarySchool	Gym	30	Gymnasium	13.3
SecondarySchool	Kitchen	15.23	Kitchen	3.3
SecondarySchool	Library	10	LibraryReading	13.3
SecondarySchool	Mechanical	0	MechElecRoom	2.2
SecondarySchool	Office	5	OfficeGeneral	4.4
SecondarySchool	Restroom	0	Restroom	19
SecondarySchool	Lobby	0	–	–
SecondarySchool	–	–	Shop	6.7
SecondarySchool	–	–	StorageSmlCond	2.2
PrimarySchool	Classroom	25	Classroom	33.3
PrimarySchool	ComputerRoom	25	CompRoomClassRm	13.3
PrimarySchool	Corridor	0	CorridorStairway	6.7
PrimarySchool	Cafeteria	100	Dining	44.4
PrimarySchool	Gym	30	Gymnasium	13.3
PrimarySchool	Kitchen	13.93	Kitchen	3.3
PrimarySchool	Library	10	LibraryReading	13.3
PrimarySchool	Lobby	0	Lobby	6.7
PrimarySchool	Office	5	OfficeGeneral	4.4
PrimarySchool	Restroom	0	Restroom	19
PrimarySchool	–	–	StorageSmlCond	2.2

Table 43. Retail (Retail and Strip Mall) Occupant Density Values by Space Type

Building Type	DOE Space Type	DOE Occupancy per Area (people/1000 ft^2)	DEER Space Type	DEER Occupancy per Area (people/1000 ft^2)
Retail	Retail	15	RetailSales	22.2
Retail	Point_of_Sale	15		
Retail	Back_Space	15	StockRoom	2.2
Retail	Entry	15	–	–
Retail	–	–	Break	6.7
Retail	–	–	Kitchen	3.3
Retail	–	–	MechElecRoom	2.2
Retail	–	–	OfficeGeneral	4.4
Retail	–	–	Restroom	19
Retail	–	–	Work	6.7
StripMall	Strip mall - type 1	8	RetailSales	22.2
StripMall	Strip mall - type 2	8		
StripMall	Strip mall - type 3	8		
StripMall	–	–	Break	6.7
StripMall	–	–	Hall	6.7
StripMall	–	–	MechElecRoom	2.2
StripMall	–	–	OfficeGeneral	4.4
StripMall	–	–	Restroom	19
StripMall	–	–	StockRoom	2.2

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Table 44. Warehouse Occupant Density Values by Space Type

Building Type	DOE Space Type	DOE Occupancy per Area (people/1000 ft^2)	DEER Space Type	DEER Occupancy per Area (people/1000 ft^2)
Warehouse	Office	1.96	OfficeGeneral	4.4
Warehouse	Fine	0	WarehouseUnCond	2.2
Warehouse	Bulk	0		
Warehouse	–	–	Restroom	19

Table 45. Occupancy Schedule Data Sources

Building Type	DOE Data Source	DEER Data Source
Small Office	ASHRAE	CPUC
Medium Office	ASHRAE	CPUC
Large Office	ASHRAE	CPUC
Primary School	Pless, Torcellini, and Long	CPUC
Secondary School	Pless, Torcellini, and Long	CPUC
Quick Service Restaurant	ASHRAE	CPUC
Full Service Restaurant	ASHRAE	CPUC
Small Hotel	Jiang et al.	CPUC
Large Hotel	Jiang et al.	CPUC
Hospital	Bonnema et al.	CPUC
Outpatient	Bonnema et al.	CPUC
Warehouse	Liu et al.	CPUC
Retail	ASHRAE	CPUC
Strip Mall	ASHRAE	CPUC

Table 46. Occupant Activity Schedules by Building Type

Schedule Name	Outside CA Activity Level (W/person)	Inside CA Activity Level (W/person)
Hospital	120	132–220
Large Hotel	120	117–220
Small Hotel	132	117–220
Outpatient	120	117–220
Quick Service Restaurant	120	132–220
Full Service Restaurant	120	132–220
Retail	120	132–220
Primary School	120	117–331
Secondary School	120	117–331
Warehouse	131.85	132–220
Small Office	120	117–220
Medium Office	120	117–220
Large Office	120	117–220

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Table 48. Mapping of Wall Construction Types from Database to ComStock

Database Type	Percent of Entries	ComStock Type	Note
FRAME	24.96%	SteelFramed	We believe that this mostly represents steel stud construction based on a survey of samples of this type
WOOD	23.93%	WoodFramed	Clearly meets wood-framed wall definition
MASONRY	20.78%	Mass	Could be CMU or brick veneer; both meet the definition of mass wall
STEEL	8.48%	SteelFramed	We believe that this mostly indicates curtain wall with steel framing for tall buildings, and steel stud for shorter buildings
BRICK	6.01%	Mass	Could either be structural brick or brick veneer; both meet the definition of mass wall
OTHER	4.49%	No Match	Meaning unclear
CONCRETE BLOCK	4.48%	Mass	Clearly meets mass wall definition
CONCRETE	3.34%	Mass	Clearly meets mass wall definition
TILT-UP (PRE-CAST CONCRETE)	1.59%	Mass	Clearly meets mass wall definition
METAL	1.26%	Metal Building	Clearly meets metal building definition
STONE	0.22%	No Match	Inconsistent, but often used to describe buildings with a small percentage of decorative stone veneer around the base of the wall. Insignificant fraction of stock
MIXED	0.21%	No Match	Meaning unclear from survey, and insignificant fraction
LOG	0.09%	No Match	Insignificant fraction
LIGHT	0.07%	No Match	Insignificant fraction
ADOBE	0.04%	No Match	Insignificant fraction
MANUFACTURED	0.03%	No Match	Meaning unclear from survey, and insignificant fraction
HEAVY	0.00%	No Match	Meaning unclear from survey, and insignificant fraction
DOME	0.00%	No Match	Meaning unclear from survey, and insignificant fraction

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Table 49. Input Distribution of Wall Construction Types by Climate Zone and Number of Stories

Climate	Mass	Metal Building	Steel Framed	Wood Framed
Cold (Zones 5–8)	51%	0%	40%	9%
1–2 stories	23%	1%	46%	30%
3–5 stories	38%	0%	35%	27%
6–10 stories	71%	0%	29%	0%
11–14 stories	57%	0%	43%	0%
15–25 stories	41%	0%	59%	0%
over 25 stories	33%	0%	67%	0%
Hot (Zones 1–3)	52%	0%	43%	5%
1–2 stories	46%	1%	33%	19%
3–5 stories	49%	0%	39%	12%
6–10 stories	64%	0%	36%	0%
11–14 stories	53%	0%	47%	0%
15–25 stories	34%	0%	66%	0%
over 25 stories	23%	0%	77%	0%
Mixed (Zone 4)	65%	0%	31%	4%
1–2 stories	43%	1%	40%	16%
3–5 stories	60%	0%	28%	12%
6–10 stories	78%	0%	22%	0%
11–14 stories	69%	0%	31%	0%
15–25 stories	56%	0%	44%	0%
over 25 stories	47%	0%	53%	0%
Grand Total	54%	0%	40%	7%

Table 50. 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	1A	2A	2B	3A	3B	4A	4B	4C	5A	5B	6A	6B	7	8
Mass	Pre-1980	4.3	4.3	4.3	4.4	4.3	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8
	1980–2004	1	2.9	2.4	3.4	3.4	8.3	5.3	10	10	7.1	14.1	12.7	16.4	21.3
	90.1-2004	1.7	1.7	1.7	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	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	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	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	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8
	1980–2004	1	6.7	4.2	7.7	6.3	11.2	10	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	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	17.5	17.5
	90.1-2010	10.8	10.8	10.8	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	16.7	16.7	16.7	20	20	20	20	22.7	25.6
Steel Framed	Pre-1980	4.3	4.3	4.3	4.4	4.3	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8
	1980–2004	1	6.7	4.2	7.7	6.3	11.2	10	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	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	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	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	13	15.6	15.6	15.6	18.2	18.2	20.4	20.4	20.4	27
Wood Framed	Pre-1980	4.3	4.3	4.3	4.4	4.3	5.6	5.4	5.7	6.4	6.2	6.9	6.9	7.4	8
	1980–2004	1	6.7	4.2	7.7	6.3	11.2	10	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	19.6
	90.1-2007	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	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	15.6	15.6	15.6	19.6	19.6	19.6	19.6	19.6	31.3

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Table 51. 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	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
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

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Table 52. Summary of Average Wall R-Value by ASHRAE Climate Zone and Wall Type

		Whole Wall Assembly R-Value by ASHRAE Climate Zone (ft^2*F*hr/Btu) Includes interior and exterior air films														
Wall Type	Energy Code	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Mass	90.1-2004	2.39	2.39		6.62	6.62		6.68	6.75	6.66	8.15	8.18	9.59			12.5
	90.1-2007	2.39	6.64	6.7	8.14	8.16		9.62	9.61	9.68	11.13	11.12	12.5	12.5	14.08	14.08
	90.1-2010	2.39	6.64		8.22	8.13		9.65		9.61	11.11	11.11	12.58	12.5		
	90.1-2013	2.39	6.66		8.2	8.13		9.67	9.61	9.61	11.16	11.11	12.5			
	DEER 1985			4.19		4.19	4.19		4.19	4.19		4.19				
	DEER 1996			4.19		4.19	4.19		4.19	4.19		4.19				
	DEER 2003					4.19	4.19		4.19	4.19		4.19		4.19		
	DEER 2007			4.19		4.19	4.19		4.19			4.19				
	DEER 2011			6.11		4.52	4.19		5.01	4.63		6.11				
	DEER 2014					4.7	4.19									
	DEER 2015					4.55	4.19		4.63			6.11				
	DEER 2017					4.66	4.19		4.63							
	DEER Pre-1975			4.19		4.19	4.19		4.19	4.19		4.19				
	1980–2004	2.4	2.98	2.48	3.5	3.52		8.35	5.31	9.98	10.01	7.2	14.05	12.61	16.3	21.28
	Pre-1980	4.42	4.39	4.38	4.48	4.44		5.65	5.58	5.76	6.45	6.3	6.96	7.08	7.46	8.0
Metal Building	90.1-2004	8.85	7.87		7.95			8.25			8.76	8.85	8.85			
	90.1-2007	7.34	7.8	8.85	8.22	8.85		8.85	8.85		8.72	8.73	8.85			
	90.1-2010		9.8		11.9	11.9		11.9			14.49	14.49				
	90.1-2013	10.64	8.4		10.19	8.4		20.0			20.0	17.66				
	1980–2004	2.4	6.7	4.17	7.72	6.47		11.14	10.0		12.22	12.37	15.38			
	Pre-1980	4.67	4.53	4.55	4.46	4.55		5.68	5.43	6.21	6.5	6.68	7.23			
Steel Framed	90.1-2004		8.06		8.22	8.06		8.09	8.06	8.06	11.97	11.98	11.97	11.9	15.62	
	90.1-2007	8.06	8.34	8.25	12.02	11.9		15.62	15.62	15.62	15.62	15.62	15.62	15.62	17.26	
	90.1-2010		8.3		11.9	11.9		15.62	15.62	15.62	15.62	15.62	15.62	15.62		
	90.1-2013		12.05	12.44	13.06	13.12		15.62	15.62	15.62	18.18	18.18	20.41			
	DEER 1985			7.65		7.65	7.65		7.65	7.65		7.65				
	DEER 1996			8.65		8.18	7.94		8.65	8.65		8.65				
	DEER 2003			8.65		8.19	8.18		8.65	8.65						
	DEER 2007			8.65		8.16	8.2		8.65			8.65				
	DEER 2011			16.81		16.12	14.84		16.81	10.88						
	DEER 2014			16.81		16.64	14.18									
	DEER 2015					16.18	14.64			10.88						
	DEER 2017			16.81		16.35	13.6			10.88						
	DEER Pre-1975			6.35		6.35	6.35		6.35	6.35		6.35				
	1980–2004	2.18	6.67	4.17	7.69	6.25		11.24	10.0	10.87	12.19	12.19	15.38	13.89	17.24	22.22
	Pre-1980	4.35	4.35	4.35	4.44	4.35		5.62	5.43	5.71	6.41	6.21	6.89	6.9	7.35	8.0
Wood Framed	90.1-2004	11.24	11.24		11.24	11.24		11.24	11.24	11.24	11.24	11.24	11.24	11.24	11.24	
	90.1-2007	11.24	11.24	11.24	11.24	11.24		11.3	11.24	11.53	15.69	15.66	19.61	19.61	19.61	27.78
	90.1-2010		11.24		11.24	11.24		11.36		11.24	15.7	15.71	19.61	19.61		
	90.1-2013	11.24	11.24	11.24	11.24	11.24		15.62	15.62	15.62	19.61	19.61	19.61	19.61		
	DEER 1985			11.99		12.01	12.02		12.07	11.99		11.99				
	DEER 1996					12.66	13.17		13.15	13.15		13.15		17.6		
	DEER 2003					12.75	12.16		13.15			13.15				
	DEER 2007					12.68	12.24			13.15		13.15				
	DEER 2011					16.66	14.66			17.63						
	DEER 2014					16.69	13.12									
	DEER 2015					16.19	13.2		17.63			17.63				
	DEER 2017					16.56	12.62			13.15						
	DEER Pre-1975					8.74	8.74		8.89	8.71		8.81		9.42		
	1980–2004	2.18	6.67	4.17	7.69	6.25		11.24	10.0	10.89	12.19	12.19	15.36	13.89	17.24	22.22
	Pre-1980	4.35	4.35	4.35	4.44	4.35		5.62	5.43	5.72	6.41	6.21	6.89	6.9	7.35	8.0

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Table 53. Window Property Data Sources

Source	Data Collection Year	Samples	Regions	Window Area	Panes	Glazing Type	Frame/ Thermal Break	Low-E Coating	Retrofit/ New	Window Vintage	U-Factor/ SHGC	Gas Fill
Guidehouse Survey	2020	800	National	P	P	P	P	P	P	P	P	P
NEEA CBSA	2014, 2018	1,996	WA, OR, MT, ID	P	P	P	P	P	P	P	P	
DOE Code Study	2016–2019	104	FL, IA, IL, NE	P	P	P	P	P			P	
CAEUS	2006	5,862	California		P	P	P	P				
EIA CBECS	2012	6,721	National		P	P			P			
EIA RECS	2015	858	National (Multi-family)	P	P		P	P				
Programs	2020	30	TX, CO, WA	P	P		P		P		P	
Other	2019	6	WA, TN	P	P	P	P	P				P
AAMA	2017	Summary Level	National (Sales)	P	P	P	P	P	P			
Manufacturer Data	2019	3,000+	National (Sales)		P	P	P	P	P			
Guidehouse Market Size Estimates	2020	Summary Level	National									

P = Present in Data Source

Table 54. Window Thermal Performance

Number of Panes	Glazing Type	Frame Material	Low-E Coating	Frame ID	WINDOW ID	U-Factor IP (Btu/h-ft^2-F)	SHGC	VLT
Single	Clear	Aluminum	No	5	2000	1.178	0.744	0.754
Single	Tinted/Reflective	Aluminum	No	5	2001	1.178	0.579	0.455
Single	Clear	Wood	No	9	2002	0.910	0.683	0.723
Single	Tinted/Reflective	Wood	No	9	2003	0.910	0.525	0.436
Double	Clear	Aluminum	No	5	2004	0.746	0.646	0.671
Double	Tinted/Reflective	Aluminum	No	5	2005	0.749	0.484	0.411
Double	Clear	Aluminum	Yes	5	2006	0.559	0.386	0.591
Double	Clear	Aluminum With Thermal Break	Yes	7	2007	0.499	0.378	0.591
Double	Tinted/Reflective	Aluminum	Yes	5	2008	0.557	0.274	0.359
Double	Tinted/Reflective	Aluminum With Thermal Break	Yes	7	2009	0.496	0.266	0.359
Triple	Clear	Aluminum With Thermal Break	Yes	8	2010	0.300	0.328	0.527
Triple	Tinted/Reflective	Aluminum With Thermal Break	Yes	8	2011	0.299	0.224	0.320

Table 55. Roof Assembly Thermal Performance (Outside California)

		Whole Roof Assembly R-Value by ASHRAE Climate Zone (ft^2*F*hr/Btu) Includes interior and exterior air films															
Roof Type	Energy Code	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
Attic and Other	Pre-1980	10	10	10	10	10	10	12	11	12	14	13	13	17	17	17	17
	1980–2004	14	15	22	14	21	11	17	17	16	19	20	20	22	20	25	32
	90.1-2004	29	29	29	29	29	29	29	29	29	29	29	29	37	37	37	37
	90.1-2007	29	37	37	37	37	37	37	37	37	37	37	37	37	37	37	48
	90.1-2010	29	37	37	37	37	37	37	37	37	37	37	37	37	37	37	48
	90.1-2013	37	37	37	37	37	37	48	48	48	48	48	48	48	48	59	59
IEAD	Pre-1980	10	10	10	10	10	10	12	11	12	14	13	13	17	17	17	17
	1980–2004	14	15	22	14	21	11	17	17	16	19	20	20	22	20	25	32
	90.1-2004	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	21
	90.1-2007	16	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
	90.1-2010	16	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
	90.1-2013	21	26	26	26	26	26	31	31	31	31	31	31	31	31	36	36
Metal Building	1980–2004	10	10	10	10	10	10	12	11	12	14	13	13	22	20	25	32
	90.1-2004	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	20
	90.1-2007	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	20
	90.1-2010	15	18	18	18	18	18	18	18	18	18	18	18	20	20	20	29
	90.1-2013	24	24	24	24	24	24	27	27	27	27	27	27	32	32	34	38

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Table 56. Roof Assembly Thermal Performance (Inside California)

		Whole Roof Assembly U-Value by CEC Climate Zone (Btu/ft^2*F*hr) Includes interior and exterior air films															
Roof Type	Energy Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
IEAD	DEER Pre-1975	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
	DEER 1985	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
	DEER 1996	18	18	18	18	18	13	13	13	13	13	18	18	18	18	18	18
	DEER 2003	18	18	18	18	18	13	13	13	13	18	18	18	18	18	18	18
	DEER 2007	20	20	20	20	20	13	13	13	13	20	20	20	20	20	20	20
	DEER 2011	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2014	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2015	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2017	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
Mass	DEER Pre-1975	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
	DEER 1985	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17
	DEER 1996	18	18	18	18	18	13	13	13	13	13	18	18	18	18	18	18
	DEER 2003	18	18	18	18	18	13	13	13	13	18	18	18	18	18	18	18
	DEER 2007	20	20	20	20	20	13	13	13	13	20	20	20	20	20	20	20
	DEER 2011	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2014	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2015	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2017	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
WoodFramed	DEER Pre-1975	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	DEER 1985	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	DEER 1996	18	18	18	18	18	13	13	13	13	13	18	18	18	18	18	18
	DEER 2003	18	18	18	18	18	13	13	13	13	18	18	18	18	18	18	18
	DEER 2007	20	20	20	20	20	13	13	13	13	20	20	20	20	20	20	20
	DEER 2011	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2014	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2015	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26
	DEER 2017	20	26	26	26	20	13	15	15	26	26	26	26	26	26	26	26

Table 57. Roof Construction Types

	DOE Ref and 90.1		DEER (CA only)	
Building Type	Construction Type	Building Category for Exterior Roofs	Construction Type	Building Category for Exterior Roofs
FullServiceRestaurant	IEAD	Nonresidential	WoodFramed	Nonresidential
Hospital	IEAD	Nonresidential	Mass	Nonresidential
LargeHotel	IEAD	Residential	IEAD	Residential
LargeOffice	IEAD	Nonresidential	Mass	Nonresidential
MediumOffice	IEAD	Nonresidential	Mass	Nonresidential
Outpatient	IEAD	Nonresidential	Mass	Nonresidential
PrimarySchool	IEAD	Nonresidential	WoodFramed	Nonresidential
QuickServiceRestaurant	IEAD	Nonresidential	WoodFramed	Nonresidential
Retail	IEAD	Nonresidential	IEAD	Nonresidential
SecondarySchool	IEAD	Nonresidential	WoodFramed	Nonresidential
SmallHotel	IEAD	Residential	WoodFramed	Residential
SmallOffice	IEAD	Nonresidential	WoodFramed	Nonresidential
StripMall	IEAD	Nonresidential	WoodFramed	Nonresidential
Warehouse	Metal Building*	Semiheated	WoodFramed	Nonresidential

*Except pre-1980, which assumes IEAD

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Table 58. Ground Contact Floor Thermal Performance

	F-Factor by ASHRAE Climate Zone (Btu/h*ft*F)							
Template	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7	CZ 8
DOE Ref Pre-1980	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.54
DOE Ref 1980–2004	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.54
90.1-2004	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.54
90.1-2007	0.73	0.73	0.73	0.73	0.73	0.54	0.52	0.52
90.1-2010	0.73	0.73	0.73	0.73	0.73	0.54	0.52	0.52
90.1-2013	0.73	0.73	0.73	0.52	0.52	0.51	0.51	0.43
DEER Pre-1975	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 1985	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 1996	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 2003	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 2007	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 2011	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 2014	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 2015	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
DEER 2017	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73

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Table 59. Interior Lighting Technologies

Lighting Technology	Generation	System Type	Fixture Type	Lamp Type	Fixture Min. Height (ft)	Fixture Max. Height (ft)	Source Efficacy (lumens/Watt)	Lamp Lumen Depreciation	Luminaire Dirt Depreciation	Lighting Loss Factor	Return Air Fraction	Radiant Fraction	Visible Fraction
T12	gen1_t12_incandescent	general	lamp	fluorescent	0	20	74	0.93	0.89	0.8277	0	0.31	0.2
HID High Bay Mercury Vapor	gen1_t12_incandescent	general	luminaire	HID	20	1,000	43	0.88	0.74	0.6512	0	0.465	0.2
Incandescent Decorative	gen1_t12_incandescent	supplemental	luminaire	incandescent	0	1,000	8.7	0.97	0.83	0.8051	0	0.125	0.2
Incandescent A-Shape	gen1_t12_incandescent	task	lamp	incandescent	0	1,000	10.3	0.97	0.81	0.7857	0	0.125	0.2
Incandescent Decorative	gen1_t12_incandescent	wall wash	luminaire	incandescent	0	1,000	8.7	0.97	0.81	0.7857	0	0.125	0.2
T8	gen2_t8_halogen	general	lamp	fluorescent	0	20	94.1	0.93	0.89	0.8277	0	0.31	0.2
HID High Bay Metal Halide	gen2_t8_halogen	general	luminaire	HID	20	1,000	90.2	0.88	0.74	0.6512	0	0.465	0.2
Halogen Decorative	gen2_t8_halogen	supplemental	luminaire	halogen	0	1,000	15	0.97	0.83	0.8051	0	0.125	0.2
Halogen A-Shape	gen2_t8_halogen	task	lamp	halogen	0	1,000	17.5	0.97	0.81	0.7857	0	0.125	0.2
Halogen Decorative	gen2_t8_halogen	wall wash	luminaire	halogen	0	1,000	15	0.97	0.81	0.7857	0	0.125	0.2
T5	gen3_t5_cfl	general	lamp	fluorescent	0	20	103.5	0.93	0.89	0.8277	0	0.31	0.2
HID High Bay Metal Halide	gen3_t5_cfl	general	luminaire	HID	20	1,000	90.2	0.88	0.74	0.6512	0	0.465	0.2
Compact Fluorescent Pin	gen3_t5_cfl	supplemental	luminaire	CFL	0	1,000	70.1	0.85	0.83	0.7055	0	0.35	0.2
Compact Fluorescent Screw	gen3_t5_cfl	task	lamp	CFL	0	1,000	62.4	0.85	0.81	0.6885	0	0.35	0.2
Compact Fluorescent Pin	gen3_t5_cfl	wall wash	luminaire	CFL	0	1,000	70.1	0.85	0.81	0.6885	0	0.35	0.2
LED Lamp Linear	gen4_led	general	lamp	LED	0	20	104	0.85	0.87	0.7395	0	0.365	0.2
LED Luminaire	gen4_led	general	luminaire	LED	0	20	96	0.85	0.85	0.7225	0	0.365	0.2
LED High Bay Luminaire	gen4_led	general	luminaire	LED	20	1,000	118	0.85	0.75	0.6375	0	0.465	0.2
LED Decorative	gen4_led	supplemental	luminaire	LED	0	1,000	87	0.85	0.9	0.765	0	0.165	0.2
LED Lamp General Purpose	gen4_led	task	lamp	LED	0	1,000	93	0.85	0.87	0.7395	0	0.165	0.2
LED Directional	gen4_led	wall wash	luminaire	LED	0	1,000	51	0.85	0.84	0.714	0	0.165	0.2
LED Lamp Linear	gen5_led	general	lamp	LED	0	20	116	0.85	0.87	0.7395	0	0.365	0.2
LED Luminaire	gen5_led	general	luminaire	LED	0	20	109	0.85	0.85	0.7225	0	0.365	0.2
LED High Bay Luminaire	gen5_led	general	luminaire	LED	20	1,000	132	0.85	0.75	0.6375	0	0.465	0.2
LED Decorative	gen5_led	supplemental	luminaire	LED	0	1,000	97	0.85	0.9	0.765	0	0.165	0.2
LED Lamp General Purpose	gen5_led	task	lamp	LED	0	1,000	105	0.85	0.87	0.7395	0	0.165	0.2
LED Directional	gen5_led	wall wash	luminaire	LED	0	1,000	57	0.85	0.84	0.714	0	0.165	0.2
LED Lamp Linear	gen6_led	general	lamp	LED	0	20	132	0.85	0.87	0.7395	0	0.365	0.2
LED Luminaire	gen6_led	general	luminaire	LED	0	20	126	0.85	0.85	0.7225	0	0.365	0.2
LED High Bay Luminaire	gen6_led	general	luminaire	LED	20	1,000	152	0.85	0.75	0.6375	0	0.465	0.2
LED Decorative	gen6_led	supplemental	luminaire	LED	0	1,000	111	0.85	0.9	0.765	0	0.165	0.2

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Lighting Technology	Generation	System Type	Fixture Type	Lamp Type	Fixture Min. Height (ft)	Fixture Max. Height (ft)	Source Efficacy (lumens/Watt)	Lamp Lumen Depreciation	Luminaire Dirt Depreciation	Lighting Loss Factor	Return Air Fraction	Radiant Fraction	Visible Fraction
LED Lamp General Purpose	gen6_led	task	lamp	LED	0	1,000	122	0.85	0.87	0.7395	0	0.165	0.2
LED Directional	gen6_led	wall wash	luminaire	LED	0	1,000	64	0.85	0.84	0.714	0	0.165	0.2
LED Lamp Linear	gen7_led	general	lamp	LED	0	20	145	0.85	0.87	0.7395	0	0.365	0.2
LED Luminaire	gen7_led	general	luminaire	LED	0	20	140	0.85	0.75	0.6375	0	0.365	0.2
LED High Bay Luminaire	gen7_led	general	luminaire	LED	20	1,000	167	0.85	0.75	0.6375	0	0.465	0.2
LED Decorative	gen7_led	supplemental	luminaire	LED	0	1,000	123	0.85	0.9	0.765	0	0.165	0.2
LED Lamp General Purpose	gen7_led	task	lamp	LED	0	1,000	136	0.85	0.87	0.7395	0	0.165	0.2
LED Directional	gen7_led	wall wash	luminaire	LED	0	1,000	71	0.85	0.84	0.714	0	0.165	0.2
LED Lamp Linear	gen8_led	general	lamp	LED	0	20	157	0.85	0.87	0.7395	0	0.365	0.2
LED Luminaire	gen8_led	general	luminaire	LED	0	20	152	0.85	0.75	0.6375	0	0.365	0.2
LED High Bay Luminaire	gen8_led	general	luminaire	LED	20	1,000	181	0.85	0.75	0.6375	0	0.465	0.2
LED Decorative	gen8_led	supplemental	luminaire	LED	0	1,000	133	0.85	0.9	0.765	0	0.165	0.2
LED Lamp General Purpose	gen8_led	task	lamp	LED	0	1,000	147	0.85	0.87	0.7395	0	0.165	0.2
LED Directional	gen8_led	wall wash	luminaire	LED	0	1,000	76	0.85	0.84	0.714	0	0.165	0.2

Lighting loss factor reference: PNNL 90.1 lighting subcommittee model
Source efficacy reference, gen1–gen3: DOE 2015 LMC Table C3
Source efficacy reference, gen4–gen8: DOE 2019 SSL Table D4
Radiant fraction references: ASHRAE RP 1282 and ASHRAE RP 1681

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Table 60. Interior Lighting Space Types

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Atrium	NA (typical all bldgs)	Atrium - first three floors	atrium_first_-three_floors	16.5	0.96	4	1	0.8	0	0	0	0	0	0	
Atrium	NA (typical all bldgs)	Atrium - each additional floor	atrium_each_-additional_floor	16.5	0.96	2	1	0.92	0	0	0	0	0	0	
Atrium	NA (typical all bldgs)	20 ft in height	atrium_less_than_-20ft	16.5	0.96	4	1	0.82	0	0	0	0	0	0.58	
Atrium	NA (typical all bldgs)	20 ft and 40 ft in height	atrium_20ft_to_-40ft	16.5	0.96	8	1	0.67	0	0	0	0	0	0.39	
Atrium	NA (typical all bldgs)	40 ft in height	atrium_greater_-than_40ft	19.5	0.96	10	1	0.62	0	0	0	0	0	0.34	
Audience Seating Area	Convention Center	Audience/Seating Area	audience_seating_-area_convention_-center	11	0.96	2	1	0.97	0	0	0	0	0	0	
Audience Seating Area	Fitness Center	Audience/Seating Area	audience_seating_-area_fitness_center	11	0.96	2	1	0.92	0	0	0	0	0	0	
Audience Seating Area	Auditorium	Audience/Seating Area	audience_seating_-area_auditorium_-auditorium	11	0.96	4	0.6	0.91	0	0	0.1	0.85	0.3	0.83	
Audience Seating Area	Auditorium	Audience/Seating Area	audience_seating_-area_education_-auditorium	11	0.96	4	0.9	0.91	0	0	0	0	0.1	0.73	changed wall wash fraction from 0.5 to 0.1, general fraction from 0.5 to 0.9
Audience Seating Area	Gymnasium	Audience Seating/Permanent Seating	audience_seating_-area_gymnasium	11	0.96	4	1	0.59	0	0	0	0	0	0	
Audience Seating Area	Motion Picture Theatre	Audience/Seating Area	audience_seating_-area_motion_-theatre	11	0.96	2	1	0.91	0	0	0	0.11	0	0	
Audience Seating Area	Performing Arts Theatre	Audience/Seating Area	audience_seating_-area_performing_-theatre	36.3	0.96	6	0.79	0.69	0	0	0	0	0.21	0.58	
Audience Seating Area	Sports Arena	Audience/Seating Area	audience_seating_-area_sports_arena	11	0.96	2	0.5	0.46	0.5	0.97	0	0	0	0	
Audience Seating Area	NA (typical all bldgs)	All other audience seating areas	audience_seating_-area_all_others	11	0.96	2	1	1.02	0	0	0	0	0	0	
Banking Activity Area	WHOLE BULDING ANALYSIS ONLY	Bank Customer Area	whole_building_-bank_activity_area	11	0.96	4	0.69	0.71	0	0	0	0	0.31	0.73	
Banking Activity Area	Office	Banking Activity Area	banking_activity_-area_office	33	0.96	4	0.86	0.71	0	0	0	0	0.14	0.73	
Workshop	Workshop	Workshop	classroom_-workshop	55	0.96	4	1	0.61	0	0.92	0	0	0	0	

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Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Classroom/Lecture/Training	NA (typical all bldgs)	Classroom/Lecture/Training	classroom	43.8	0.96	2	1	0.8	0	0.92	0	0	0	0.83	changed general fraction to 1.0
Computer Room	NA (typical all bldgs)	Computer Room	computer_room	55	0.96	2	1	0.92	0	0	0	0	0	0	
Conference/Meeting/Multipurpose Room	NA (typical all bldgs)	Conference Meeting/Multipurpose	conference_-meeting_-multipurpose	33	0.96	4	0.85	0.59	0.08	0.89	0	0	0.075	0.69	changed general fraction to 0.85, task and wall wash to 0.075
Conference/Meeting/Multipurpose Room	WHOLE BULDING ANALYSIS ONLY	Hotel/Conference Center - Conference/Meeting	whole_building_-conference_center	33	0.96	2	0.44	0.45	0.44	0.92	0	0	0.11	0.87	
Control Room	Manufacturing Facility	Equipment Room	control_room_-manufacturing_-facility	22	0.96	4	0.77	0.49	0.23	0.38	0	0	0	0	
Copy/Print Room	NA (typical all bldgs)	Copy/Print Room	copy_print_room	33	0.96	4	1	0.74	0	0	0	0	0	0	
Corridor	NA (typical all bldgs)	Corridor/Transition	corridor_all_other	16.5	0.96	8	1	0.64	0	0	0	0	0	0.6	changed general fraction to 1.0
Corridor	Manufacturing Facility	Corridor/Transition	corridor_-manufacturing_-facility	15.4	0.96	6	1	0.48	0	0	0	0	0	0	
Courtroom	Court House	Courtroom	courtroom	44	0.96	4	0.4	0.51	0.5	0.84	0	0	0.1	0.83	
Dining Areas	NA (typical all bldgs)	Dining Area	dining_areas_all_-other	28.6	0.96	2	0.85	0.79	0.05	0.92	0	0	0.1	0.83	changed general fraction to 0.85, task to 0.05, wall wash to 0.1
Dining Areas	Cafeteria or fast food	Dining Area	dining_areas_-cafeteria_or_fast_-food	22	0.96	2	0.85	0.79	0.05	0.92	0	0	0.1	0.83	changed general fraction to 0.85, task to 0.05, wall wash to 0.1
Dining Areas	Civil Services	Dining Area	dining_areas_-civil_services	16.5	0.96	4	1	0.71	0	0	0	0	0	0	
Dining Areas	Transportation	Dining Area	dining_areas_-transportation	16.5	0.96	4	0.63	0.85	0.38	0.34	0	0	0	0	
Dining Areas	Hotel	Dining Area	dining_areas_hotel	11	0.96	2	0.33	0.45	0.33	0.97	0	0	0.33	0.23	
Dining Areas	Motel	Dining Area	dining_areas_-motel	11	0.96	2	0.77	0.97	0.23	0.9	0	0	0	0	
Dining Areas	Lounge/Leisure Dining	Dining Area	dining_areas_-lounge_dining	11	0.96	2	0.59	1	0.25	0.45	0.16	0.9	0	0	

Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Dining Areas	Family Dining	Dining Area	dining_areas_-family_dining	22	0.96	2	0.70	0.92	0.09	0.45	0	0	0.22	0.9	
Electrical/Mechanical	NA (typical all bldgs)	Electrical/Mechanical	electrical_-mechanical	18.7	0.96	4	0.9	0.49	0.1	0.38	0	0	0	0	changed general fraction to 0.9, task fraction to 0.1
Emergency Vehicle Garage	Police/Fire Station	Fire Station Engine room	emergency vehicle garage_fire_-station_engine	33	0.96	2	1	0.8	0	0	0	0	0	0	
Emergency Vehicle Garage	NA (typical all bldgs)	Emergency Vehicle Garage	emergency vehicle garage	33	0.96	2	1	0.79	0	0	0	0	0	0	
Food Preparartion	NA (typical all bldgs)	Food Preparation	food_preparation	50	0.96	4	0.82	0.65	0.18	0.65	0	0	0	0	
Guest Room	NA (typical all bldgs)	Guest Room	guest_room	16.5	0.96	4	0	0.64	1	0.83	0	0	0	0	adjusted general fraction to force A19-style use
Laboratory	NA (All buildings)	Medical/Industrial Research Laboratory	laboratory_-medical_-industrial_research	55	0.96	4	0.79	0.59	0.21	0.77	0	0	0	0.64	
Laboratory	NA (All buildings)	Education Laboratory	laboratory_-education	50	0.96	4	0.84	0.59	0.02	0.48	0.04	0.73	0.10	0.64	
Laundry/Washing Area	WHOLE BULDING ANALYSIS ONLY	Laundry-Ironing Sorting	whole_building_-laundry	33	0.96	2	1	0.81	0	0	0	0	0	0	
Laundry/Washing Area	NA (typical all bldgs)	Laundry/Washing Area	laundry_washing_-area	33	0.96	2	1	0.81	0	0	0	0	0	0	
Loading Dock, Interior	NA (typical all bldgs)	Loading Dock, Interior	loading_dock_-interior	33	0.96	4	1	0.46	0	0	0	0	0	0	
Lobby	NA (typical all bldgs)	Lobby	lobby_all_other	11	0.96	2	0.69	0.45	0.14	0.92	0	0	0.17	0.75	
Lobby	WHOLE BULDING ANALYSIS ONLY	Elevator Lobbies	whole_building_-elevator_lobby	16.5	0.96	4	0.62	0.77	0.12	0.76	0	0	0.26	0.56	
Lobby	Hotel	Lobby	lobby_hotel	16.5	0.96	3	0.67	0.93	0	0	0	0.96	0.33	0.91	
Lobby	Performing Arts theatre	Lobby	lobby_perform-ing_theatre	27.5	0.96	7	0.86	0.72	0	0	0.14	0.29	0	0.76	
Lobby	Auditorium	Lobby	lobby_auditorium	25.3	0.96	2	0.43	0.97	0.13	0.45	0	0	0.43	0.75	
Lobby	Motion Picture Theatre	Lobby	lobby_motion_-picture_theatre	11	0.96	2	1	0.92	0	0	0	0	0	0	
Lobby	Religious Buildings	Lobby	lobby_religious_-buildings	16.5	0.96	4	0.67	0.77	0	0	0	0	0.33	0.76	

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Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Lobby	Post Office	Lobby	lobby_post_office	22	0.96	4	1	0.44	0	0	0	0	0	0.56	changed general fraction to 1 and Suppl. fraction to 0
Locker Room	Gymnasium/Fitness Center	Locker Room	locker_room	22	0.96	4	0.88	0.65	0.125	0.77	0	0	0	0	
Lounge/Breakroom	NA (typical all bldgs)	Mother's or Wellness Room	lounge_mother_-wellness	16.5	0.96	6	0.6	0.39	0.4	0.82	0	0	0	0	
Lounge/Breakroom	NA (typical all bldgs)	Lounge/Recreation	lounge_-breakroom_all_-other	22	0.96	2	0.9	0.92	0	0	0	0	0.1	0.82	changed general fraction to 0.9, wall wash to 0.1
Lounge/Breakroom	Hotel	Reception/Waiting	lounge_-breakroom_hotel	16.5	0.96	2	0.41	1	0	0	0.29	0.4	0.29	0.88	
Lounge/Breakroom	Motel	Reception/Waiting	lounge_-breakroom_motel	16.5	0.96	2	0.41	0.92	0	0	0.29	0.4	0.29	0.88	
Office	NA (typical all bldgs)	Office - enclosed <=250 ft2	office_enclosed_-less_than_250ft2	33	0.96	6	1	0.56	0	0.47	0	0	0	0	
Office	NA (typical all bldgs)	Office - enclosed and 250 ft2	office_enclosed_-greater_than_-250ft2	33	0.96	5	1	0.62	0	0.52	0	0	0	0	
Office	NA (typical all bldgs)	Office - open plan	office_open	38.5	0.96	2	0.88	0.76	0	0.74	0	0	0.12	0.91	
Parking Garage	Parking Garage	Garage Daylight Transition	parking_garage_-daylight_transition	50	0.96	2	1	0.67	0	0	0	0	0	0	
Parking Garage	Parking Garage	Parking	parking_garage	5	0.96	2	1	0.67	0	0	0	0	0	0	
Pharmacy	Hospital/Healthcare	Pharmacy	pharmacy	82.5	0.96	4	0.88	0.65	0.12	0.65	0	0	0	0	
Restroom	NA (typical all bldgs)	Restrooms (small/single)	restroom	16.5	0.96	10	0.9	0.51	0	0.69	0	0	0.1	0.57	changed general fraction to 0.9, wall wash to 0.1
Sales Area	Retail	Sales Area	retail_sales_area	44	0.96	4	0.9	0.6	0	0	0.06	0.83	0.04	0.56	changed general fraction to 0.9, Suppl. to 0.06, wall wash to 0.04
Seating Area	NA (typical all bldgs)	Seating Area, General	seating_area	11	0.96	2	1	1.02	0	0	0	0	0	0	
Security Screening	Security Screening	Airport/Transportation	security_-screening_airport	50	0.96	4	1	0.59	0	0	0	0	0	0	
Security Screening	Security Screening	Airport/Transportation Queue	security screen-ing_line_airport	30	0.96	4	1	0.59	0	0	0	0	0	0	

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Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Security Screening	Security Screening	General Security Screening	security_screening	30	0.96	4	1	0.9	0	0	0	0	0	0	
Stairway/Stairwell	NA (typical all bldgs)	Stairway	stairway	16.5	0.96	8	0.9	0.42	0.05	0.27	0	0	0.05	0	changed general fraction to 0.9, task to 0.05, wall wash to 0.05
Stairway/Stairwell	Assisted Living	Stairways	stairway_-assisted_living	100	0.96	8	0.67	0.36	0.33	0.27	0	0	0	0	
Stairway/Stairwell	NA (typical all bldgs)	Stairs - Inactive	stairway_inactive	16.5	0.96	8	1	0.42	0	0.27	0	0	0	0	
Stairway/Stairwell	NA (typical all bldgs)	Stairs - Inactive	stairway_incative2	11	0.96	8	0.5	0.36	0.5	0.27	0	0	0	0	
Stairway/Stairwell	NA (typical all bldgs)	Stairwell	stairwell	11	0.96	8	0.9	0.36	0.05	0.27	0	0	0.05	0	changed general fraction to 0.9, task to 0.05, wall wash to 0.05
Storage	WHOLE BULDING ANALYSIS ONLY	Office Common Activity Areas - Inactive Storage	whole_building_-storage	5.5	0.96	4	1	0.65	0	0	0	0	0	0	
Storage	NA (typical all bldgs)	Inactive storage	storage_inactive	5.5	0.96	4	1	0.65	0	0	0	0	0	0	
Storage	NA (typical all bldgs)	Active storage (50 ft2)	storage_active_-less_than_50ft2	11	0.96	8	1	0.42	0	0	0	0	0	0	
Storage	NA (typical all bldgs)	Active storage (50 ft2 and 1000 ft2)	storage_active_-50ft2_to_1000ft2	11	0.96	4	1	0.61	0	0	0	0	0	0	
Storage	NA (typical all bldgs)	All other storage rooms	storage_all_other	11	0.96	4	1	0.65	0	0	0	0	0	0	
Vehicular Maintenance Area	Automotive Facility	Garage Service/Repair	vehicular_-maintenance_-area_automotive_-facility	33	0.96	2	0.83	0.7	0.17	0.56	0	0	0	0	
Vehicular Maintenance Area	NA (typical all bldgs)	Vehicular Maintenance Area	vehicular_-maintenance_area	33	0.96	2	1	0.68	0	0	0	0	0	0	
Conference/Meeting/ Multipurpose Room	NA (typical all bldgs)	Conference Meeting/ Multipurpose	video_conference	33	0.96	4	0.67	0.59	0.17	0.89	0	0	0.17	0.69	reduced wall wash from 0.5 to 0.17 to sum to 1
Workshop	Workshop	Workshop	workshop	55	0.96	4	1	0.61	0	0	0	0	0	0	
Casino - Gaming Area	Casino	Slot Machine/Digital Gaming Area	casino_gaming_-area_slot_machine	22	0.96	3	0.8	0.91	0.1	0.34	0.1	0.42	0	0	
Casino - Gaming Area	Casino	Table Games Area	casino_gaming_-area_table_games	44	0.96	3	0.8	0.91	0.1	0.34	0.1	0.42	0	0	

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Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Casino - Gaming Area	Casino	High Limit Game Area	casino_gaming area_high_limit	55	0.96	2	0.7	0.98	0.2	0.4	0.1	0.5	0	0	
Casino - Gaming Area	Casino	Betting/Sports Book/Keno/Bingo Area	casino_gaming_-area_betting	33	0.96	3	0.8	0.91	0.1	0.34	0.1	0.42	0	0	
Convention Center	Convention Center	Exhibit space	convention_-center_exhibit_-space	33	0.96	2	1	0.81	0	0	0	0	0	0	
Correctional Facilities	Court House	Audience/Seating Area	correctional_-facilities_-courthouse_-seating_area	11	0.96	4	0.67	0.84	0	0	0	0	0.33	0.49	
Correctional Facilities	Police/Fire Stations	Audience/Seating Area	correctional_-facilities_police_-fire_stations_-seating_area	11	0.96	2	0.67	0.92	0	0	0	0	0.33	0.62	
Correctional Facilities	Penitentiary	Audience/Seating Area	correctional_-facilities_-penitentiary_-seating_area	33	0.96	2	1	0.91	0	0	0	0	0	0	
Correctional Facilities	Penitentiary	Classroom/Lecture/Training	correctional_-facilities_-penitentiary_-classroom	43.8	0.96	2	1	0.82	0	0	0	0	0	0	changed general fraction to 1 and Suppl. fraction to 0
Correctional Facilities	Penitentiary	Confinement Cells	correctional_-facilities_-penitentiary_-confinement_cells	27.5	0.96	4	0.91	0.73	0.09	0.68	0	0	0	0	
Correctional Facilities	Court House	Confinement Cells	correctional_-facilities_-court_house_-confinement_cells	22	0.96	4	0.91	0.73	0.09	0.68	0	0	0	0	
Correctional Facilities	Court House	Judges Chambers	correctional_-facilities_court_-house_judges_-chambers	33	0.96	6	0.86	0.57	0	0	0	0	0.14	0.72	
Correctional Facilities	Penitentiary	Dining Area	correctional_-facilities_-penitentiary_-dining_area	16.5	0.96	4	1	0.73	0	0	0	0	0	0	
Dormitory - Living Quarters	WHOLE BULDING ANALYSIS ONLY	Dormitory Study Hall	whole_building_-dormitory_study_-hall	33	0.96	4	0.88	0.74	0	0	0	0	0.12	0.73	
Dormitory - Living Quarters	WHOLE BULDING ANALYSIS ONLY	Dormitory Bedroom	whole_building_-dormitory_-bedroom	16.5	0.96	6	0.85	0.52	0.15	0.38	0	0.33	0	0	

Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Dormitory - Living Quarters	Dormitory	Living quarters	dormitory_living_quarters	16.5	0.96	6	0.85	0.52	0.15	0.38	0	0.33	0	0	
Dormitory - Living Quarters	Hotel	Living quarters	dormitory_hotel_living_quarters	16.5	0.96	4	0.77	0.44	0.23	0.73	0	0	0	0	
Dormitory - Living Quarters	Motel	Living quarters	dormitory_motel_living_quarters	16.5	0.96	4	0.77	0.44	0.23	0.73	0	0	0	0	
Facility for the Visually Impaired	Assisted Living	Chapel	facility_for_the_visually_impaired_chapel	35	0.96	2	0.86	0.92	0	0	0	0	0.14	0.9	
Facility for the Visually Impaired	Assisted Living	Corridor/Transition	facility_for_the_visually_impaired_corridor	30	0.96	8	0.90	0.31	0	0	0	0	0.1	0.56	
Dining Areas	Assisted Living	Dining Area	facility_for_the_visually_impaired_dining_areas	35	0.96	4	0.32	0.85	0.54	0.51	0.00	0.33	0.14	0.73	changed Suppl. coefficient to 0.33
Dining Areas	Assisted Living	Dining Area	facility_for_the_visually_impaired_dining_areas_senior	40	0.96	4	0.40	0.48	0.5	0.51	0	0	0.1	0.73	
Facility for the Visually Impaired	Visually Impaired Facility	Lobby	facility_for_the_visually_impaired_lobby	50	0.96	4	0.62	0.49	0.15	0.85	0.11	0.33	0.12	0.56	changed Suppl. coefficient to 0.33
Facility for the Visually Impaired	Assisted living	Restrooms	facility_for_the_visually_impaired_restrooms	35	0.96	6	0.82	0.46	0	0.69	0.18	0.33	0	0.57	changed Suppl. coefficient to 0.33
Fire Station - Sleeping Quarters	Police/Fire Station	Sleeping Quarters	police_fire_station_sleeping_quarters	5.5	0.96	4	0.5	0.65	0.5	0.43	0	0	0	0	
Gymnasium/Fitness Center	Fitness Center	Exercise Area	fitness_center_exercise_area	44	0.96	2	1	0.59	0	0	0	0	0	0	
Gymnasium/Fitness Center	Gymnasium	Fitness Area	fitness_center_fitness_area	44	0.96	2	1	0.59	0	0	0	0	0	0	
Gymnasium/Fitness Center	Gymnasium	Playing Area	fitness_center_playing_area	55	0.96	2	1	0.8	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Control Room (MRI/CT/Radiology/PET)	healthcare_imaging_equipment_control_room	35	0.96	6	1	0.56	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Exam/Treatment	healthcare_exam	55	0.96	6	1	0.58	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Emergency	healthcare_emergency_room	82.5	0.96	4	0.9	0.7	0.1	374	0	0	0	0	changed general fraction to 0.9, task fraction to 0.1

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Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Healthcare Facility	Hospital/Healthcare	Public Staff Lounge	healthcare_lounge_breakroom	22	0.96	4	0.9	0.77	0	0.77	0	0	0.1	0.64	changed general fraction to 0.9, task fraction to 0, wall wash to 0.1
Healthcare Facility	Hospital/Healthcare	Hospital Corridor	healthcare_corridor	33	0.96	4	0.9	0.71	0	0	0	0	0.1	0.83	changed general fraction to 0.9, wall wash to 0.1
Healthcare Facility	Hospital/Healthcare	Radiology/Imaging	healthcare_imaging	33	0.96	4	1	0.74	0	0.73	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Hospital/Medical supplies	healthcare_medical_supplies	33	0.96	4	1	0.74	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Hospital - Nursery	healthcare_nursery	33	0.96	4	1	0.59	0	0.84	0	0	0	0.73	
Healthcare Facility	Hospital/Healthcare	Laundry-Washing	heatlhcare_laundry	33	0.96	1	1	0.81	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Nurse station	healthcare_nurse_station	33	0.96	4	0.8	0.59	0.2	0.58	0	0	0	0.73	changed general fraction to 0.8, task fraction to 0.2
Healthcare Facility	Hospital/Healthcare	Physical therapy	healthcare_physical_therapy	44	0.96	4	0.8	0.59	0.2	0.59	0	0	0	0	changed general fraction to 0.8, task fraction to 0.2
Healthcare Facility	Hospital/Healthcare	Patient Room	healthcare_patient_room	33	0.96	4	0.46	0.73	0.54	0.7	0	0	0	0	changed general fraction from 0.435 to 0.457 and Suppl. fraction to 0
Healthcare Facility	Hospital/Healthcare	Operating Room	healthcare_operating_room	110	0.96	4	1	0.71	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Recovery	healthcare_recovery	55	0.96	4	0.89	0.73	0	0	0	0	0.11	0.73	
Healthcare Facility	Hospital/Healthcare	Active storage	healthcare_pharmacy_storage	33	0.96	4	1	0.61	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Active storage	healthcare_storage	22	0.96	4	1	0.61	0	0	0	0	0	0	
Healthcare Facility	Hospital/Healthcare	Telehealth	healthcare_telehealth	33	0.96	6	1	0.4	0	0	0	0	0	0.57	reduced wall wash to zero to sum to 1
Library	Library	Library-Audio Visual	library_library_audio_visual	11	0.96	2	0.91	0.79	0.09	0.65	0	0	0	0	
Library	Library	Stacks	library_stacks	33	0.96	2	0.38	0.68	0.62	0.82	0	0	0	0.66	

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Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Library	Library	Card File Cataloguing	library_card_file	33	0.96	2	0.83	0.9	0	0	0	0	0.17	0.66	
Library	Library	Reading Area	library_reading_-area	55	0.96	2	0.68	0.76	0.32	0.97	0	0	0	0	
Manufacturing Facility	Manufacturing Facility	Detailed manufacturing area	manufacturing_-facility_detailed	55	0.96	1	1	0.94	0	0	0	0	0	0	
Manufacturing Facility	Manufacturing Facility	Equipment Room	manufacturing_-facility_-equipment_room	22	0.96	4	0.77	0.49	0.23	0.38	0	0	0	0	
Manufacturing Facility	Manufacturing Facility	General Low Bay	manufacturing_-facility_low_bay	55	0.96	2	1	0.79	0	0	0	0	0	0	
Manufacturing Facility	Manufacturing Facility	General High Bay	manufacturing_-facility_high_bay	55	0.96	5	1	0.54	0	0	0	0	0	0	
Manufacturing Facility	Manufacturing Facility	Extra High Bay	manufacturing_-facility_extra_-high_bay	55	0.96	7	1	0.47	0	0	0	0	0	0	
Museum	Museum	Active Storage	museum_active_-storage	22	0.96	4	1	0.61	0	0	0	0	0	0	
Museum	Museum	General exhibition	museum_-exhibition	11	0.96	4	1	0.89	0	0	0	0	0	0	
Museum	Museum	Restoration	museum_-restoration	55	0.96	4	0.73	0.7	0.27	0.74	0	0	0	0	
Performing Arts Theater - Dressing Room	Auditorium	Dressing/Fitting Room	performing_arts_-theater_auditorium	22	0.96	4	0.68	0.74	0.32	0.81	0	0	0	0	
Performing Arts Theater - Dressing Room	Performing Arts theatre	Dressing/Fitting Room	performing_arts_-theater_dressing_-room	22	0.96	4	1	0.7	0	0	0	0	0	0	
Post Office - Sorting Area	Post Office	Sorting Area	post_office_-sorting_area	44	0.96	2	1	0.8	0	0	0	0	0	0	
Religious Facility	Religious	Audience/Seating Area	religious_facility_-audience_seating_-area	33	0.96	2	0.63	0.97	0.17	0.4	0	0	0.21	0.45	
Religious Facility	Religious Buildings	Fellowship Hall	religious_facility_-fellowship_hall	33	0.96	2	0.8	0.92	0.2	1.03	0	0	0	0	
Religious Facility	Religious	Worship - pulpit, choir	religious facility_-pulpit	33	0.96	2	0.63	0.97	0.17	0.4	0	0	0.21	0.91	
Retail Facilities	Retail	Dressing/Fitting Room	retail_dressing_-room	22	0.96	6	0.43	0.6	0.57	0.6	0	0	0	0	
Retail Facilities	WHOLE BULDING ANALYSIS ONLY	Barber Beauty Parlor	whole_building_-barber_salon	33	0.96	4	0.73	0.74	0.27	0.82	0	0	0	0	
Retail Facilities	WHOLE BULDING ANALYSIS ONLY	Manicure	whole_building_-nail_salon	38.5	0.96	4	0.73	0.74	0.27	0.82	0	0	0	0	
Retail Facilities	Retail	Mall Concourse	retail_mall_-concourse	22	0.96	2	0.71	0.97	0	0	0.29	0.4	0	0.75	

Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Retail Facilities	WHOLE BULDING ANALYSIS ONLY	Massage	whole_building_-massage	33	0.96	6	0.73	0.89	0.27	0.82	0	0	0	0	
Retail Facilities	Retail	Personal Services Sales Area	retail_personal_-services_sales_-area	25.3	0.96	4	0.9	0.59	0.06	0.85	0	0	0.04	0.56	changed general fraction to 0.9, task fraction to 0.06, wall wash fraction to 0.04
Retail Facilities	Retail	Mass Merchandising Sales Area	retail_mass_-merchandising_-sales_area	45.1	0.96	2	0.9	0.81	0.1	0.81	0	0	0	0	changed general fraction to 0.9, task fraction to 0.1
Retail Facilities	Retail	Retail 1/Supermarket Sales Area	retail_supermarket_sales_area	72.6	0.96	2	0.9	0.59	0.06	0.83	0	0	0.04	0.83	changed general fraction to 0.9, task fraction to 0.06, wall wash fraction to 0.04
Retail Facilities	Retail	Retail 2/Specialty Store Sales Area	retail_specialty_-store_sales_area	39.6	0.96	4	0.9	0.44	0.06	0.76	0	0	0.04	0.76	changed general fraction to 0.9, task fraction to 0.06, wall wash fraction to 0.04
Retail Facilities	Retail	Retail 3/Department Store Sales Area	retail_-department_-store_sales_area	55	0.96	2	0.9	0.79	0.06	0.97	0	0	0.04	0.75	changed general fraction to 0.9, task fraction to 0.06, wall wash fraction to 0.04
Retail Facilities	Retail	Retail 4/Fine Merchandise Sales Area	retail_fine_-merchandise_-sales_area	31.9	0.96	4	0.9	0.91	0.06	0.76	0	0	0.04	0.76	changed general fraction to 0.9, task fraction to 0.06, wall wash fraction to 0.04
Sports Arena	Sports Arena	Ring Sports Area	sports_arena_-ring_sports	110	0.96	2	1	0.82	0	0	0	0	0	0	
Sports Arena	Sports Arena	Class 1 -Court Sports Area	sports_arena_-class1	165	0.96	2	1	0.71	0	0	0	0	0	0	

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Continued from previous page

90.1 Space or Building Category	90.1 Building Type	90.1 Space Type Description	Prototype Lighting Space Type	Total Horizontal Illuminance (lumens/ft^2)	Room Surface Dirt Depreciation	Current Room Cavity Ratio	General Lighting Fraction	General Lighting Coefficient of Utilization	Task Lighting Fraction	Task Lighting Coefficient of Utilization	Suppl. Lighting Fraction	Suppl. Lighting Coefficient of Utilization	Wall Wash Lighting Fraction	Wall Wash Lighting Coefficient of Utilization	Notes
Sports Arena	Sports Arena	Class 2 - Court Sports Area	sports arena_-class2	110	0.96	2	1	0.68	0	0	0	0	0	0	
Sports Arena	Sports Arena	Class 3 - Court Sports Area	sports arena_-class3	82.5	0.96	2	1	0.79	0	0	0	0	0	0	
Sports Arena	Sports Arena	Class 4 - Court Sports Area	sports arena_-class4	55	0.96	2	1	0.79	0	0	0	0	0	0	
Sports Arena	Sports Arena	Class 1 - Natatorium	sports arena_-natatorium_class1	93.8	0.96	2	1	0.47	0	0	0	0	0	0	
Sports Arena	Sports Arena	Class 2 - Natatorium	sports arena_-natatorium_class2	62.5	0.96	2	1	0.47	0	0	0	0	0	0	
Sports Arena	Sports Arena	Class 3 - Natatorium	sports arena_-natatorium_class3	55	0.96	2	1	0.68	0	0	0	0	0	0	
Sports Arena	Sports Arena	Class 4 - Natatorium	sports arena_-natatorium_class4	33	0.96	2	1	0.68	0	0	0	0	0	0	
Transportation Facility	Transportation	Airport Hanger	transportation_-facility_airport_-hanger	55	0.96	7	1	0.47	0	0	0	0	0	0	
Transportation Facility	Transportation	Air/Train/Bus - Baggage Area	transportation facility_baggage_-area	22	0.96	2	0.45	0.92	0.3	0.76	0	0	0.25	0.87	
Transportation Facility	Transportation	Airport - Concourse	transportation facility_airport_-concourse	33	0.96	2	0.5	0.92	0.3	0.79	0	0	0.2	0.75	
Transportation Facility	Transportation	Passenger Loading	transportation_-facility_-passenger_loading	27.5	0.96	4	0.35	0.77	0.65	0.46	0	0	0	0	
Transportation Facility	Transportation	Terminal - Ticket counter	transportation facility_ticket_-counter	27.5	0.96	2	0.4	0.79	0.4	0.92	0	0	0.2	0.83	
Transportation Facility	Transportation	Reception/Waiting	transportation_-facility_reception	22	0.96	2	0.55	0.59	0	0	0	0	0.45	0.83	
Warehouse - Storage Area	Warehouse	Fine Material	warehouse_fine_-material	33	0.96	4	1	0.59	0	0	0	0	0	0	
Warehouse - Storage Area	Warehouse	Medium/Bulky Material	warehouse_bulk_-material	22	0.96	2	1	0.81	0	0	0	0	0	0	

Source: PNNL 90.1 Lighting Subcommittee Model, modified per Notes column

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Table 61. Interior Lighting Generation Start and End Years Used To Generate Gaussian Distributions

Generation	Start Year	End Year
gen1_t12_incandescent	1950	2040
gen2_t8_halogen	1980	2040
gen3_t5_cfl	1995	2035
gen4_led	2005	2040
gen5_led	2017	2040
gen6_led	2021	2040
gen7_led	2026	2040
gen8_led	2031	2043

Table 66. Electric Equipment Power Density by Space Type

Building Type	Space Type	Pre-1980	1980-2004	90.1-2004	90.1-2007	90.1-2010	90.1-2013
FullServiceRestaurant	Dining	2.5	2.5	2.5	2.5	2.5	2.5
	Basement	0.7	0.7	0.8	0.8	0.8	0.8
	Corridor	0.0	0.0	0.0	0.0	0.0	0.0
	Dining	1.0	1.0	1.0	1.0	1.0	1.0
	ER_Exam	1.5	1.5	1.5	1.5	1.5	1.5
	ER_NurseStn	1.4	1.4	1.4	1.4	1.4	1.4
	ER_Trauma	4.0	4.0	4.0	4.0	4.0	4.0
	ER_Triage	2.7	2.7	2.0	2.0	2.0	2.0
	HospitalOfficeFlr1						1.1
	HospitalOfficeFlr5						1.0
	ICU_NurseStn	2.0	2.0	2.0	2.0	2.0	2.0
	ICU_Open	3.0	3.0	3.0	3.0	3.0	3.0
	ICU_PatRm	3.0	3.0	3.0	3.0	3.0	3.0
	Lab	4.0	4.0	4.0	4.0	4.0	4.0
	Lobby	0.1	0.1	0.1	0.1	0.1	0.1
	NurseStn	1.0	1.0	1.0	1.0	1.0	1.0
	Office	1.0	1.0	1.0	1.0	1.0	1.0
	OR	4.0	4.0	4.0	4.0	4.0	4.0
	PatCorridor	0.0	0.0	0.0	0.0	0.0	0.0
	PatRoom	2.0	2.0	2.0	2.0	2.0	2.0
	PhysTherapy	1.5	1.5	1.5	1.5	1.5	1.5
Hospital	Radiology	4.9	4.9	10.0	10.0	10.0	10.0
	Banquet	6.3	6.3	6.3	6.3	6.3	6.3
	Basement	0.5	0.5	0.5	0.5	0.5	0.5
	Cafe	0.5	0.5	0.5	0.5	0.5	0.5
	Corridor	0.0	0.0	0.0	0.0	0.0	0.0
	GuestRoom	1.3	1.3	0.6	0.6	0.6	0.6
	GuestRoom2	1.3	1.3	1.0	1.0	1.0	1.0
	GuestRoom3	1.3	1.3	0.6	0.6	0.6	0.6
	GuestRoom4	1.3	1.3	1.0	1.0	1.0	1.0
	GuestRoom8			1.0	1.0	1.0	1.0
	Laundry	5.7	5.7	5.7	5.7	5.7	5.7
	Lobby	0.8	0.8	0.8	0.8	0.8	0.8
	Mechanical	0.5	0.5	0.5	0.5	0.5	0.5
	Retail	1.0	1.0	1.0	1.0	1.0	1.0
	Retail2	1.0	1.0	1.0	1.0	1.0	1.0
LargeHotel	Storage	0.3	0.3	0.3	0.3	0.3	0.3
	BreakRoom	5.6	5.6	5.6	4.5	4.5	4.5
	Classroom	0.9	0.9	0.9	0.9	0.9	0.9
	ClosedOffice	0.9	0.9	0.9	0.6	0.6	0.6
	Conference	1.0	1.0	1.0	0.4	0.4	0.4
	Corridor	0.3	0.3	0.3	0.2	0.2	0.2
	Dining	1.0	1.0	1.0	1.0	1.0	1.0
	Elec/MechRoom	0.3	0.3	0.3	0.3	0.3	0.3
	IT_Room	2.0	2.0	2.0	1.6	1.6	1.6
	Lobby	0.3	0.3	0.3	0.1	0.1	0.1
	MediumOffice - Breakroom	1.3	1.3	5.6	5.6	5.6	5.6
	MediumOffice - Classroom	1.2	1.2	0.9	0.9	0.9	0.9
	MediumOffice - ClosedOffice	1.2	1.2	0.9	0.9	0.9	0.9
	MediumOffice - Conference	1.3	1.3	1.0	1.0	1.0	1.0
	MediumOffice - Corridor	0.4	0.4	0.3	0.3	0.3	0.3
	MediumOffice - Dining	1.3	1.3	1.0	1.0	1.0	1.0
	MediumOffice - Elec/MechRoom	0.4	0.4	0.3	0.3	0.3	0.3
	MediumOffice - Lobby	0.4	0.4	0.3	0.3	0.3	0.3
	MediumOffice - OpenOffice	1.3	1.3	1.0	1.0	1.0	1.0

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Continued from previous page

Building Type	Space Type	Pre-1980	1980–2004	90.1-2004	90.1-2007	90.1-2010	90.1-2013
	MediumOffice - Restroom	0.4	0.4	0.3	0.3	0.3	0.3
	MediumOffice - Stair	0.0	0.0	0.0	0.0	0	0.0
	MediumOffice - Storage	0.0	0.0	0.0	0.0	0.0	0.0
	OfficeLarge Data Center	20.0	20.0	20.0	20.0	20.0	20.0
	OfficeLarge Main Data Center	45.0	45.0	45.0	45.0	45.0	45.0
	OpenOffice	1.0	1.0	1.0	0.7	0.7	0.7
	PrintRoom	5.4	5.4	5.4	2.8	2.8	2.8
	Restroom	0.3	0.3	0.3	0.1	0.1	0.1
	SmallOffice - Breakroom	1.3	1.3	5.6	5.6	5.6	5.6
	SmallOffice - Classroom	1.2	1.2	0.9	0.9	0.9	0.9
	SmallOffice - ClosedOffice	1.2	1.2	0.9	0.9	0.9	0.9
	SmallOffice - Conference	1.3	1.3	1.0	1.0	1.0	1.0
	SmallOffice - Corridor	0.4	0.4	0.3	0.3	0.3	0.3
	SmallOffice - Dining	1.3	1.3	1.0	1.0	1.0	1.0
	SmallOffice - Elec/MechRoom	0.4	0.4	0.3	0.3	0.3	0.3
	SmallOffice - Lobby	0.4	0.4	0.3	0.3	0.3	0.3
	SmallOffice - OpenOffice	1.3	1.3	1.0	1.0	1.0	1.0
	SmallOffice - Restroom	0.4	0.4	0.3	0.3	0.3	0.3
	SmallOffice - Stair	0.0	0.0	0.0	0.0	0.0	0.0
	SmallOffice - Storage	0.0	0.0	0.0	0.0	0.0	0.0
	Stair	0.0	0.0	0.0	0.0	0.0	0.0
	Storage	0.0	0.0	0.0	0.0	0.0	0.0
	Vending	3.9	3.9	3.9	3.9	3.9	3.9
	WholeBuilding - Lg Office	1.0	1.0	0.8	0.8	0.8	0.8
	WholeBuilding - Lg Office-basement			0.5	0.5	0.5	0.5
	WholeBuilding - Lg Office-others			0.8	0.8	0.8	0.8
	WholeBuilding - Md Office	1.0	1.0	0.8	0.8	0.8	0.8
Office	WholeBuilding - Sm Office	1.0	1.0	0.6	0.6	0.6	0.6
	Anesthesia	2.0	2.0	2.0	2.0	2.0	2.0
	BioHazard	0.1	0.1	0.1	0.1	0.1	0.1
	Cafe	1.0	1.0	1.0	1.0	1.0	1.0
	CleanWork	2.0	2.0	2.0	2.0	2.0	2.0
	Conference	1.0	1.0	1.0	1.0	1.0	1.0
	DressingRoom	1.1	1.1	1.1	1.1	1.1	1.1
	Elec/MechRoom	5.0	5.0	5.0	5.0	5.0	5.0
	ElevatorPumpRoom	0.0	0.0	5.3	5.3	3.5	2.1
	Exam	1.1	1.1	1.1	1.1	1.1	1.1
	Hall	0.4	0.4	0.4	0.4	0.4	0.4
	Hall_infil	0.4	0.4	0.4	0.4	0.4	0.4
	IT_Room	1.1	1.1	1.1	1.1	1.1	1.1
	Janitor	0.0	0.0	0.1	0.1	0.1	0.1
	Lobby	1.1	1.1	1.1	1.1	1.1	1.1
	LockerRoom	3.0	3.0	3.0	3.0	3.0	3.0
	Lounge	3.0	3.0	3.0	3.0	3.0	3.0
	MedGas	0.1	0.1	0.1	0.1	0.1	0.1
	MRI	53.3	53.3	10.0	10.0	10.0	10.0
	MRI_Control	1.1	1.1	10.0	10.0	10.0	10.0
	NurseStation	2.0	2.0	2.0	2.0	2.0	2.0
	Office	1.1	1.1	1.1	1.1	1.1	1.1
	OR	4.0	4.0	4.0	4.0	4.0	4.0
	OutpatientFloor2Work						0.9
	PACU	3.0	3.0	3.0	3.0	3.0	3.0
	PhysicalTherapy	1.5	1.5	1.5	1.5	1.5	1.5
	PreOp	2.0	2.0	2.0	2.0	2.0	2.0
	ProcedureRoom	3.0	3.0	3.0	3.0	3.0	3.0
	Reception	1.1	1.1	1.1	1.1	1.1	1.1
	Soil Work	2.0	2.0	2.0	2.0	2.0	2.0
	Stair	0.0	0.0	0.4	0.4	0.4	0.4
	Toilet	0.7	0.7	0.4	0.4	0.4	0.4
	Undeveloped	0.0	0.0	1.1	1.1	1.1	1.1
Outpatient	Xray	1.3	1.3	10.0	10.0	10.0	10.0
	Cafeteria	0.3	0.3	0.3	0.3	0.3	0.3
	Classroom	0.2	0.2	0.2	0.2	0.2	0.2
	ComputerRoom			0.2	0.2	0.2	0.2
	Corridor	0.0	0.0	0.0	0.0	0.0	0.0
	Gym	0.1	0.1	0.1	0.1	0.1	0.1
	Library	0.2	0.2	0.2	0.2	0.2	0.2
	Lobby	0.0	0.0	0.0	0.0	0.0	0.0
	Mechanical	0.0	0.0	0.1	0.1	0.1	0.1
	Office	0.1	0.1	0.1	0.1	0.1	0.1
PrimarySchool	Restroom	0.0	0.0	0.0	0.0	0.0	0.0

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Continued from previous page

Building Type	Space Type	Pre-1980	1980–2004	90.1-2004	90.1-2007	90.1-2010	90.1-2013
QuickServiceRestaurant	Dining	5.5	5.5	5.6	5.6	5.6	5.6
	Back_Space	0.6	0.6	0.6	0.6	0.6	0.6
	Core_Retail					0.2	0.2
	Entry	0.2	0.2	0.2	0.2	0.2	0.2
	Front_Retail					0.2	0.2
	Point_of_Sale	1.5	1.5	1.5	1.5	1.5	1.5
Retail	Retail	0.2	0.2	0.2	0.2	0.2	0.2
	Auditorium	0.4	0.4	0.1	0.1	0.1	0.1
	Cafeteria	0.1	0.1	0.2	0.2	0.2	0.2
	Classroom	0.2	0.2	0.3	0.3	0.3	0.3
	ComputerRoom			0.1	0.1	0.1	0.1
	Corridor	0.1	0.1	0.1	0.1	0.1	0.1
	Gym	0.2	0.2	0.2	0.2	0.2	0.2
	Gym - audience	0.1	0.1				
	Library	0.1	0.1	0.1	0.1	0.1	0.1
	Lobby	0.1	0.1	0.1	0.1	0.1	0.1
	Mechanical	0.1	0.1	0.2	0.2	0.2	0.2
	Office	0.2	0.2	0.1	0.1	0.1	0.1
SecondarySchool	Restroom	0.1	0.1	1.2	1.2	1.2	1.2
	Corridor	0.0	0.0	0.0	0.0	0.0	0.0
	Elec/MechRoom	198.2	198.2	198.2	198.2	198.2	198.2
	Exercise	1.1	1.1	1.7	1.7	1.7	1.7
	GuestLounge	1.4	1.4	2.4	2.4	2.4	2.4
	GuestRoom	1.3	1.3				0.1
	GuestRoom4Occ	1.3	1.3	1.1	1.1	1.1	1.1
	GuestRoom4Vac	1.3	1.3	1.1	1.1	1.1	1.1
	GuestRoom123Occ	1.3	1.3	1.1	1.1	1.1	1.1
	GuestRoom123Vac	1.3	1.3	1.1	1.1	1.1	1.1
	Laundry	2.0	2.0	2.6	2.6	2.6	2.6
	Mechanical	0.0	0.0	0.0	0.0	0.0	0.0
	Meeting	1.2	1.2	0.6	0.6	0.6	0.6
	Office	1.2	1.2	1.3	1.3	1.3	1.3
	PublicRestroom	1.0	1.0	0.0	0.0	0.0	0.0
	StaffLounge	7.2	7.2	2.0	2.0	2.0	2.0
	Stair	0.0	0.0	0.0	0.0	0.0	0.0
SmallHotel	Storage	0.0	0.0	0.0	0.0	0.0	0.0
	Strip mall - type 1	0.4	0.4	0.4	0.4	0.4	0.4
	Strip mall - type 2	0.4	0.4	0.4	0.4	0.4	0.4
StripMall	Strip mall - type 3	0.4	0.4	0.4	0.4	0.4	0.4
	Bulk	0.8	0.8	0.8	0.8	0.8	0.8
	Fine	0.0	0.0	0.0	0.0	0.0	0.0
Warehouse	Office	2.6	2.6	2.6	2.6	2.6	2.6

Table 84. Building Summary Statistics

Building Summary Statistic	Description
stat.hours_cooling_setpoint_not_met	Annual number of hours the building was not meeting the cooling thermostat set point tolerance for all of its zones
stat.hours_heating_setpoint_not_met	Annual number of hours the building was not meeting the heating thermostat set point tolerance for all of its zones
stat.air_system_fan_power_minimum_flow_fraction	Fan power design minimum airflow fraction for air systems
stat.air_system_fan_static_pressure	Fan static pressure for air systems
stat.air_system_fan_total_efficiency	Total air system fan efficiency
stat.average_cooling_setpoint_max	Average maximum cooling thermostat set point
stat.average_cooling_setpoint_min	Average minimum cooling thermostat set point
stat.average_wall_u_value	Average exterior wall u-value
stat.average_heating_setpoint_max	Average maximum heating thermostat set point
stat.average_heating_setpoint_min	Average minimum heating thermostat set point
stat.average_outdoor_air_fraction	Average outdoor air ventilation fraction
stat.average_roof_absorptance	Average roof absorptance
stat.average_roof_u_value	Average roof u-value
stat.building_fraction_cooled	Fraction of building that is served by a cooling system
stat.building_fraction_heated	Fraction of building that is served by a heating system
stat.daylight_control_fraction	Fraction of building lighting by floor area that is controlled by daylight sensors
stat.design_outdoor_air_flow_rate	Design outdoor air ventilation flow rate for air systems

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Continued from previous page

Building Summary Statistic	Description
stat.elevator_energy_consumption	Annual energy consumption of elevators
stat.exterior_lighting_power	Peak exterior lighting electricity usage
stat.hot_water_volume	Annual hot water usage by volume
stat.area_fraction_with_dcv	Fraction of floor area served by HVAC with DCV
stat.area_fraction_with_economizer	Fraction of floor area served by HVAC with economizer
stat.area_fraction_with_heat_recovery	Fraction of floor area served by HVAC with heat recovery
stat.area_fraction_with_motorized_oa_damper	Fraction of floor area served by HVAC with motorized outdoor air damper
stat.area_fraction_with_mz_vav_optimization	Fraction of floor area served by HVAC with multizone vav optimization
stat.area_fraction_with_supply_air_temperature_reset	Fraction of floor area served by HVAC with supply air temperature reset
stat.area_fraction_with_unoccupied_shutdown	Fraction of floor area served by HVAC with unoccupied shutdown
stat.average_boiler_efficiency	Average efficiency of boilers
stat.average_chiller_cop	Average cop of chillers
stat.average_gas_coil_efficiency	Average gas coil efficiency
stat.boiler_capacity	Sum of boiler capacity
stat.chiller_capacity	Sum of chiller capacity
stat.cooling_equipment_capacity	Sum of cooling equipment capacity
stat.hvac_count_boilers_0_to_300_kbtuh	Count of boilers in size range
stat.hvac_count_boilers_2500_plus_kbtuh	Count of boilers in size range
stat.hvac_count_boilers_300_to_2500_kbtuh	Count of boilers in size range
stat.hvac_count_chillers_0_to_75_tons	Count of chillers in size range
stat.hvac_count_chillers_150_to_300_tons	Count of chillers in size range
stat.hvac_count_chillers_300_to_600_tons	Count of chillers in size range
stat.hvac_count_chillers_600_plus_tons	Count of chillers in size range
stat.hvac_count_chillers_75_to_150_tons	Count of chillers in size range
stat.hvac_count_dx_cooling_0_to_30_kbtuh	Count of dx cooling equipment in size range
stat.hvac_count_dx_cooling_135_to_240_kbtuh	Count of dx cooling equipment in size range
stat.hvac_count_dx_cooling_240_to_760_kbtuh	Count of dx cooling equipment in size range
stat.hvac_count_dx_cooling_30_to_65_kbtuh	Count of dx cooling equipment in size range
stat.hvac_count_dx_cooling_65_to_135_kbtuh	Count of dx cooling equipment in size range
stat.hvac_count_dx_cooling_760_plus_kbtuh	Count of dx cooling equipment in size range
stat.hvac_count_dx_heating_0_to_30_kbtuh	Count of dx heating equipment in size range
stat.hvac_count_dx_heating_135_to_240_kbtuh	Count of dx heating equipment in size range
stat.hvac_count_dx_heating_240_plus_kbtuh	Count of dx heating equipment in size range
stat.hvac_count_dx_heating_30_to_65_kbtuh	Count of dx heating equipment in size range
stat.hvac_count_dx_heating_65_to_135_kbtuh	Count of dx heating equipment in size range
stat.hvac_count_furnace_0_to_30_kbtuh	Count of furnace equipment in size range
stat.hvac_count_furnace_135_to_240_kbtuh	Count of furnace equipment in size range
stat.hvac_count_furnace_240_plus_kbtuh	Count of furnace equipment in size range
stat.hvac_count_furnace_30_to_65_kbtuh	Count of furnace equipment in size range
stat.hvac_count_furnace_65_to_135_kbtuh	Count of furnace equipment in size range
stat.design_chiller_cop	Design cop of chiller
stat.dx_cooling_average_cop	DX cooling COP during operation averaged across all cooling coils
stat.dx_cooling_capacity_tons	Sum of dx cooling capacity
stat.dx_cooling_design_cop	DX cooling COP at rated conditions averaged across all cooling coils
stat.dx_cooling_design_seer_0_to_30_kbtuh	Design seer of dx cooling coils for 0–30 kBtuh equipment
stat.dx_cooling_design_seer_30_to_65_kbtuh	Design seer of dx cooling coils for 30–65 kBtuh equipment
stat.dx_cooling_design_eer_65_to_135_kbtuh	Design eer of dx cooling coils for 65–135 kBtuh equipment
stat.dx_cooling_design_ieer_65_to_135_kbtuh	Design ieer of dx cooling coils for 65–135 kBtuh equipment

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Continued from previous page

Building Summary Statistic	Description
stat.dx_cooling_design_eer_135_to_240_kbtuh	Design eer of dx cooling coils for 135–240 kBtuh equipment
stat.dx_cooling_design_ieer_135_to_240_kbtuh	Design ieer of dx cooling coils for 135–240 kBtuh equipment
stat.dx_cooling_design_eer_240_to_760_kbtuh	Design eer of dx cooling coils for 240–760 kBtuh equipment
stat.dx_cooling_design_ieer_240_to_760_kbtuh	Design ieer of dx cooling coils for 240–760 kBtuh equipment
stat.dx_cooling_design_eer_760_plus_kbtuh	Design eer of dx cooling coils for 760 plus kBtuh equipment
stat.dx_cooling_design_ieer_760_plus_kbtuh	Design ieer of dx cooling coils for 760 plus kBtuh equipment
stat.dx_heating_average_cop	Average dx heating cop
stat.dx_heating_average_minimum_operating_temperature	Average minimum operating temperature of DX heating coils
stat.dx_heating_capacity_at_17F	Sum of dx heating capacity at 17°F
stat.dx_heating_capacity_at_5F	Sum of dx heating capacity at 5°F
stat.dx_heating_capacity_at_rated	Sum of dx heating capacity
stat.dx_heating_design_cop	Design cop of dx heating coils
stat.dx_heating_design_cop_135_to_240_kbtuh	Design cop of dx heating coils for 135–240 kBtuh equipment
stat.dx_heating_design_cop_17f	Design cop of dx heating coils at 17°F
stat.dx_heating_design_cop_240_plus_kbtuh	Design cop of dx heating coils for 240 plus kBtuh equipment
stat.dx_heating_design_cop_5f	Design cop of dx heating coils at 5°F
stat.dx_heating_design_cop_65_to_135_kbtuh	Design cop of dx heating coils for 65–135 kBtuh equipment
stat.dx_heating_design_hspf_0_to_30_kbtuh	Design hspf of dx heating coils for 0–30 kBtuh equipment
stat.dx_heating_design_hspf_30_to_65_kbtuh	Design hspf of dx heating coils for 30–65 kBtuh equipment
stat.dx_heating_supplemental_capacity_electric	Sum of dx heating supplemental capacity electric
stat.dx_heating_supplemental_capacity_gas	Sum of dx heating supplemental capacity gas
stat.dx_heating_supplemental_capacity	Sum of dx heating supplemental capacity
stat.dx_heating_fraction_supplemental	Fraction of dx heating system load met by associated supplemental coil
stat.dx_heating_defrost_energy	Sum of defrost energy use of a dx heating coil
stat.dx_heating_ratio_defrost	Ratio of defrost energy use to total heating load of dx heating system
stat.dx_heating_hours_below_minus_20F	Number of hours with an outdoor air temperature below -20°F
stat.dx_heating_hours_below_0F	Number of hours with an outdoor air temperature below 0°F
stat.dx_heating_hours_below_5F	Number of hours with an outdoor air temperature below 5°F
stat.dx_heating_hours_below_17F	Number of hours with an outdoor air temperature below 17°F
stat.furnace_capacity	Sum of furnace capacity
stat.heating_equipment	Sum of heating equipment capacity
stat.interior_electric_equipment_eflh	Annual interior electric equipment effective full load hours
stat.interior_electric_equipment_power_density	Interior electric equipment power density
stat.interior_lighting_eflh	Annual interior lighting effective full load hours
stat.interior_lighting_power_density	Interior lighting power density
stat.internal_mass_area_ratio	Ratio of internal mass to floor area
stat.occupant_density_ppl_per_m_2	Occupant density, people per unit area
stat.occupant_eflh	Effective full load hours of occupants
stat.average_window_shgc	Solar heat gain coefficient of windows
stat.average_window_u_value	Conductivity of windows
stat.window_to_wall_ratio	Ratio of window area to exterior facade area

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Continued from previous page

Building Summary Statistic	Description
stat.zone_hvac_fan_power_minimum_flow_fraction	Fan power minimum flow fraction for zone HVAC equipment
stat.zone_hvac_fan_static_pressure	Fan static pressure for zone HVAC equipment
stat.zone_hvac_fan_total_efficiency	Fan total efficiency for zone HVAC equipment

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Table 62. Interior Lighting Generation Distributions for ComStock 90.1-2013 Code Year

Energy Code	Year	gen1_t12_incandescent	gen2_t8_halogen	gen3_t5_cfl	gen4_led	gen5_led	gen6_led	gen7_led	gen8_led
ComStock 90.1-2013	pre_1978	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1978	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1979	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1980	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1981	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1982	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1983	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1984	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1985	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1986	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1987	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1988	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1989	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1990	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1991	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1992	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1993	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1994	0	1	0	0	0	0	0	0
ComStock 90.1-2013	1995	0	0.990	0.010	0	0	0	0	0
ComStock 90.1-2013	1996	0	0.983	0.017	0	0	0	0	0
ComStock 90.1-2013	1997	0	0.992	0.008	0	0	0	0	0
ComStock 90.1-2013	1998	0	0.985	0.015	0	0	0	0	0
ComStock 90.1-2013	1999	0	0.987	0.013	0	0	0	0	0
ComStock 90.1-2013	2000	0	0.973	0.027	0	0	0	0	0
ComStock 90.1-2013	2001	0	0.981	0.019	0	0	0	0	0
ComStock 90.1-2013	2002	0	0.967	0.033	0	0	0	0	0
ComStock 90.1-2013	2003	0	0.966	0.034	0	0	0	0	0
ComStock 90.1-2013	2004	0	0.964	0.036	0	0	0	0	0
ComStock 90.1-2013	2005	0	0.911	0.040	0.049	0	0	0	0
ComStock 90.1-2013	2006	0	0.910	0.049	0.041	0	0	0	0
ComStock 90.1-2013	2007	0	0.887	0.050	0.062	0	0	0	0
ComStock 90.1-2013	2008	0	0.826	0.058	0.115	0	0	0	0
ComStock 90.1-2013	2009	0	0.810	0.047	0.143	0	0	0	0
ComStock 90.1-2013	2010	0	0.782	0.050	0.168	0	0	0	0
ComStock 90.1-2013	2011	0	0.738	0.055	0.207	0	0	0	0
ComStock 90.1-2013	2012	0	0.598	0.055	0.348	0	0	0	0
ComStock 90.1-2013	2013	0	0.670	0.043	0.287	0	0	0	0
ComStock 90.1-2013	2014	0	0.568	0.055	0.377	0	0	0	0
ComStock 90.1-2013	2015	0	0.553	0.059	0.387	0	0	0	0
ComStock 90.1-2013	2016	0	0.519	0.051	0.430	0	0	0	0
ComStock 90.1-2013	2017	0	0.413	0.042	0.313	0.231	0	0	0
ComStock 90.1-2013	2018	0	0.241	0.031	0.345	0.382	0	0	0
ComStock 90.1-2013	2019	0	0.191	0.022	0.264	0.523	0	0	0
ComStock 90.1-2013	2020	0	0.195	0.022	0.311	0.472	0	0	0
ComStock 90.1-2013	2021	0	0.146	0.011	0.196	0.551	0.096	0	0
ComStock 90.1-2013	2022	0	0.107	0.009	0.168	0.612	0.104	0	0
ComStock 90.1-2013	2023	0	0.058	0.006	0.116	0.738	0.082	0	0
ComStock 90.1-2013	2024	0	0.049	0.004	0.100	0.689	0.157	0	0
ComStock 90.1-2013	2025	0	0.037	0.003	0.069	0.695	0.195	0	0
ComStock 90.1-2013	2026	0	0.025	0.002	0.061	0.691	0.154	0.067	0
ComStock 90.1-2013	2027	0	0.017	0.002	0.043	0.594	0.213	0.131	0
ComStock 90.1-2013	2028	0	0.013	0.002	0.035	0.615	0.195	0.140	0
ComStock 90.1-2013	2029	0	0.011	0.001	0.024	0.463	0.236	0.264	0
ComStock 90.1-2013	2030	0	0.007	0.001	0.017	0.396	0.220	0.360	0
ComStock 90.1-2013	2031	0	0.00683	0.000283	0.012582	0.33231	0.167166	0.444878	0.03595
ComStock 90.1-2013	2032	0	0.009644	0.000405	0.013502	0.286907	0.163947	0.409868	0.115727
ComStock 90.1-2013	2033	0	0.004305	0.000171	0.009392	0.182943	0.142833	0.508719	0.151637
ComStock 90.1-2013	2034	0	0.005903	0.000172	0.008657	0.175607	0.096412	0.408274	0.304976
ComStock 90.1-2013	2035	0	0.002496	0.000182	0.005823	0.132581	0.089427	0.317155	0.452336
ComStock 90.1-2013	2036	0	0.003223	0	0.006906	0.097836	0.069061	0.310773	0.512201
ComStock 90.1-2013	2037	0	0.006475	0	0.005396	0.080264	0.051261	0.168623	0.687981
ComStock 90.1-2013	2038	0	0.005624	0	0.005624	0.07683	0.068294	0.130561	0.713066
ComStock 90.1-2013	2039	0	0.004154	0	0.004154	0.088266	0.046729	0.116822	0.739875
ComStock 90.1-2013	2040	0	0.006483	0	0.004862	0.068882	0.008104	0.060778	0.850891
ComStock 90.1-2013	2041	0	0	0	0	0	0	0	1
ComStock 90.1-2013	2042	0	0	0	0	0	0	0	1
ComStock 90.1-2013	2043	0	0	0	0	0	0	0	1

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Table 63. Parking; Values From Thornton et al. Table 4.17

Building Type	Building Area Per Spot (ft^2)	Units Per Spot	Students Per Spot	Beds Per Spot	Parking Area Per Spot (ft^2)
SmallOffice	250				405
MediumOffice	250				405
LargeOffice	620				405
Retail	285.7				405
StripMall	215				405
PrimarySchool			17		405
SecondarySchool			8		405
Outpatient	200				405
Hospital				0.83	405
SmallHotel		1			405
LargeHotel		1			405
Warehouse	1,000				405
QuickServiceRestaurant	100				405
FullServiceRestaurant	100				405

Table 64. Exterior Lighting Power

Template	Building Facade and Landscape Automatic Shutoff	Occupancy Setback Reduction	Base Site Allowance Power (W)	Base Site Allowance Fraction	Parking Areas and Drives (W/ft^2)	Main Entries (W/ft)	Other Doors (W/ft)	Entry Canopies (W/ft^2)	Building Facades (W/ft^2)	Loading Areas For Emergency Vehicles (W/ft^2)	Drive Through Windows and Doors (W)
Pre-1980	FALSE	0		0.05	0.18	30	25	10	0.25	4	400
1980–2004	FALSE	0		0.05	0.049749	30	25	1.5	0.25	4	400
90.1-2004	TRUE	0		0.05	0.041458	30	20	1.25	0.2	0.5	400
90.1-2007	TRUE	0		0.05	0.041458	30	20	1.25	0.2	0.5	400
90.1-2010	TRUE	0.3	750		0.027638	30	20	0.4	0.15	0.5	400
90.1-2013	TRUE	0.3	750		0.027638	30	20	0.4	0.15	0.5	400
90.1-2016	TRUE	0.3	750		0.027638	30	20	0.4	0.15	0.5	400
90.1-2019	TRUE	0.3	750		0.027638	30	20	0.4	0.15	0.5	400
DEER 1985	FALSE	0		0.05	0.036491	30	25	1.5	0.25	4	400
DEER 1996	FALSE	0		0.05	0.036491	30	25	1.5	0.25	4	400
DEER 2003	TRUE	0		0.05	0.036491	30	20	1.25	0.2	0.5	400
DEER 2007	TRUE	0		0.05	0.036491	30	20	1.25	0.2	0.5	400
DEER 2011	TRUE	0.3	750		0.036491	30	20	0.4	0.15	0.5	400
DEER 2014	TRUE	0.3	750		0.018246	30	20	0.4	0.15	0.408	125
DEER 2015	TRUE	0.3	750		0.018246	30	20	0.4	0.15	0.408	125
DEER 2017	TRUE	0.3	520		0.018246	21	21	0.4	0.05	0.408	125

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Table 65. Entryways; Values From Thornton et al. Table 4.18

Building Type	Rollup Doors (per 10,000 ft^2)	Entrance Doors (per 10,000 ft^2)	Other Doors (per 10,000 ft^2)	Entrance Canopies	Emergency Canopies	Canopy Size (ft^2)	Floor Area Per Drive Through Window (ft^2)
SmallOffice	0.47	2	2				
MediumOffice	0.13	1	3				
LargeOffice		1	3				
Retail	1.84	1	2.93				
StripMall	0.05	6	6.6				
PrimarySchool	0.07	2	3.3				
SecondarySchool	0.1	2	2.45				
Outpatient	0.1	1	5.19				
Hospital	0.03	2	3.8		1	720	
SmallHotel		2	28.91	1		720	
LargeHotel		2	2.27	1		1,620	
Warehouse	3.67	1	2				
QuickServiceRestaurant		2	1				2,500
FullServiceRestaurant		1	3				

Table 67. Passenger Elevators

Building Type	Avg. Area Per Passenger Elevator (ft^2)	Avg. Beds Per Passenger Elevator	Avg. Units Per Passenger Elevator
FullServiceRestaurant	15,000		
Hospital		100	
LargeHotel			75
LargeOffice	45,000		
MediumOffice	45,000		
Outpatient	15,000		
PrimarySchool	100,000		
QuickServiceRestaurant	15,000		
Retail	45,000		
SecondarySchool	100,000		
SmallHotel			75
SmallOffice	45,000		
StripMall	45,000		
Warehouse	100,000		

Table 68. Freight Elevators

Building Type	Avg. Area Per Freight Elevator (ft^2)	Avg. Beds Per Freight Elevator	Avg. Units Per Freight Elevator
Hospital		100	
LargeHotel			150
LargeOffice	500,000		
Warehouse	250,000		

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Table 69. Water Heating Efficiency by HVAC Template, Heater Capacity, and Fuel Type

Template	Fuel Type	Minimum Capacity (Btu/hr)	Maximum Capacity (Btu/hr)	Energy Factor Base (%)	Energy Factor Volume Derate (%/gal)	Standby Loss Base (Btu/hr)	Standby Loss Capacity Allowance	Standby Loss Volume Allowance (Btu/hr*gal)	Hourly Loss Base (%)	Hourly Loss Volume Allowance (%/gal)	Thermal Efficiency (%)	Notes
Pre-1980 Through 1980–2004	Electricity	0	40945.99	0.93	0.00132							From DOE Reference Buildings
	Electricity	40946	No max			20		35				
	Natural gas	0	No max								0.78	
90.1-2004 Through 2010	Electricity	0	40945.99	0.93	0.00132							From 90.1 Table 7.8
	Electricity	40946	No max			20		35				
	Natural gas	0	74999.99	0.62	0.0019							
	Natural gas	75000	No max				800	110			0.8	
90.1-2013	Electricity	0	40945.99	0.97	0.00132							From 90.1-2013 Table 7.8
	Electricity	40946	No max						0.3	27		
	Natural gas	0	74999.99	0.67	0.0019							
	Natural gas	75000	No max				800	110			0.8	
90.1-2016 Through 2019	Electricity	0	40945.99	0.96	0.0003							From 90.1 Table F-2, Rated Storage Volume <= 55 gal
	Electricity	40946	No max						0.3	27		
	Natural gas	0	74999.99	0.675	0.0015							From 90.1 Table F-2, Rated Storage Volume <= 55 gal
	Natural gas	75000	No max				800	110			0.8	

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Table 70. Service Water Heating Flow Rate and Schedule Assignments Based on Template, Building Type, and Space Type (Part 1 of 3)

Template	Building Type	Space Type	Service Water Heating Peak Flow per Area (gal/h*ft^2)	Service Water Heating Schedule
All	FullServiceRestaurant	Kitchen	0.08861	RestaurantSitDown BLDG_SWH_SCH
All	Hospital	ER_Exam	0.00333	Hospital BLDG_-SWH_EXTD_SCH
All	Hospital	ER_Trauma	0.00333	Hospital BLDG_-SWH_EXTD_SCH
All	Hospital	ER_Triage	0.00333	Hospital BLDG_-SWH_EXTD_SCH
All	Hospital	Kitchen	0.015	Hospital BLDG_-SWH_EXTD_SCH
All	Hospital	Lab	0.0007	Hospital BLDG_-SWH_SCH
All	Hospital	OR	0.00333	Hospital BLDG_-SWH_SCH
All	Hospital	PatRoom	0.00357	Hospital BLDG_-SWH_EXTD_SCH
All	Hospital	PhysTherapy	0.00019	Hospital BLDG_-SWH_SCH
All	Hospital	Radiology	0.00019	Hospital BLDG_-SWH_EXTD_SCH
All	LargeHotel	GuestRoom	0.00298	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom2	0.00473	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom2	0.08994	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom3	0.00298	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom4	0.00473	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom4	0.0426	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom5	0.0036	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom6	0.00294	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom7	0.00215	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	GuestRoom8	0.00473	HotelLarge GuestRoom_SWH_Sch
All	LargeHotel	Kitchen	0.1196	HotelLarge BLDG_-SWH_SCH
90.1-2004 and Later	LargeHotel	Laundry	0.18643	HotelLarge LaundryRoom_SWH_Sch_-Post2004
Pre 90.1-2004	LargeHotel	Laundry	0.18643	HotelLarge LaundryRoom_SWH_Sch_-Pre2004

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Table 71. Service Water Heating Flow Rate and Schedule Assignments Based on Template, Building Type, and Space Type (Part 2 of 3)

Template	Building Type	Space Type	Service Water Heating Peak Flow per Area (gal/h*ft^2)	Service Water Heating Schedule
Pre 90.1-2004	Office	MediumOffice - Elec/MechRoom	0.01845	Medium Office Bldg Swh
90.1-2004 and Later	Office	MediumOffice - Elec/MechRoom	0.03171	OfficeMedium BLDG_SWH_SCH
All	Office	Restroom	0.20471	OfficeLarge BLDG_-SWH_SCH
All	Office	SmallOffice - Elec/MechRoom	0.00055	OfficeSmall BLDG_-SWH_SCH
Pre 90.1-2004	Office	WholeBuilding - Lg Office	0.00013	OfficeLarge BLDG_-SWH_SCH
90.1-2004 and Later	Office	WholeBuilding - Lg Office	0.00052	OfficeLarge BLDG_-SWH_SCH
All	Office	WholeBuilding - Lg Office-basement	0.00052	OfficeLarge BLDG_-SWH_SCH
All	Office	WholeBuilding - Lg Office-others	0.00052	OfficeLarge BLDG_-SWH_SCH
Pre 90.1-2004	Office	WholeBuilding - Md Office	0.00055	OfficeMedium BLDG_SWH_SCH
90.1-2004 and Later	Office	WholeBuilding - Md Office	0.00095	OfficeMedium BLDG_SWH_SCH
All	Office	WholeBuilding - Sm Office	0.00055	OfficeSmall BLDG_-SWH_SCH
All	Retail	Back_Space	0.00535	RetailStandalone BLDG_SWH_SCH
All	SecondarySchool	Gym	0.0075	SchoolSecondary BLDG_SWH_SCH
All	SecondarySchool	Gym - audience	0.0075	SchoolSecondary BLDG_SWH_SCH
All	SecondarySchool	Kitchen	0.0572	SchoolSecondary BLDG_SWH_SCH
All	SecondarySchool	Restroom	0.0231	SchoolSecondary BLDG_SWH_SCH
All	SmallHotel	GuestRoom	0.00499	HotelSmall Gue-stRoom_SHW_Sch
Pre 90.1-2004	SmallHotel	GuestRoom123Occ	0.00499	HotelSmall Gue-stRoom_SHW_Sch
90.1-2004 and Later	SmallHotel	GuestRoom123Occ	0.00632	HotelSmall Gue-stRoom_SHW_Sch
Pre 90.1-2004	SmallHotel	GuestRoom123Vac	0.00499	HotelSmall Gue-stRoom_SHW_Sch
90.1-2004 and Later	SmallHotel	GuestRoom123Vac	0.00632	HotelSmall AlwaysOff
Pre 90.1-2004	SmallHotel	GuestRoom4Occ	0.00499	HotelSmall Gue-stRoom_SHW_Sch
90.1-2004 and Later	SmallHotel	GuestRoom4Occ	0.00632	HotelSmall Gue-stRoom_SHW_Sch
Pre 90.1-2004	SmallHotel	GuestRoom4Vac	0.00499	HotelSmall Gue-stRoom_SHW_Sch
90.1-2004 and Later	SmallHotel	GuestRoom4Vac	0.00632	HotelSmall AlwaysOff
All	SmallHotel	Laundry	0.0641	HotelSmall Laundry-Room_SHW_Sch

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Table 72. Service Water Heating Flow Rate and Schedule Assignments Based on Template, Building Type, and Space Type (part 3 of 3)

Template	Building Type	Space Type	Service Water Heating Peak Flow per Area (gal/h*ft^2)	Service Water Heating Schedule
Pre 90.1-2004	Outpatient	Anesthesia	0.00926	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	Anesthesia	0.01852	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	MRI	0.00227	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	MRI	0.00455	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	MRI_Control	0.00595	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	MRI_Control	0.0119	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	OR	0.01271	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	OR	0.02542	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	PACU	0.00316	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	PACU	0.00633	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	PhysicalTherapy	0.00106	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	PhysicalTherapy	0.00211	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	PreOp	0.0038	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	PreOp	0.00759	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	ProcedureRoom	0.00351	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	ProcedureRoom	0.00702	OutPatientHealthCare BLDG_SWH_SCH
Pre 90.1-2004	Outpatient	Xray	0.00111	OutPatientHealthCare BLDG_SWH_SCH_-Pre2004
90.1-2004 and Later	Outpatient	Xray	0.00222	OutPatientHealthCare BLDG_SWH_SCH
All	PrimarySchool	Kitchen	0.05531	SchoolPrimary BLDG_SWH_SCH
All	PrimarySchool	Restroom	0.02763	SchoolPrimary BLDG_SWH_SCH
Pre 90.1-2004	QuickServiceRestaurant	Kitchen	0.032	QuickServiceRestaurant Bldg Swh
90.1-2004 and Later	QuickServiceRestaurant	Kitchen	0.032	RestaurantFastFood BLDG_SWH_SCH

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Table 73. Unitary DX Cooling Efficiency and Performance Curve Assignment

Template	Minimum Capacity (Btu/hr)	Maximum Capacity (Btu/hr)	Minimum Seasonal Energy Efficiency Ratio (SEER)	Minimum Energy Efficiency Ratio (EER)*	Minimum Integrated Part Load Value (kW/ton)*	Capacity Function of Temperature	Capacity Function of Airflow	EIR Function of Temperature	EIR Function of Airflow	EIR Function of PLR
Pre-1980	-	64,999	11.06	-	-	DX Clg Coil Cool-Cap-fT	DX Clg Coil Cool-CAP-fFlow	DX Clg Coil Cool-EIR-fT	DX Clg Coil Cool-EIR-fFlow	DX Clg Coil Cool-PLF-fPLR
Pre-1980	65,000	134,999	-	9.63	-					
Pre-1980	135,000	239,999	-	9.28	-					
Pre-1980	240,000	759,999	-	8.92	-					
Pre-1980	760,000	no max	-	8.63	-					
1980–2004	-	64,999	9.7		-					
1980–2004	65,000	134,999	-	8.9	8.3					
1980–2004	135,000	759,999	-	8.5	7.5					
1980–2004	760,000	no max	-	8.2	7.5					
90.1-2004	-	64,999	9.7		-	CoilClg_DXQRatio_fTwbToadbSI	CoilClg_DXSngl_QRatio_fCFMRatio	CoilClg_DXEIRRatio_fTwbToadbSI	CoilClg_DXSnglEIRRatio_fCFMRatio	CoilClg_DXEIRRatio_fQFrac
90.1-2004	65,000	134,999	-	10.1	-					
90.1-2004	135,000	239,999	-	9.5	-					
90.1-2004	240,000	759,999	-	9.3	9.5					
90.1-2004	760,000	no max	-	9	9.2					
90.1-2007	-	64,999	13	-	-					
90.1-2007	65,000	134,999	-	10.1	-					
90.1-2007	135,000	239,999	-	9.5	-					
90.1-2007	240,000	759,999	-	9.3	9.5					
90.1-2007	760,000	no max	-	9	9.2					
90.1-2010	-	64,999	13	-	-	PSZ-Fine Storage DX Coil Cap-FT	DX Coil Cap-FF	PSZ-AC DX Coil EIR-FT	Split DX Coil EIR-FF	HPACCOOLPLFFPLR
90.1-2010	65,000	134,999	-	11	-					
90.1-2010	135,000	239,999	-	10.8	-	PSZ-AC-Cool-CLennox-Standard-10Ton-TGA120S2B-CapFT	AHU-1-CoolC-Standard-10Ton-CapFF	PSZ-AC-CoolC-Standard-10Ton-EIRFT	CoolC-Lennox-Standard10-Ton-TGA120S2B-EIRFFF	PSZ-AC-CoolC-Lennox-Standard-10Ton-TGA120S2BPLR
90.1-2010	240,000	759,999	-	9.8	-					
90.1-2010	760,000	no max	-	9.5	9.2					
90.1-2013	-	64,999	13		-	PSZ-AC_Unitary_PackagecoolCapFT	PSZ-AC_Unitary_PackagecoolFFF	PSZ-AC DX Unitary Package EIRFT	PSZ-AC_Unitary_PackagecoolEIRFFF	PSZ-AC_Unitary_PackagecoolPLR
90.1-2013	-	64,999	14		-					
90.1-2013	65,000	134,999	-	11	11.2					
90.1-2013	135,000	239,999	-	10.8	11					
90.1-2013	240,000	759,999	-	9.8	9.9					
90.1-2013	760,000	no max	-	9.5	9.6					
90.1-2013	65,000	134,999	-	11	12.7					
90.1-2013	135,000	239,999	-	10.8	12.2					
90.1-2013	240,000	759,999	-	9.8	11.4					
90.1-2013	760,000	no max	-	9.5	11					
90.1-2016	-	64,999	14		-					
90.1-2016	65,000	134,999	-	11	11.2					
90.1-2016	135,000	239,999	-	10.8	11					
90.1-2016	240,000	759,999	-	9.8	9.9					
90.1-2016	760,000	no max	-	9.5	9.6					
90.1-2019	-	64,999	14	-	-					
90.1-2019	65,000	134,999	-	11	12.7					
90.1-2019	135,000	239,999	-	10.8	12.2					
90.1-2019	240,000	759,999	-	9.8	11.4					
90.1-2019	760,000	no max	-	9.5	11					

*EER and kW/ton are 0.2 higher when electric resistance heating is used.

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Table 74. PTAC DX Cooling Efficiency and Performance Curve Assignment

<table>
<tr><th>Template</th><th>Minimum Capacity (Btu/hr)</th><th>Maximum Capacity (Btu/hr)</th><th>Minimum Energy Efficiency Ratio (EER)</th><th>PTAC_-EER_-Coefficient_1</th><th>PTAC_-EER_-Coefficient_2</th><th>Capacity Function of Temperature</th><th>Capacity Function of Airflow</th><th>EIR Function of Temperature</th><th>EIR Function of Airflow</th><th>EIR Function of PLR</th></tr>
<tr><td>Pre-1980</td><td>-</td><td>no max</td><td></td><td>10</td><td>0.16</td><td rowspan="2">DOE Ref DX Clg Coil</td><td rowspan="2">DOE Ref DX Clg Coil</td><td rowspan="2">DOE Ref DX Clg Coil</td><td rowspan="2">DOE Ref DX Clg Coil</td><td rowspan="2">DOE Ref DX Clg Coil</td></tr>
<tr><td>1980–2004</td><td>-</td><td>no max</td><td></td><td>10</td><td>0.16</td></tr>
<tr><td>90.1-2004</td><td>-</td><td>no max</td><td></td><td>12.5</td><td>0.213</td><td rowspan="8">Cool-Cap-fT
PSZ-Fine Storage DX Coil Cap-FT</td><td rowspan="8">Cool-CAP-fFlow
DX Coil Cap-FF</td><td rowspan="8">Cool-EIR-fT
PSZ-AC DX Coil EIR-FT</td><td rowspan="8">Cool-EIR-fFlow
Split DX Coil EIR-FF</td><td rowspan="8">Cool-PLF-fPLR
HPAC-COOLPL-FFPLR</td></tr>
<tr><td>90.1-2007</td><td>-</td><td>no max</td><td></td><td>12.5</td><td>0.213</td></tr>
<tr><td>90.1-2010</td><td>-</td><td>no max</td><td></td><td>13.8</td><td>0.3</td></tr>
<tr><td>90.1-2013</td><td>-</td><td>no max</td><td></td><td>14</td><td>0.3</td></tr>
<tr><td>90.1-2016</td><td>-</td><td>no max</td><td></td><td>14</td><td>0.3</td></tr>
<tr><td>90.1-2019</td><td>-</td><td>6,999</td><td>11.9</td><td></td><td></td></tr>
<tr><td>90.1-2019</td><td>6,999</td><td>14,999</td><td></td><td>14</td><td>0.3</td></tr>
<tr><td>90.1-2019</td><td>14,999</td><td>no max</td><td>9.5</td><td></td><td></td></tr>
</table>

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Table 75. Motor Efficiency for Fans and Pumps

Template	Minimum Capacity (HP)	Maximum Capacity (HP)	Nominal Full Load Efficiency (%)	Notes
Pre-1980 Through 90.1-2007	0	0.999	29.00%	PNNL Motors <1 HP
	1	1.499	82.50%	From 90.1 Table 10.8B
	1.5	2.999	84.00%	
	3	7.499	87.50%	
	7.5	14.999	89.50%	
	15	24.999	91.00%	
	25	39.999	92.40%	
	40	59.999	93.00%	
	60	74.999	93.60%	
	75	99.999	94.10%	
	100	149.999	94.50%	
	150	9999	95.00%	
90.1-2010	0	0.999	29.00%	PNNL Motors <1 HP
	1	1.499	85.50%	From 90.1 Table 10.8B
	1.5	2.999	86.50%	
	3	7.499	89.50%	
	7.5	14.999	91.70%	
	15	19.999	92.40%	
	20	24.9999	93.00%	
	25	39.999	93.60%	
	40	49.999	94.10%	
	50	59.999	94.50%	
	60	74.999	95.00%	
	75	149.999	95.40%	
	150	199.999	95.80%	
	200	9999	96.20%	
90.1-2013 Through 90.1-2019	0	0.0833	29.00%	PNNL Motors <1 HP
	0.08334	0.999	70.00%	
	1	1.499	85.50%	From 90.1 Table 10.8B
	1.5	2.999	86.50%	
	3	7.499	89.50%	
	7.5	14.999	91.70%	
	15	19.999	92.40%	
	20	24.999	93.00%	
	25	39.999	93.60%	
	40	49.999	94.10%	
	50	59.999	94.50%	
	60	74.999	95.00%	
	75	149.999	95.40%	
	150	199.999	95.80%	
	200	249.999	96.20%	
	250	299.999	95.00%	
	300	9999	95.40%	

All motors >1 HP are assumed to be enclosed, four-pole motors with a synchronous speed of 1,800 RPM.

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Table 76. AHU Unoccupied Operation Mode Percentages by Building Type Informed by BAS Data Source

Building Type	Scheme1	Scheme2	Scheme3
All Types	27%	50%	23%
Full Service Restaurant	36%	54%	10%
Large Office	54%	35%	11%
Medium Office	54%	35%	11%
Primary School	12%	37%	36%
Quick-Service Restaurant	36%	54%	10%
Grocery	27%	37%	36%
Retail	14%	56%	30%
Secondary School	12%	37%	36%
Small Office	54%	35%	11%
Strip Mall	14%	56%	30%
Warehouse	57%	29%	14%

Table 77. Fraction of Floor Area Controlled by HVAC System With DCV by Building Type and Code Year

Building Type	DOE Ref Pre-1980	DOE Ref 1980–2004	90.1-2004	90.1-2007	90.1-2010	90.1-2013	DEER: All Years
FullService-Restaurant	0	0	0	0.349	0.072	0.085	0
Hospital	0	0	0	0	0	0	0
LargeHotel	0	0	0	0.001	0.001	0.016	0
LargeOffice	0	0	0	0	0	0	0
MediumOffice	0	0	0	0	0	0	0
Outpatient	0	0	0	0.036	0.028	0.027	0
PrimarySchool	0	0	0	0.111	0.009	0.046	0
QuickService-Restaurant	0	0	0	0.05	0.008	0.045	0
RetailStandalone	0	0	0	0	0	0	0
RetailStripmall	0	0	0	0.105	0.043	0.026	0
SecondarySchool	0	0	0	0.045	0.004	0.054	0
SmallHotel	0	0	0	0.004	0	0	0
SmallOffice	0	0	0	0	0	0	0
Warehouse	0	0	0	0	0	0	0

Table 78. Boiler Performance Curves

Name	Form	Dependent Variable	Independent Variable 1	coefficient 1	coefficient 2	coefficient 3	coefficient 4	Notes
Boiler Constant Efficiency Curve	Cubic	Efficiency Multiplier	Part Load Ratio	1	0	0	0	From DOE Reference Building
Boiler With Minimum Turndown				0.7791	1.4745	-2.5795	1.3467	From Regression of Prototype Building EMS
Boiler With No Minimum Turndown				0.7463	1.3196	-2.2154	1.1674	From Regression of Prototype Building EMS

Table 79. Air-Source Heat Pump Performance Curves

Template	Subcategory	Minimum Capacity (Btu/hr)	Maximum Capacity (Btu/hr)	Capacity Function of Temperature	Capacity Function of Airflow	EIR Function of Temperature	EIR Function of Airflow	EIR Function of PLR
Pre-1980 Through 90.1-2010	All	All	All	DXHEAT-NECB2011-REF-CAPFT	DXHEAT-NECB2011-REF-CAPFFLOW	DXHEAT-NECB2011-REF-EIRFT	DXHEAT-NECB2011-REF-EIRFFLOW	DXHEAT-NECB2011-REF-PLFFPLR
90.1-2013 Through 90.1-2019	PTHP	0	no max					
	Split System, Single Package	0	29,999					
	Split System	0	64,999	HPACHeat-CapFT	HPACHeat-CapFFF	HPACHeat-EIRFT	HPACHeat-EIRFFF	HPACCOOL-PLFFPLR
	Single Package	0	64,999					
	Single Package	65,000	134,999					
	Single Package	135,000	no max					

Table 80. Air-Cooled Chiller Performance Curves

Schedule Name	Form	Dep. Var	Ind. Var 1	Ind. Var 2	coeff_1	coeff_2	coeff_3	coeff_4	coeff_5	coeff_6	Notes
AirCooled_-Chiller_2010_-PathA_CAPFT	Biquadratic	QRatio	Tchws	Toadb	1.0433825	0.0407073	0.0004506	-0.00415	-8.9E-05	-0.00035	Based on Dick Lord's study dated January 17, 2010.
AirCooled_-Chiller_2010_-PathA_EIRFT	Biquadratic	EIR_-Ratio	Tchws	Toadb	0.5961915	-0.00995	0.0007888	0.000451	0.000488	-0.00076	
AirCooled_-Chiller_All-Capacities_-2004_2010_-EIRFPLR	Quadratic	EIR_-Ratio	PLR	-	1.41E-01	6.55E-01	2.03E-01	-	-	-	
ChlrAir_Re-cipQRatio_-fTchwsToad-bSI	Biquadratic	QRatio	Tchws	Toadb	1.12603	0.041571	0.000253	-0.01053	0.00001	-0.00026	From CBECC Ap-pendix_-3.7_-Perfor-mance_-Curves-S901G_-.xlsx
ChlrAir_-RecipEIRRa-tio_fTchw-sToadbSI	Biquadratic	EIR_-Ratio	Tchws	Toadb	0.542784	-0.013907	0.000476	0.012197	0.000149	-0.00033	
ChlrAir_-RecipEIRRa-tio_fQRatio	Quadratic	EIR_-Ratio	PLR	-	0.114437	0.545933	0.342299	-	-	-	
ChlrAir_-ScrollEIRRa-tio_fTchw-sToadbSI	Biquadratic	EIR_-Ratio	Tchws	Toadb	0.702194	-0.004466	0.000535	-0.00551	0.000544	-0.00073	
ChlrAir_Scrol-lQRatio_fTch-wsToadbSI	Biquadratic	QRatio	Tchws	Toadb	1.02138	0.037021	0.000233	-0.00389	-6.5E-05	-0.00027	
ChlrAir_-ScrollEIRRa-tio_fQRatio	Quadratic	EIR_-Ratio	PLR	-	0.063691	0.584888	0.352803	-	-	-	

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Table 81. Water-Cooled Chiller Performance Curves

Schedule Name	Form	Dependent Var	Ind. Var 1	Ind. Var 2	coeff_1	coeff_2	coeff_3	coeff_4	coeff_5	coeff_6	Notes
ChlrWtr-PosDisp-PathAAll-EIRRatio_-fQRatio	Quadratic	EIRPLR	QRatio		0.310965	0.322519	0.372745				From CBECC Appendix_-3.7_-Performance_-Curves-S901G.xlsx
ChlrWtr-PosDisp-PathAAll-QRatio_-fTchw-sTcwsSI	Biquadratic	CapFT	Tchws	Tcws	0.96744	0.037082	0.000434	-0.00584	-4.9E-05	-0.00027	
ChlrWtr-PosDisp-PathAAll-EIRRatio_-fTchw-sTcwsSI	Biquadratic	EIRFT	Tchws	Tcws	0.665307	-0.009339	0.000483	0.009492	0.000544	-0.00086	
WaterCooled_-PositiveDisplacement_-Chiller_-LT150_-2010_-PathA_-CAPFT	Biquadratic	CapFT	Tchws	Toadb	0.906115	0.029228	-0.00036	-0.00097	-9.1E-05	0.000253	Based on Dick Lord's study dated January 17, 2010.
WaterCooled_-PositiveDisplacement_-Chiller_-LT150_-2010_-PathA_-EIRFT	Biquadratic	EIRFT	Tchws	Toadb	0.361711	-0.022983	0.000952	0.013189	0.000375	-0.00071	

Table 82. Walk-In Refrigeration Data

Walk-in Type	Vintage	Rated Cooling Capacity (BTU/h)	Defrost Power (W)	Floor Surface Area (ft^2)	Fan Power (W)	Lighting Power (W)
Primary School Cooler	all	9,200	0	120	200	120
Secondary School Cooler	all	19,100	0	240	400	240
Large Hotel Cooler	all	9,200	0	120	200	120
Hospital Cooler	all	27,000	0	360	600	360
Quick Service Restaurant Cooler	90.1-2010 and older	7,700	0	100	200	100
Full Service Restaurant Cooler	90.1-2010 and older	7,700	0	100	200	100
Quick Service Restaurant Cooler	90.1-2013 and newer	7,700	0	100	188.5	100
Full Service Restaurant Cooler	90.1-2013 and newer	7,700	0	100	188.5	100
Primary School Freezer	all	9,200	2,000	120	250	120
Secondary School Freezer	all	18,300	3,000	240	500	240
Large Hotel Freezer	all	9,200	2,000	120	250	120
Hospital Freezer	all	27,500	4,000	360	760	360
Quick Service Restaurant Freezer	90.1-2010 and older	5,700	2,000	80	180	80
Full Service Restaurant Freezer	90.1-2010 and older	5,700	2,000	80	180	80
Quick Service Restaurant Freezer	90.1-2013 and newer	5,700	2,000	80	51.6	80
Full Service Restaurant Freezer	90.1-2013 and newer	5,700	2,000	80	51.6	80

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Table 83. Refrigeration Compressor Data

Template	Compressor Type	Power Curve	Capacity Curve	Rated capacity (BTU/h)
90.1-2010 and older	Medium Temperature	MT_compressor_-power_smallandold	MT_compressor_-capacity_smallan-dold	17,599.82
90.1-2010 and older	Low Temperature	LT_compressor_-power_smallandold	LT_compressor_ca-pacity_smallandold	36,499.679
90.1-2013 and newer	Medium Temperature	MT_compressor_-power	MT_compressor_-capacity	143,415.725
90.1-2013 and newer	Low Temperature	LT_compressor_-power	LT_compressor_-capacity	50,567.94

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Table 85. Cooking equipment quantities by food service type and comstock building type

Restaurant Type	ComStock Building Type	Fraction of Building Type	Griddle	Fryer	Broiler	Oven	Range	Steamer
Restaurant A	full_service_restaurant	0.42	1	2	1	1	1	0
Restaurant B	full_service_restaurant	0.01	1	2	2	2	2	3
Restaurant C	full_service_restaurant	0.13	1	3	4	2	2	1
Chinese A	full_service_restaurant	0.16	0	2	0	1	1	1
Chinese B	full_service_restaurant	0.03	0	3	1	2	1	2
Pancake	full_service_restaurant	0.01	2	2	0	0	0	0
Grills	full_service_restaurant	0.02	1	1	0	0	1	0
Diner	full_service_restaurant	0.02	1	1	0	0	0	0
Pubs/Taverns	full_service_restaurant	0.21	1	2	1	2	2	3
Hospitals Large	hospital	0.75	1	2	1	10	1	10
Hospitals Small	hospital	0.25	0	2	0	4	2	5
Hotel A	large_hotel	0.69	0	3	3	4	6	3
Hotel B	large_hotel	0.31	1	2	1	1	1	1
None	large_office	1.00	0	0	0	0	0	0
None	medium_office	1.00	0	0	0	0	0	0
None	outpatient	1.00	0	0	0	0	0	0
None	primary_school	0.70	0	0	0	0	0	0
High School	primary_school	0.30	2	2	1	4	3	2
Burger A	quick_service_restaurant	0.06	1	3	1	0	0	0
Burger B	quick_service_restaurant	0.10	3	3	0	1	0	0
Chicken A	quick_service_restaurant	0.06	1	10	0	1	0	1
Chicken B	quick_service_restaurant	0.04	0	4	1	5	0	1
Fish A	quick_service_restaurant	0.01	1	4	1	2	1	2
Fish B	quick_service_restaurant	0.07	1	4	0	0	0	0
Hot Dog	quick_service_restaurant	0.01	1	2	0	0	0	1
Pizza A	quick_service_restaurant	0.14	0	1	0	1.5	0	1
Pizza B	quick_service_restaurant	0.14	0	1	0	2	0	0
Roast Beef	quick_service_restaurant	0.01	0	2	0	1	0	0
Donut	quick_service_restaurant	0.12	0	1	0	2	0	0
Muffin	quick_service_restaurant	0.02	0	0	0	3	0	0
Potato	quick_service_restaurant	0.02	1	3	0	0	0	0
Cookie	quick_service_restaurant	0.01	0	0	0	1	0	0
Cafe	quick_service_restaurant	0.14	0	1	0	0	1	0
Truck Stop	quick_service_restaurant	0.01	1	1	0	0	1	0
Dept. Stores	quick_service_restaurant	0.04	1	2	1	2	2	3
None	retail	1.00	0	0	0	0	0	0
None	secondary_school	0.65	0	0	0	0	0	0
High School	secondary_school	0.35	2	2	1	4	3	2
None	small_hotel	1.00	0	0	0	0	0	0
None	small_office	1.00	0	0	0	0	0	0
Burger A	strip_mall	0.06	1	3	1	0	0	0
Burger B	strip_mall	0.10	3	3	0	1	0	0
Chicken A	strip_mall	0.06	1	10	0	1	0	1
Chicken B	strip_mall	0.04	0	4	1	5	0	1
Fish A	strip_mall	0.01	1	4	1	2	1	2
Fish B	strip_mall	0.07	1	4	0	0	0	0
Hot Dog	strip_mall	0.01	1	2	0	0	0	1
Pizza A	strip_mall	0.14	0	1	0	1.5	0	1
Pizza B	strip_mall	0.14	0	1	0	2	0	0
Roast Beef	strip_mall	0.01	0	2	0	1	0	0
Donut	strip_mall	0.12	0	1	0	2	0	0
Muffin	strip_mall	0.02	0	0	0	3	0	0
Potato	strip_mall	0.02	1	3	0	0	0	0
Cookie	strip_mall	0.01	0	0	0	1	0	0
Cafe	strip_mall	0.14	0	1	0	0	1	0
Truck Stop	strip_mall	0.01	1	1	0	0	1	0
Dept. Stores	strip_mall	0.04	1	2	1	2	2	3
None	warehouse	1.00	0	0	0	0	0	0

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Table 86. Average Undisturbed Ground Temperature by Climate Zone

2012 IECC Climate zone	Annual average undisturbed ground temperature (C)
1A	25.9
2A	20.9
2B	25
3A	17.9
3B	19.7
3C	17
4A	14.7
4B	16.3
4C	13.3
5A	11.5
5B	12.9
6A	9
6B	9.3
7A	7
7AK	5.4
7B	6.5
8AK	2.3

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Appendix B Figures

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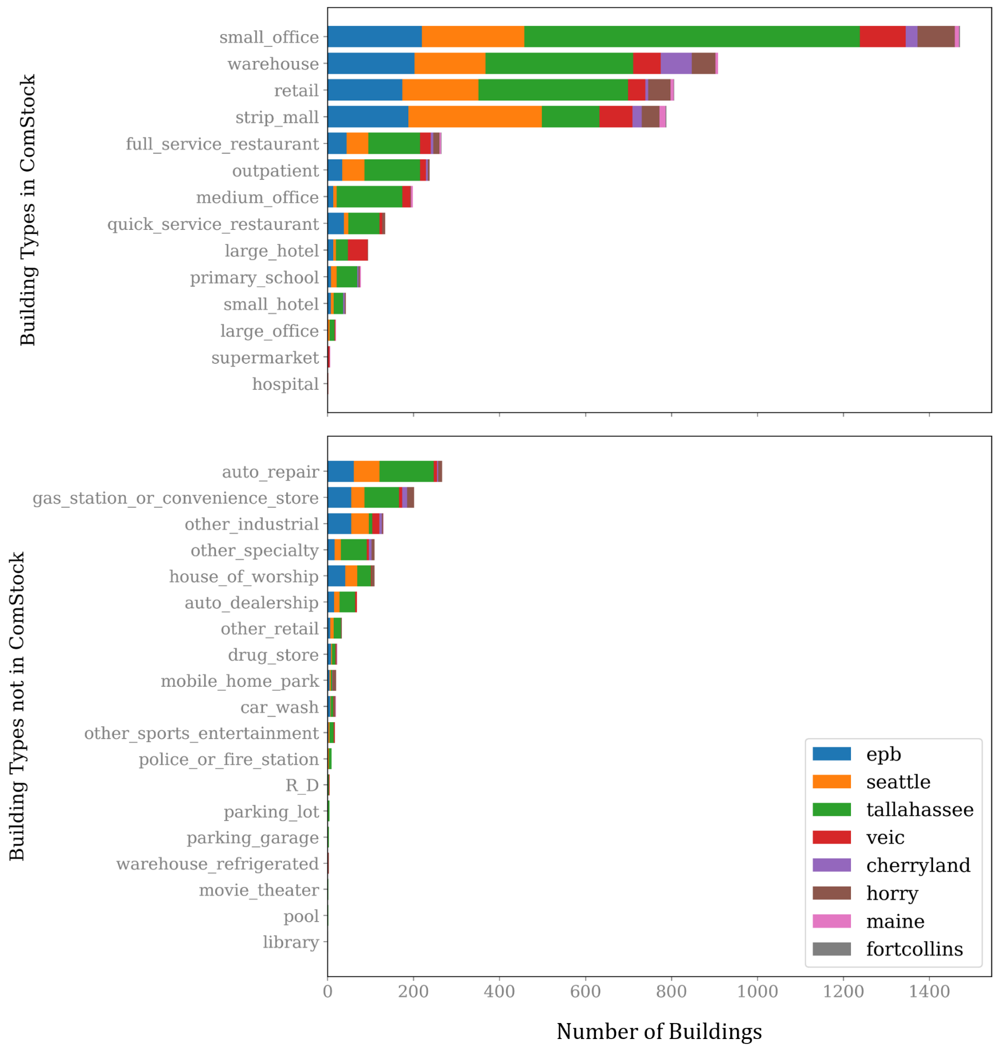

Figure 67. Number of samples by building type and utility in the commercial AMI data set used to derive hours of operation schedules. See EULP Final Technical Report Table 10 for more detail. For example, "epb" is AMI data from Chattanooga, TN.

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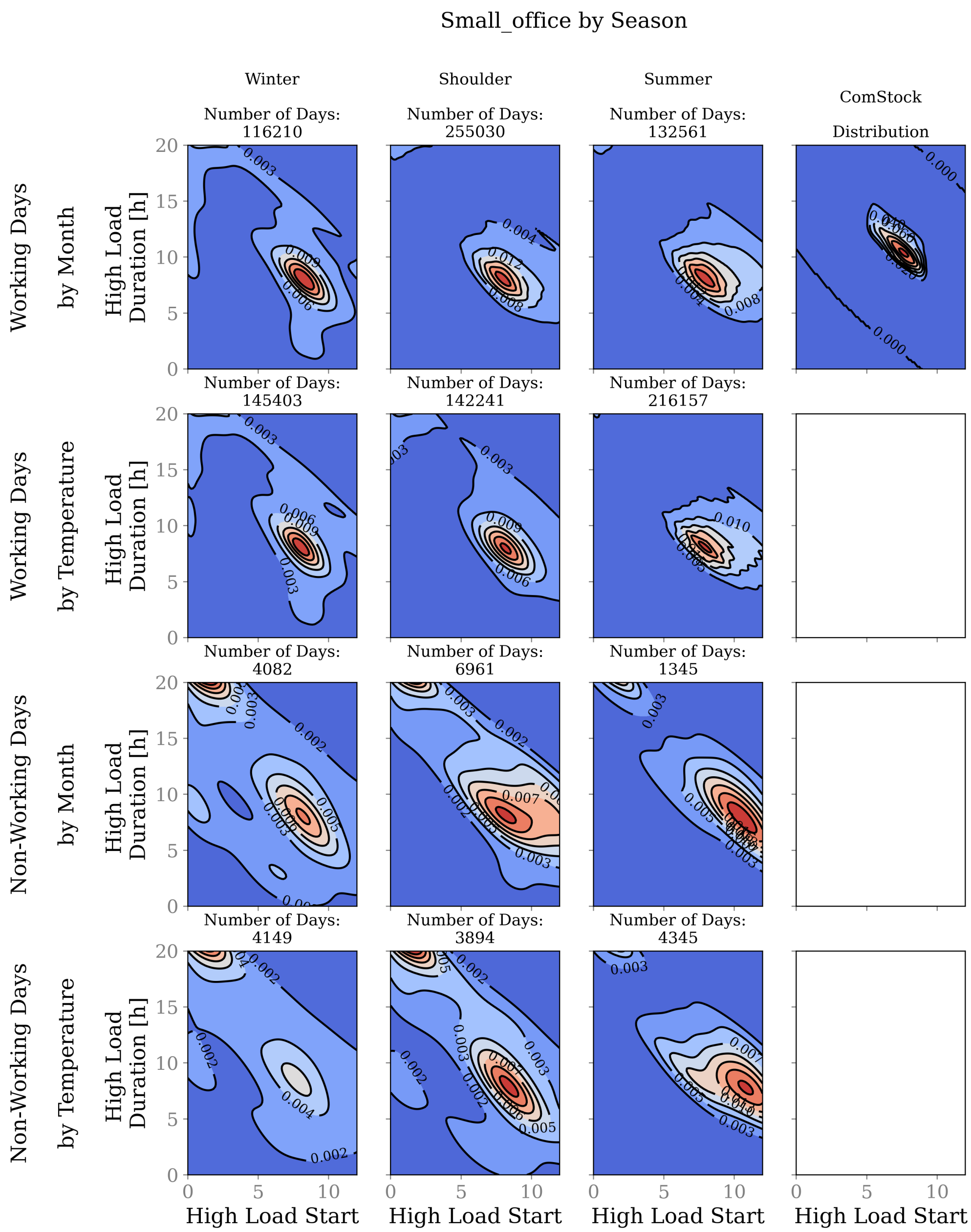

Figure 68. Distribution of small office hours of operations extracted from AMI data (from seven utilities), by day type and season, and compared to ComStock before updates. This figure shows how the hours of operation (start time and duration of the high load period) are influenced by season (all utilities are combined in this plot).

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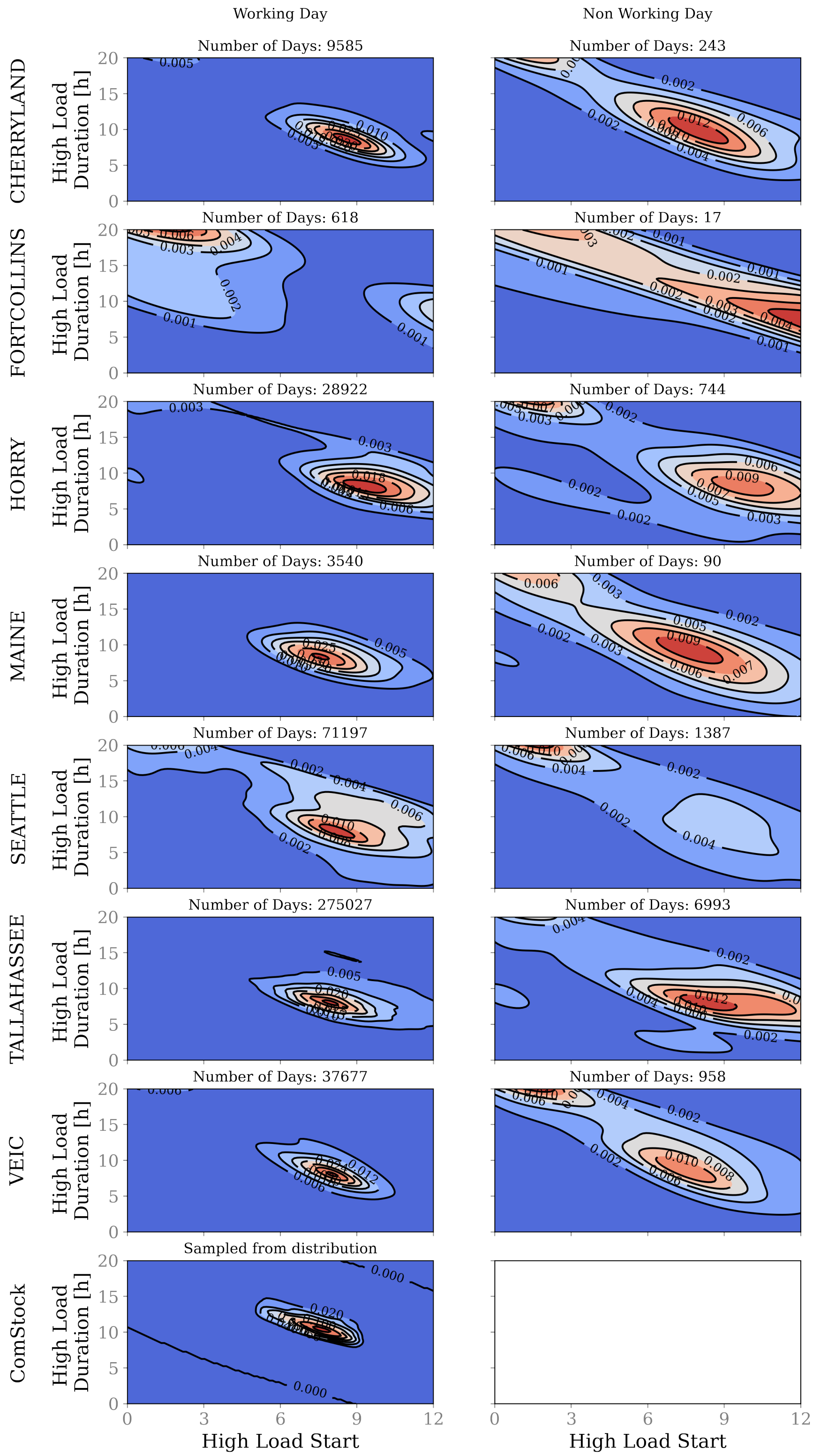

Figure 69. Distribution of small office hours of operations extracted from AMI data (from seven utilities), by utility and day type, and compared to ComStock before updates. This figure shows how the hours of operation (start time and duration of the high load period) are influenced by utility region (all seasons are combined in this plot).

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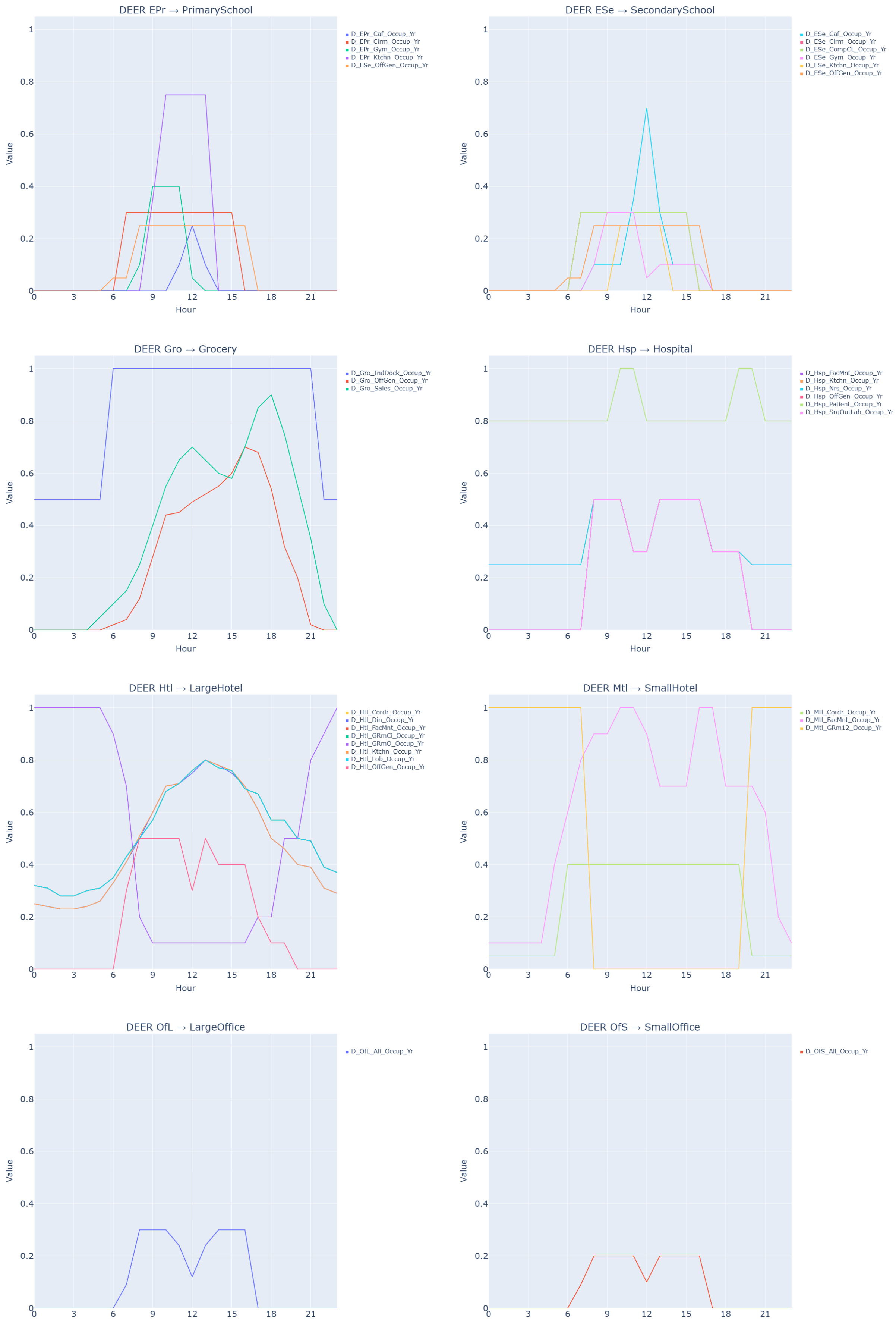

Figure 70. California base occupancy schedules for food service, lodging, healthcare, and education ComStock building types.

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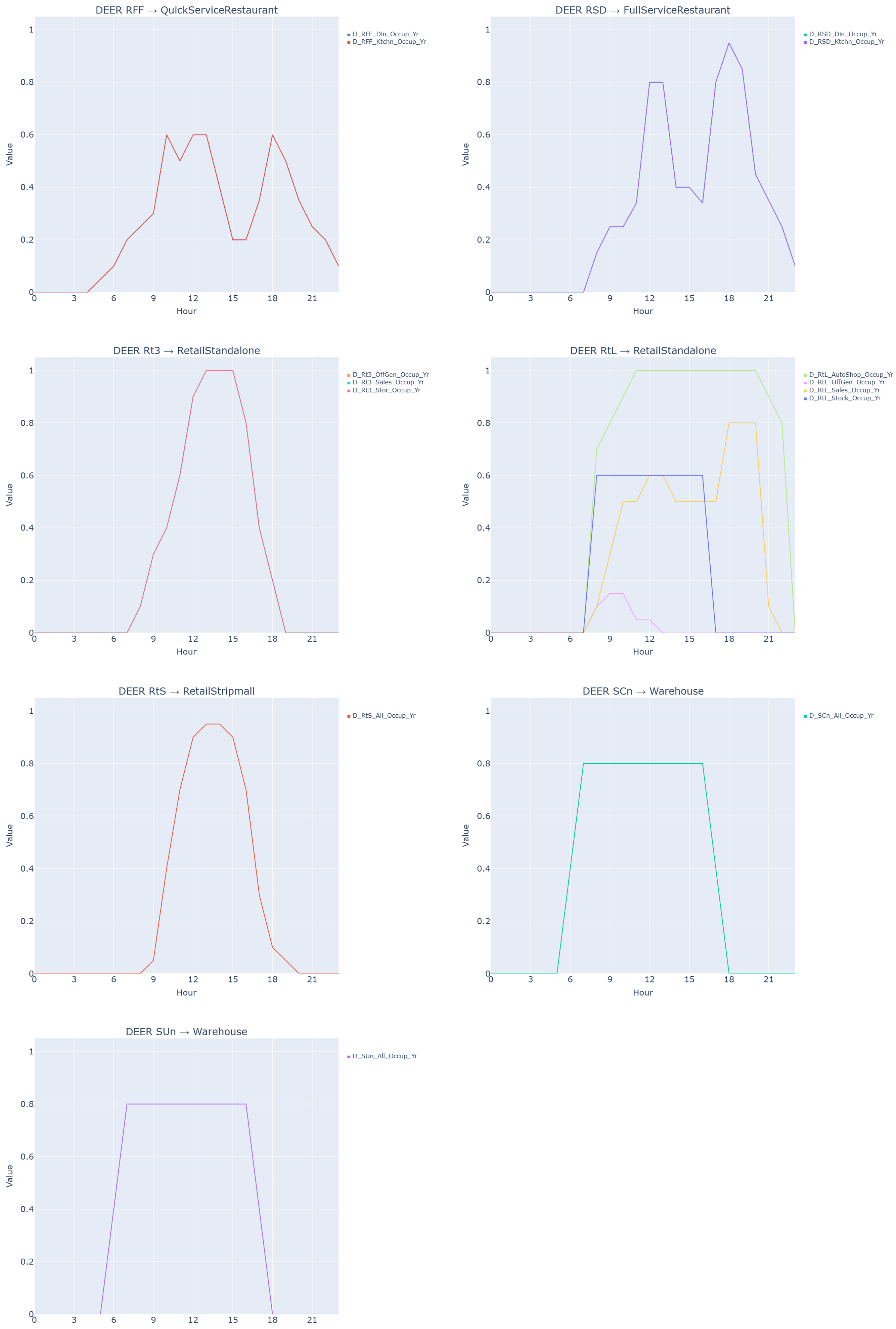

Figure 71. California base occupancy schedules for retail, office, and warehouse ComStock building types.

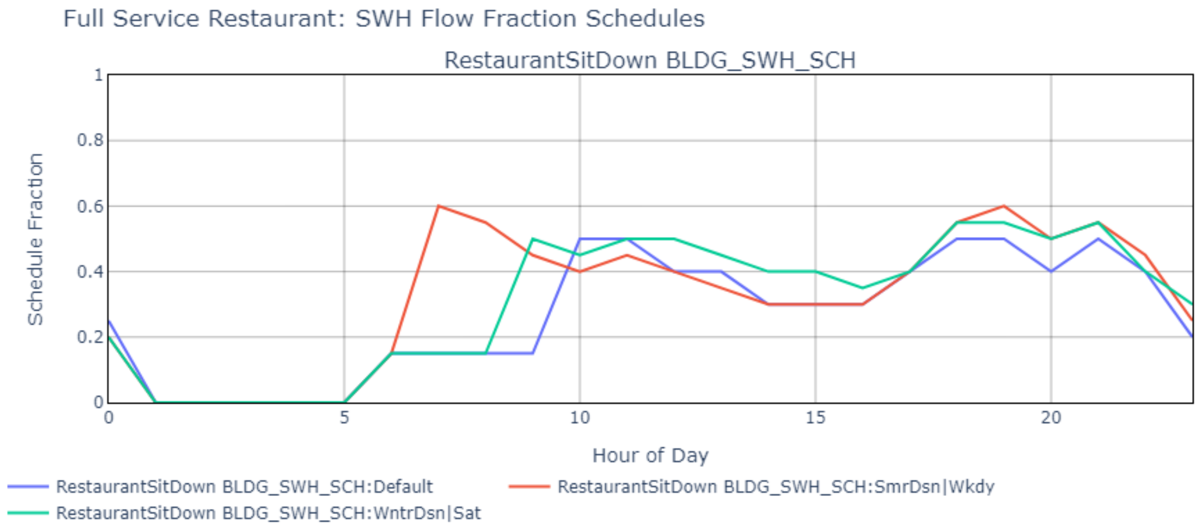

Figure 72. SWH heating usage schedule for full service restaurants.

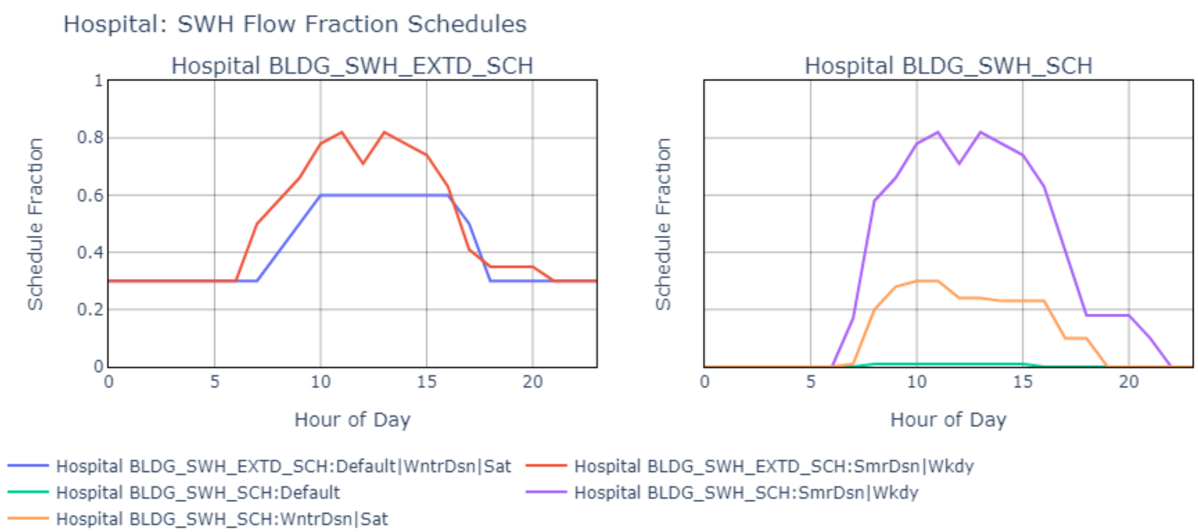

Figure 73. SWH heating usage schedule for hospitals.

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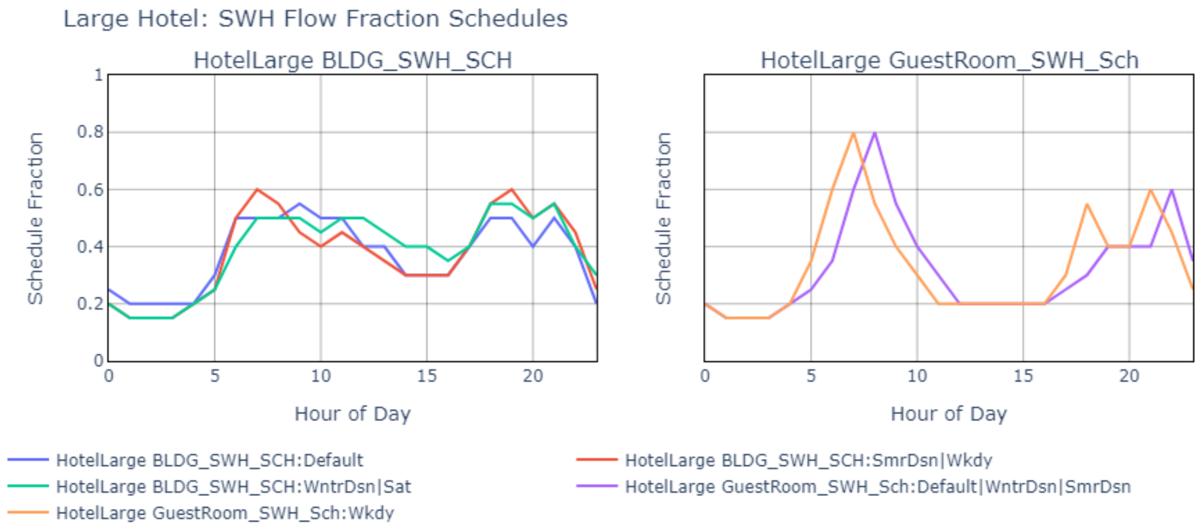

Figure 74. SWH heating usage schedule for large hotel.

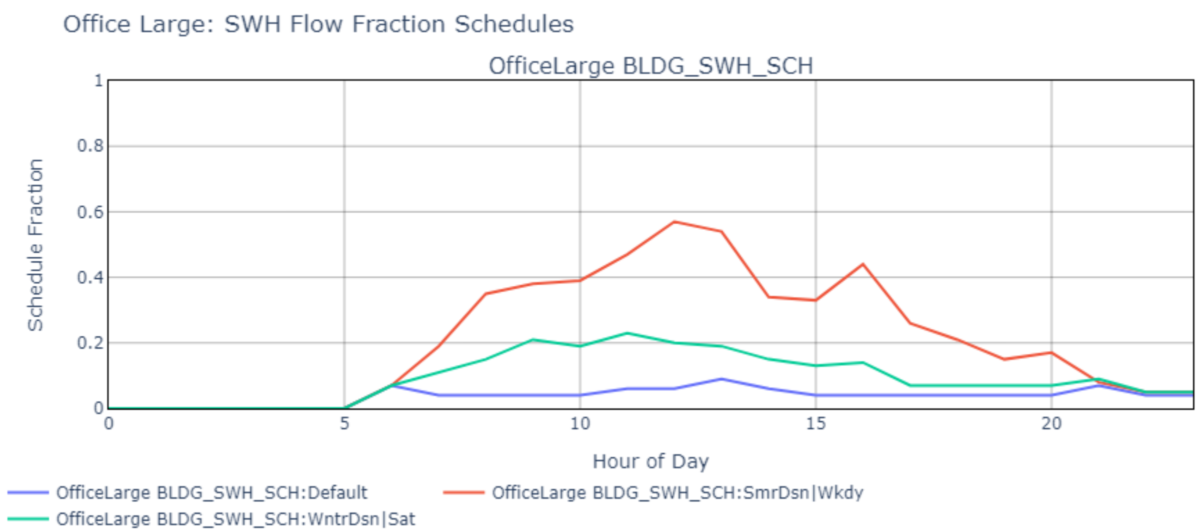

Figure 75. SWH heating usage schedule for large office.

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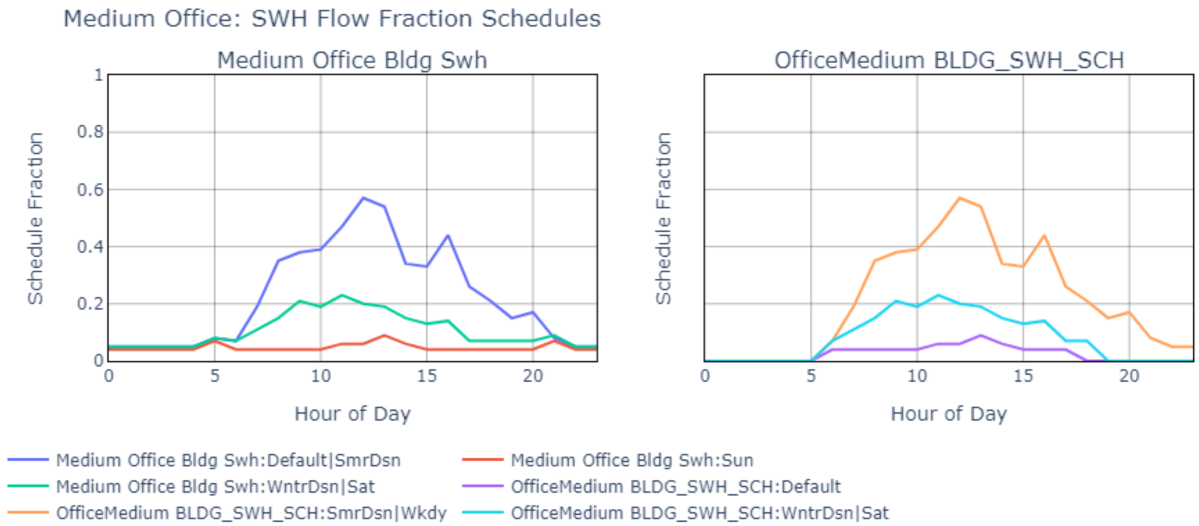

Figure 76. SWH heating usage schedule for medium office.

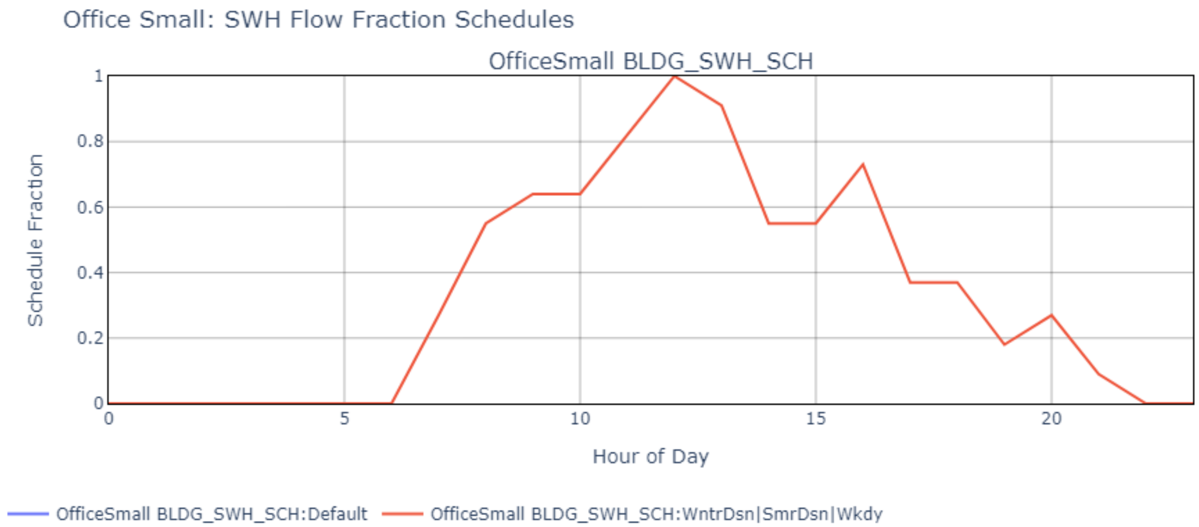

Figure 77. SWH heating usage schedule for small offices.

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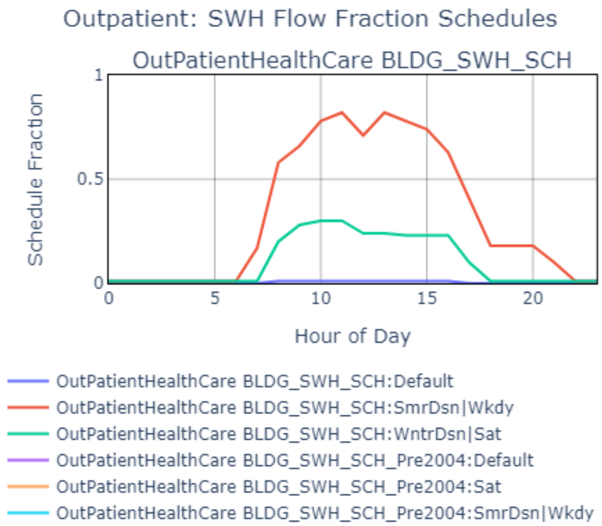

Figure 78. SWH heating usage schedule for outpatient.

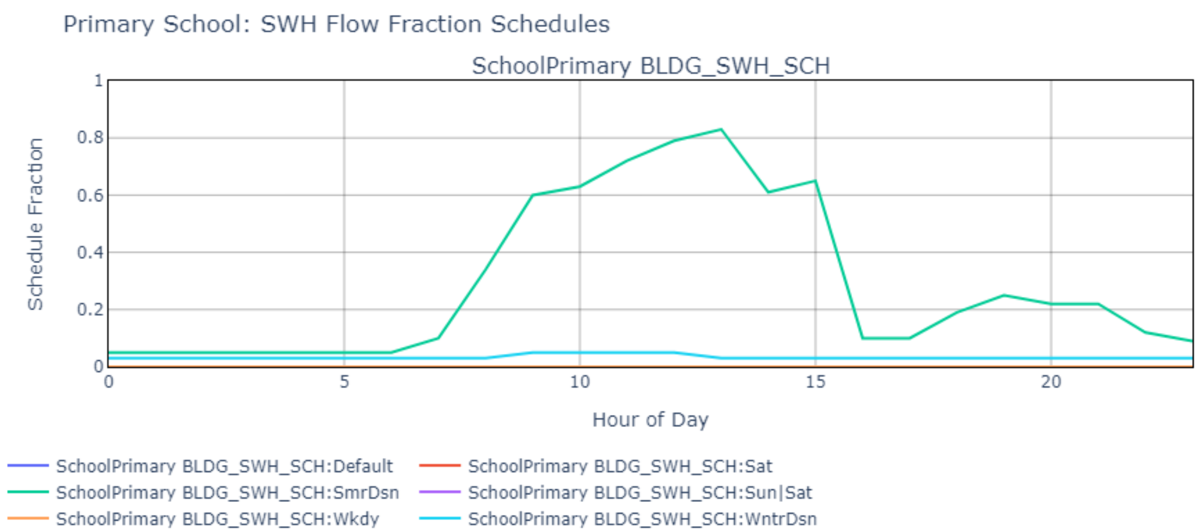

Figure 79. SWH heating usage schedule for primary school.

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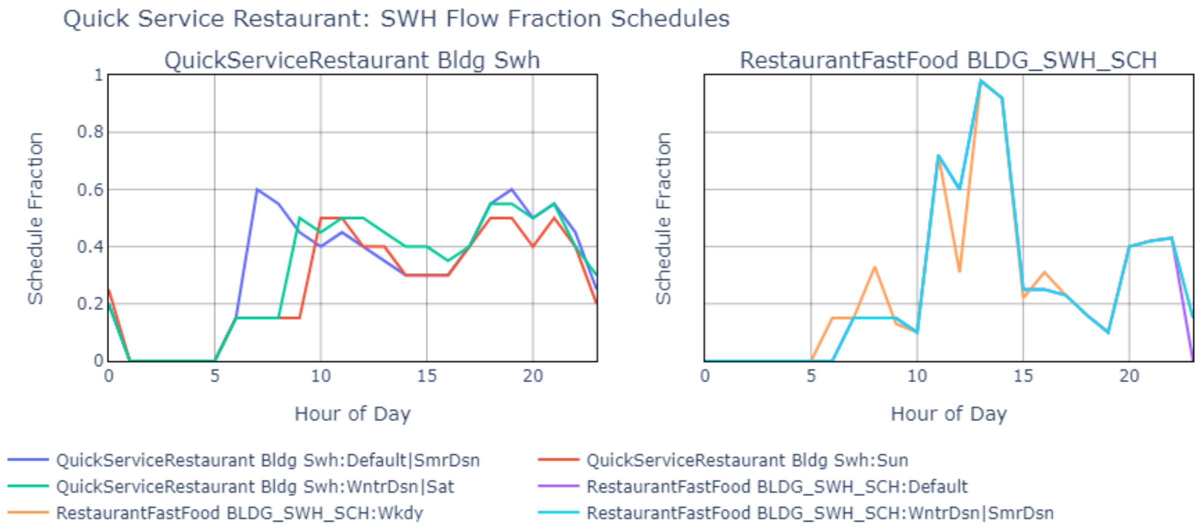

Figure 80. SWH heating usage schedule for quick service restaurant.

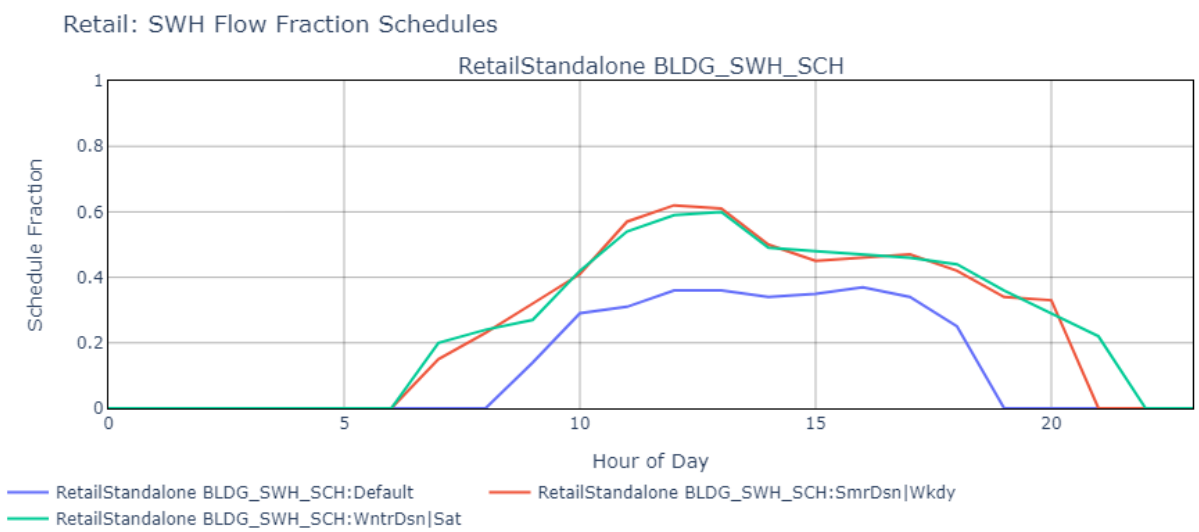

Figure 81. SWH heating usage schedule for retail.

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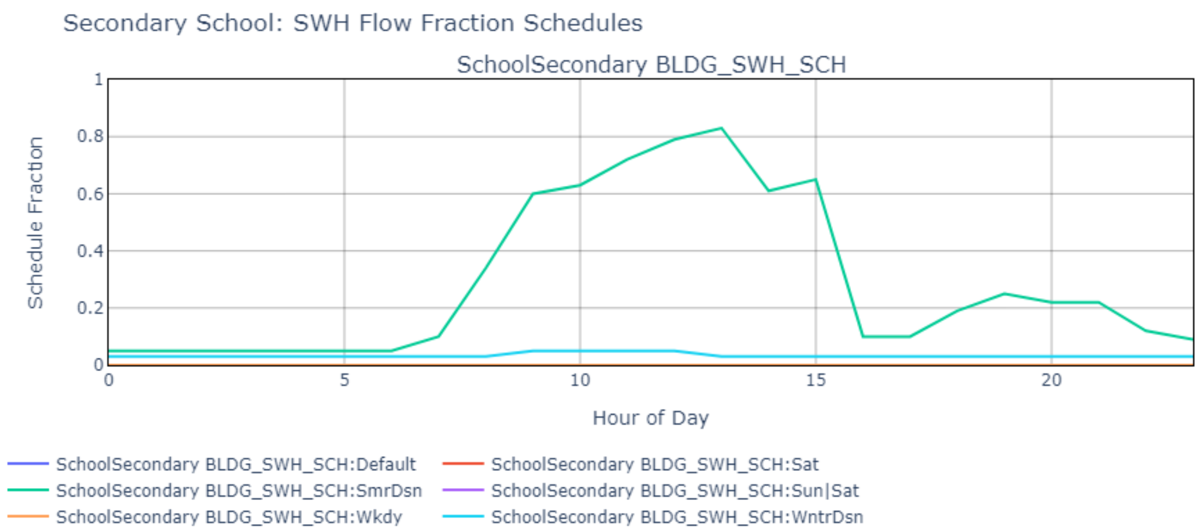

Figure 82. SWH heating usage schedule for secondary school.

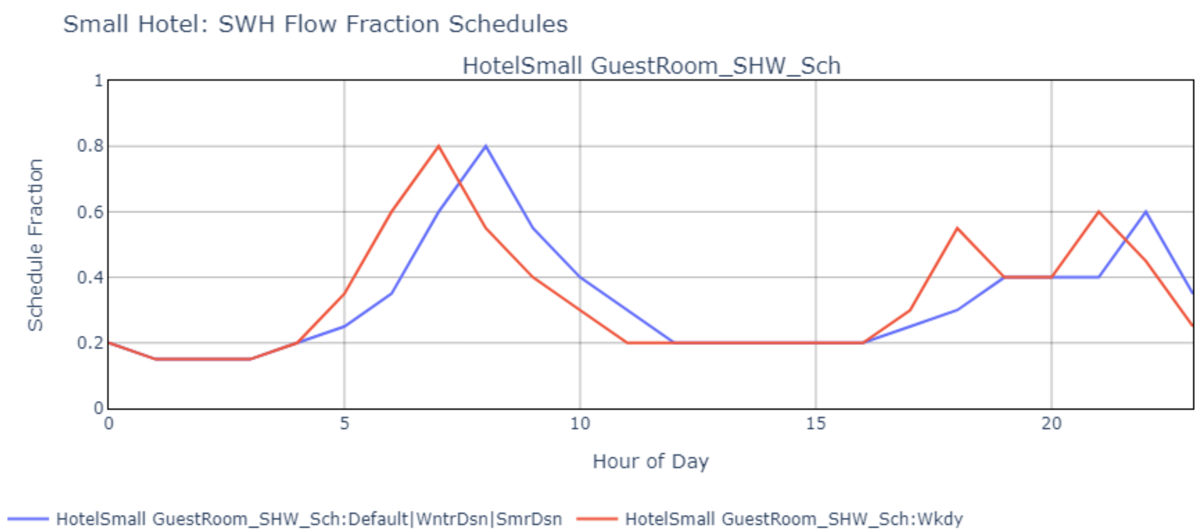

Figure 83. SWH heating usage schedule for small hotel.

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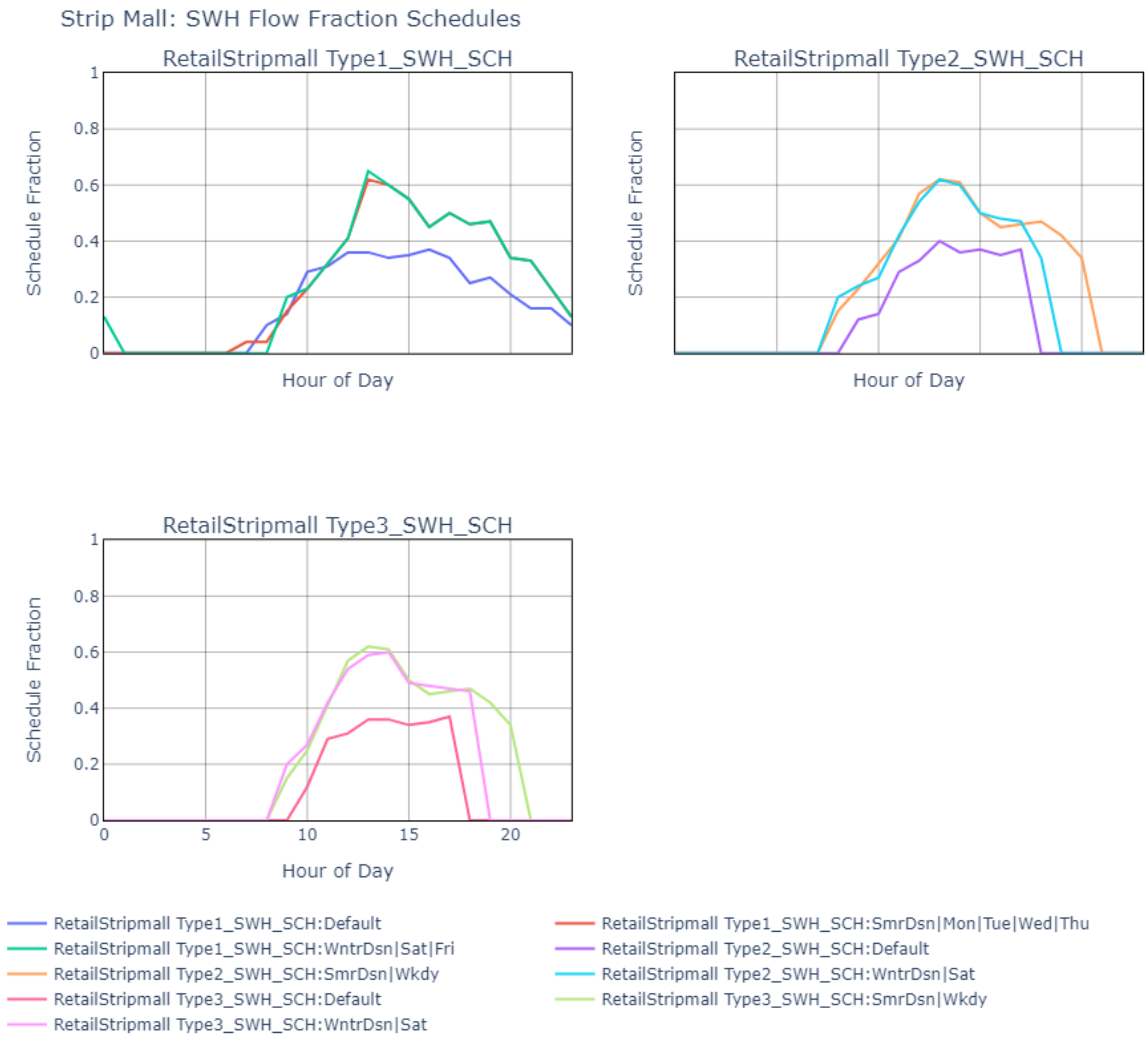

Figure 84. SWH heating usage schedule for strip mall.

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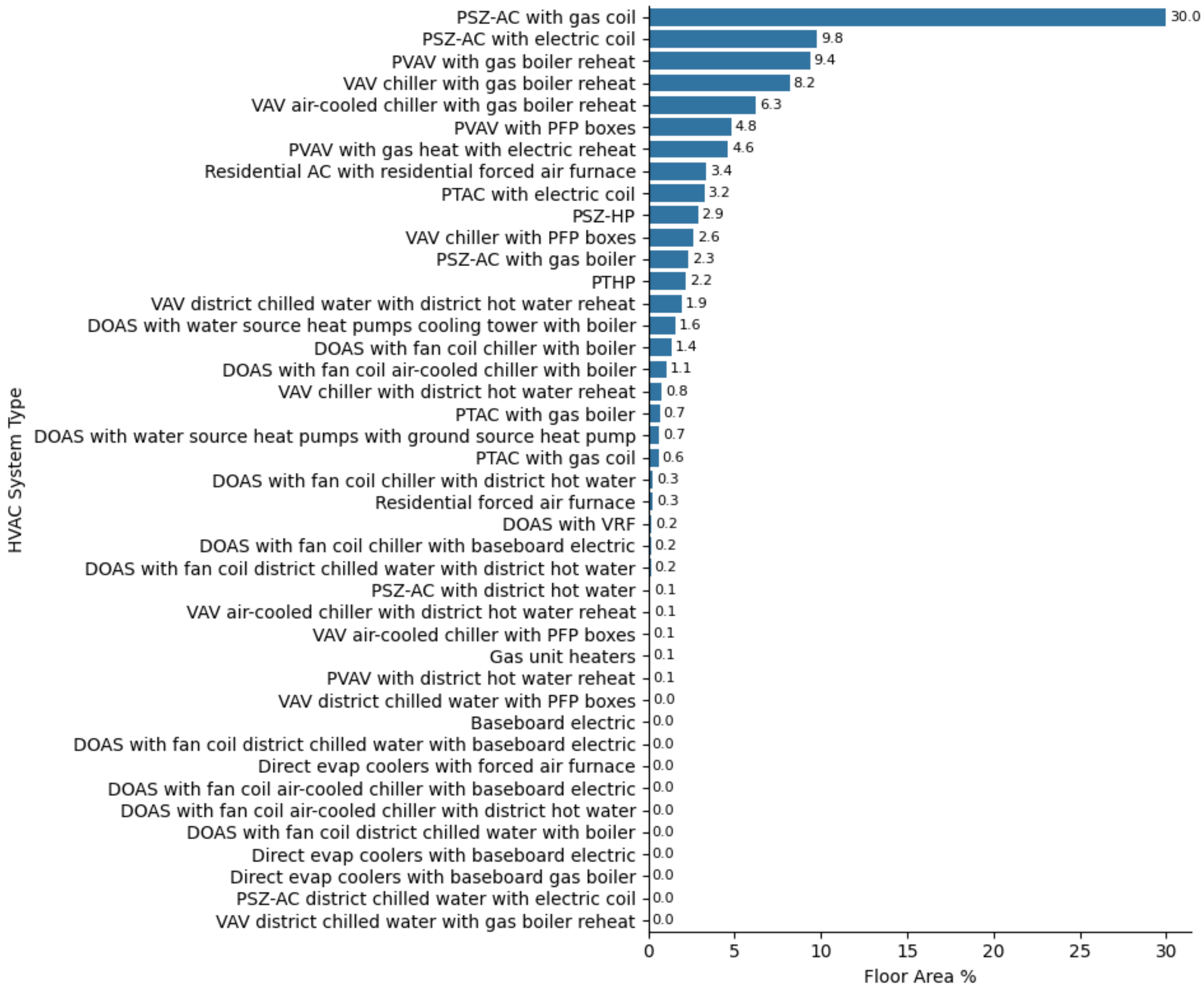

Figure 85. Prevalence of ComStock HVAC system types by total stock floor area; all building types.

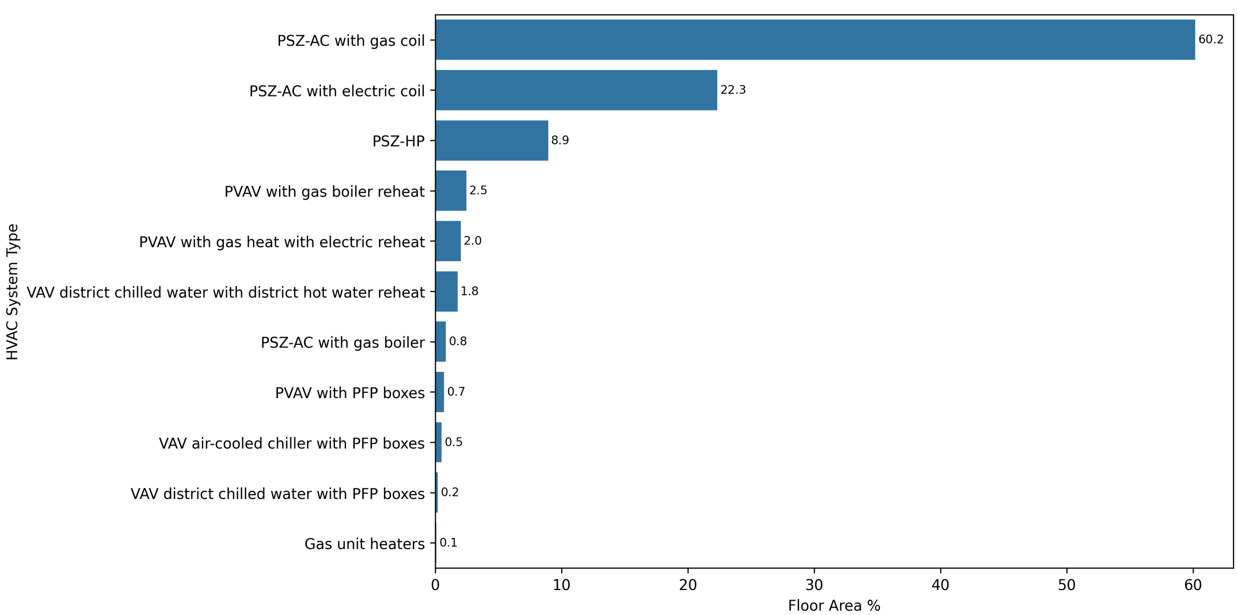

Figure 86. Prevalence of ComStock HVAC system types by total stock floor area; full service restaurants.

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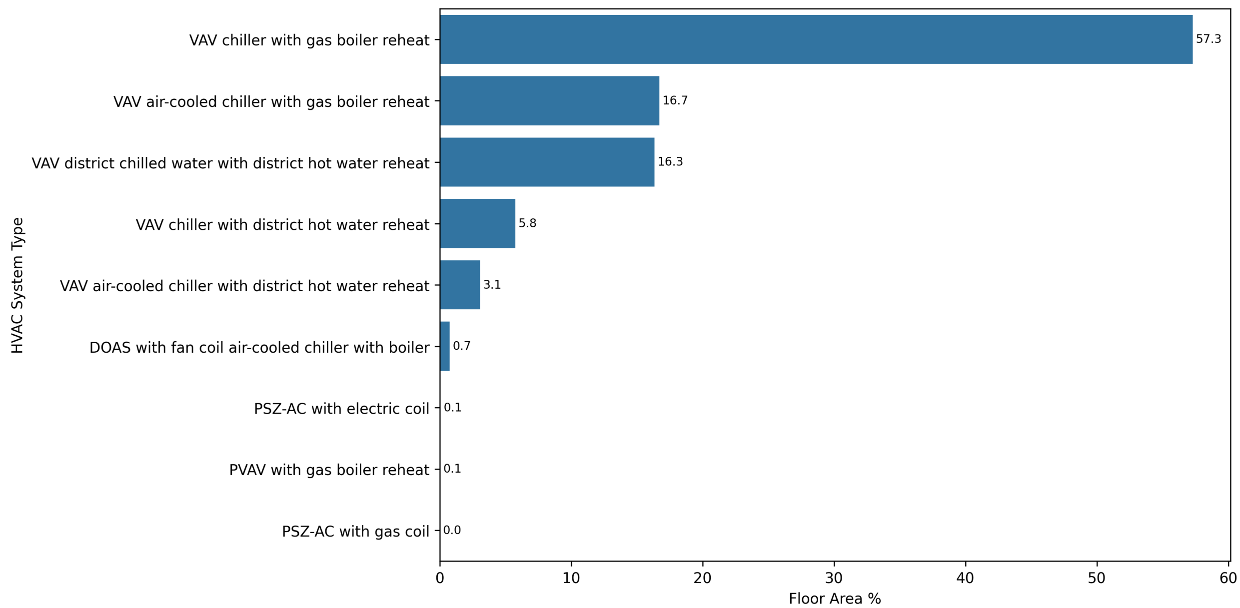

Figure 87. Prevalence of ComStock HVAC system types by total stock floor area; hospitals.

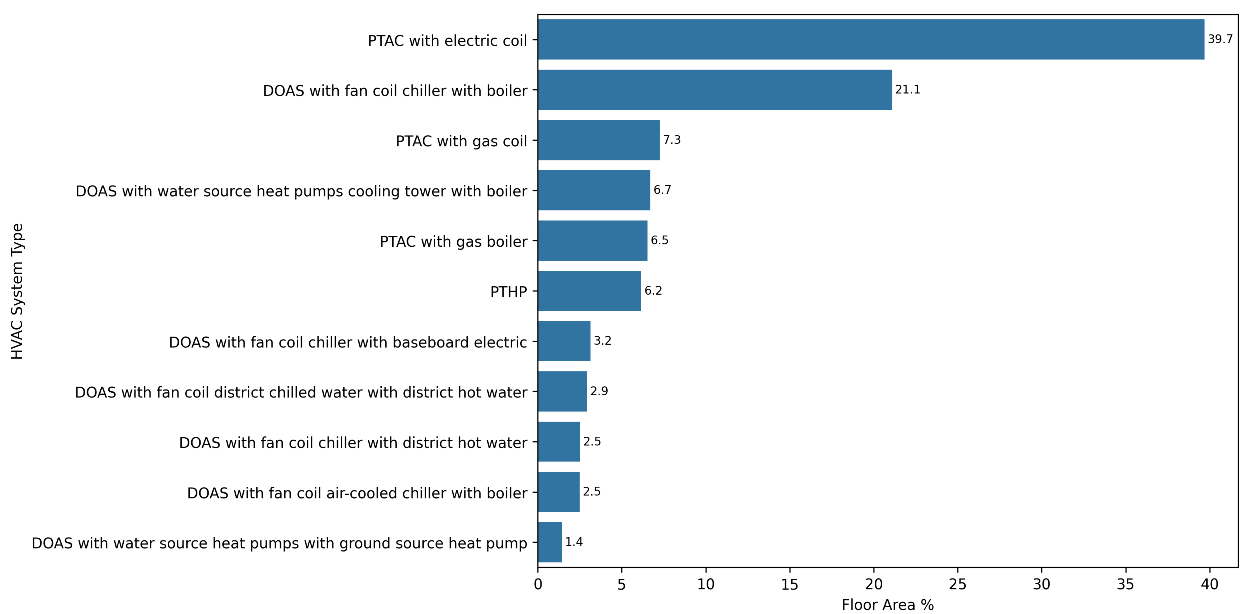

Figure 88. Prevalence of ComStock HVAC system types by total stock floor area; large hotels.

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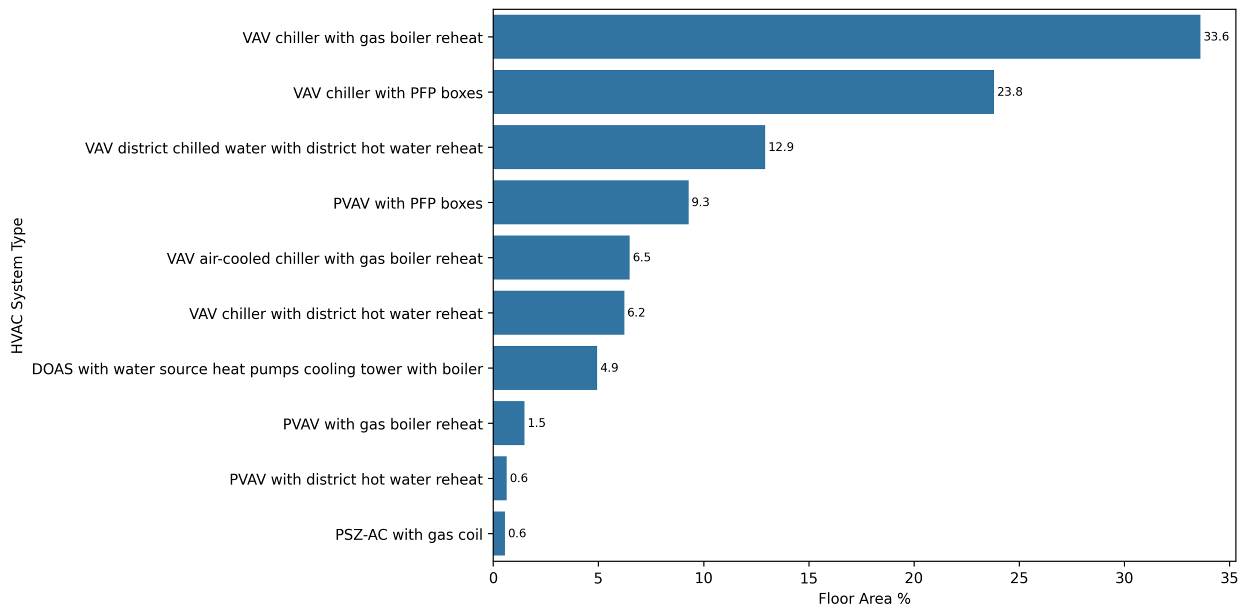

Figure 89. Prevalence of ComStock HVAC system types by total stock floor area; large offices.

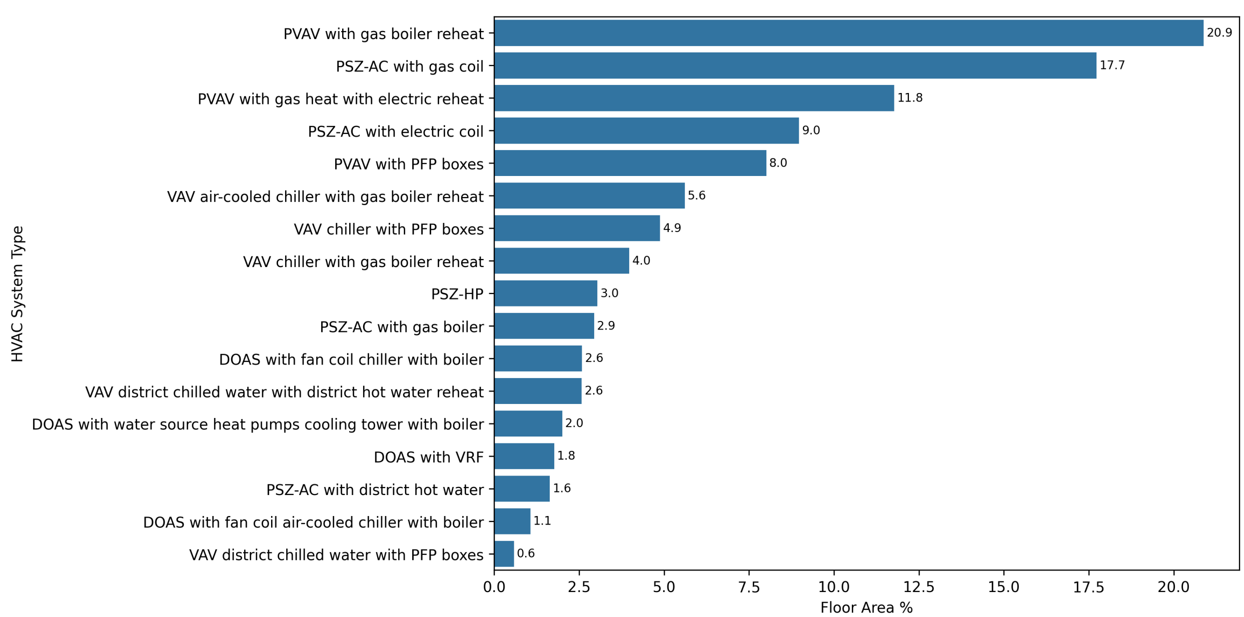

Figure 90. Prevalence of ComStock HVAC system types by total stock floor area; medium offices.

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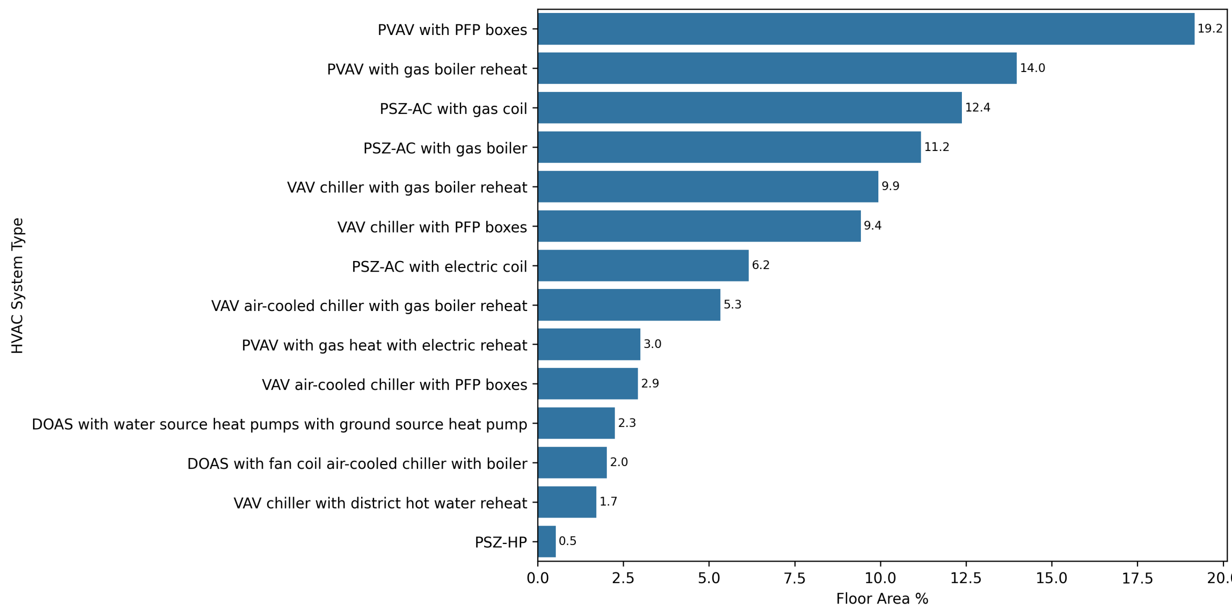

Figure 91. Prevalence of ComStock HVAC system types by total stock floor area; outpatient.

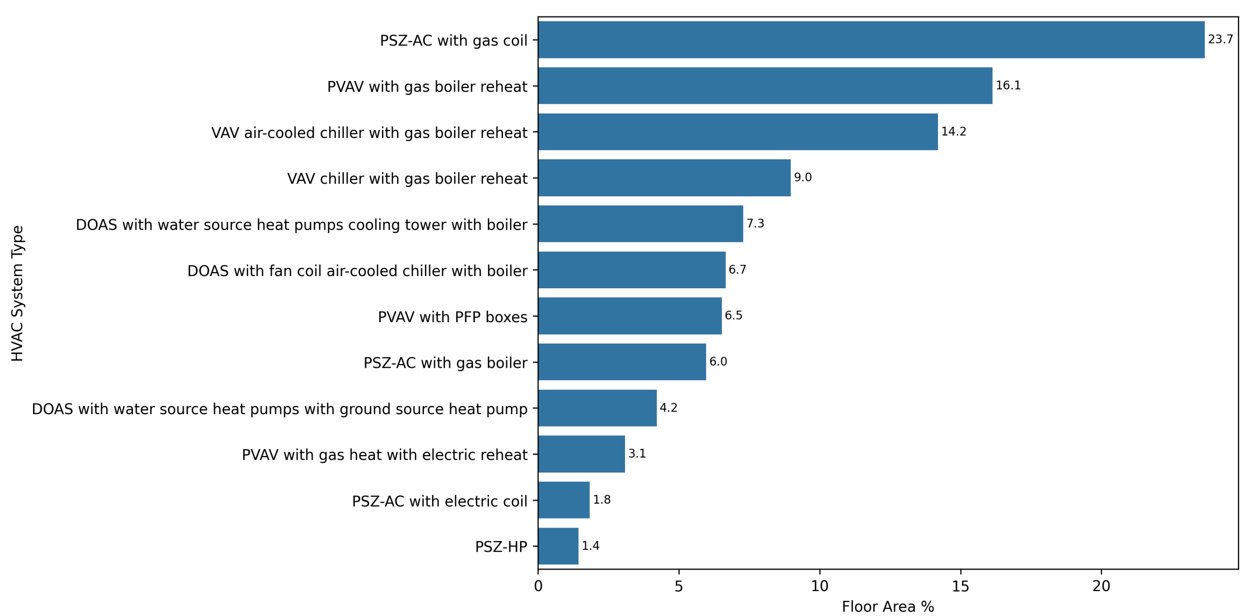

Figure 92. Prevalence of ComStock HVAC system types by total stock floor area; primary schools.

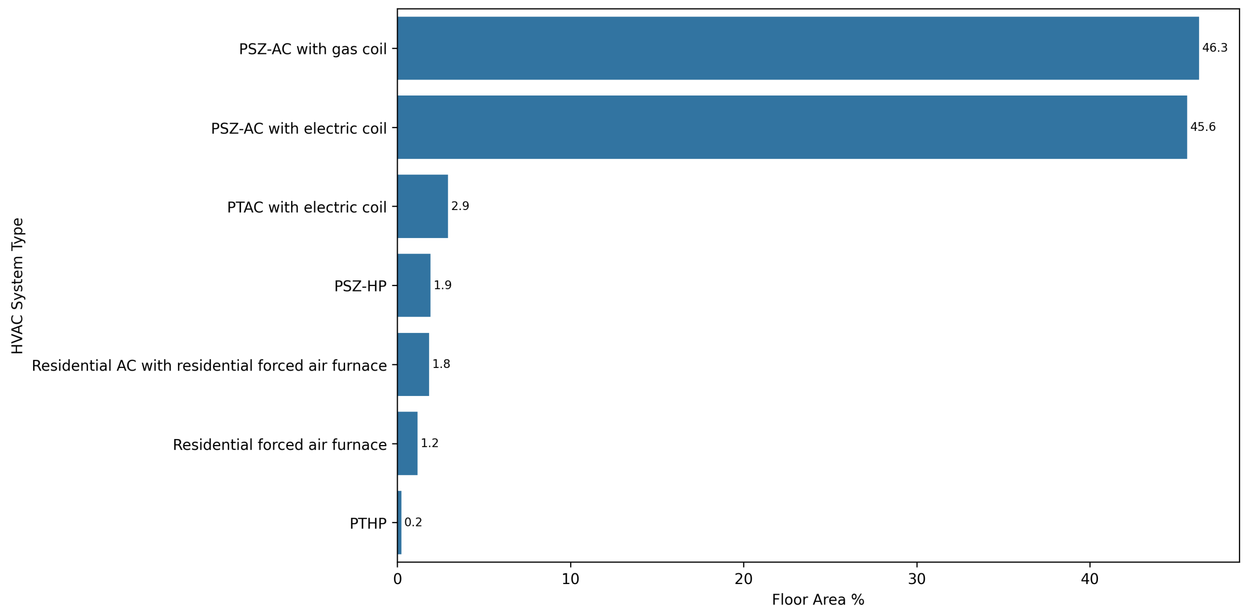

Figure 93. Prevalence of ComStock HVAC system types by total stock floor area; quick service restaurants.

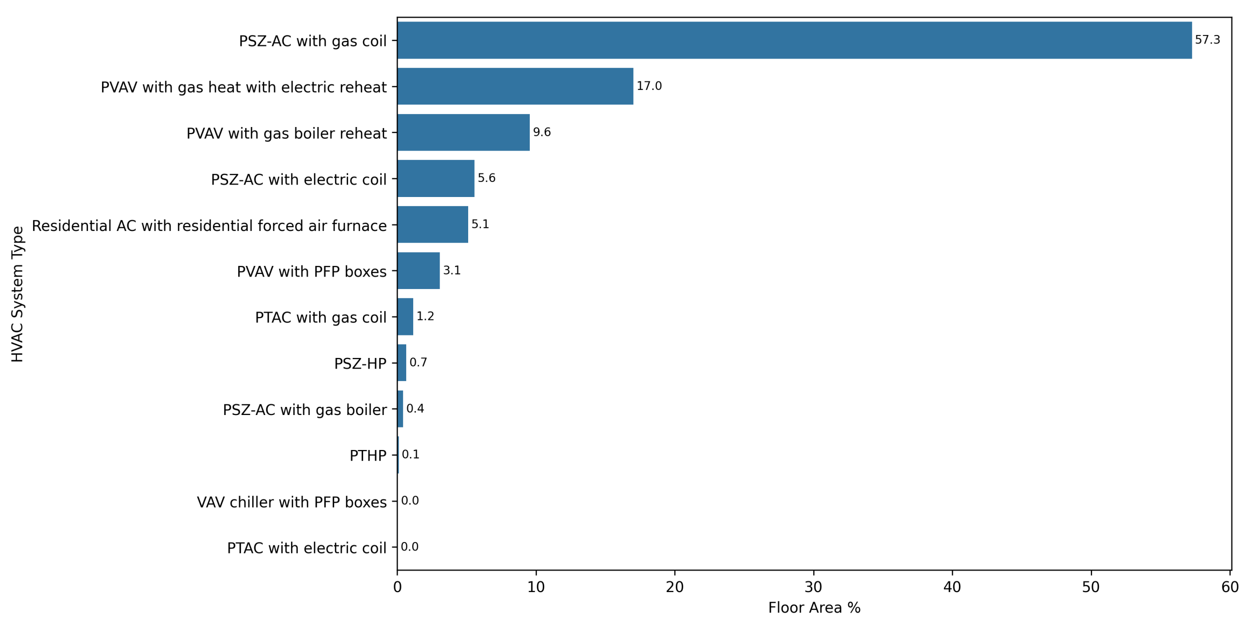

Figure 94. Prevalence of ComStock HVAC system types by total stock floor area; strip malls.

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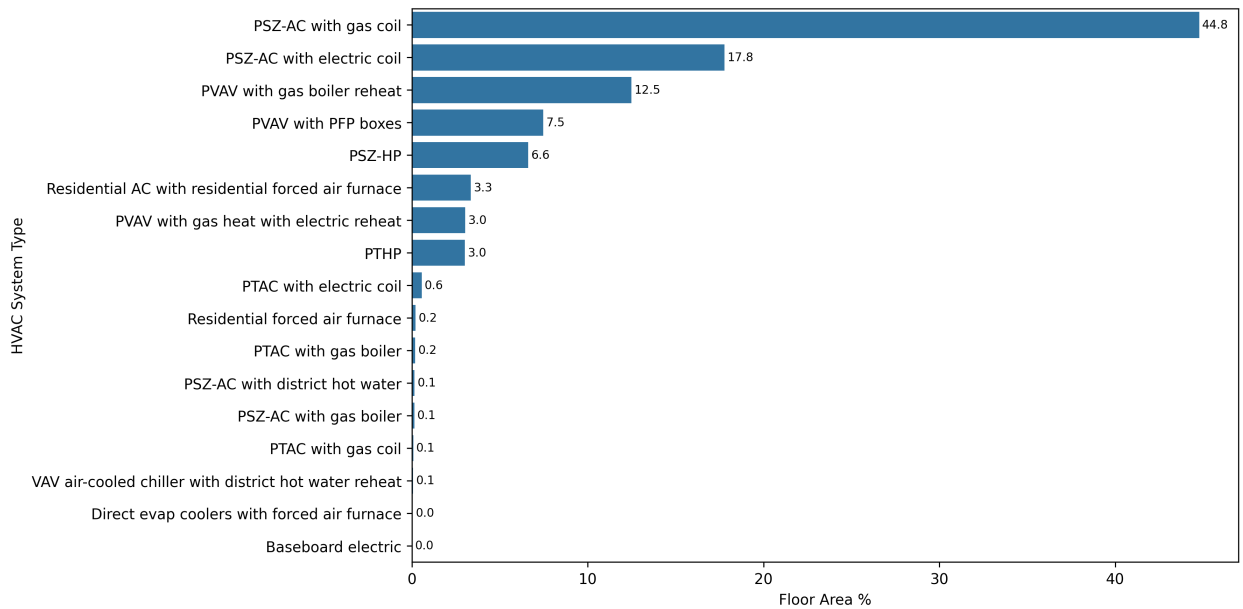

Figure 95. Prevalence of ComStock HVAC system types by total stock floor area; retail.

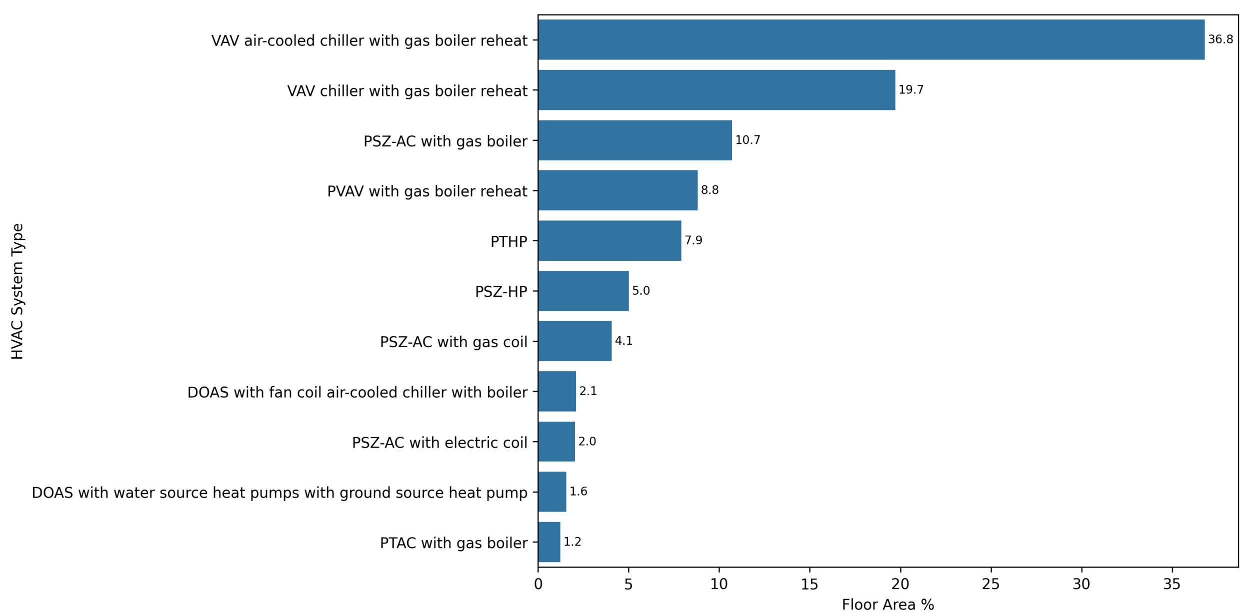

Figure 96. Prevalence of ComStock HVAC system types by total stock floor area; secondary schools.

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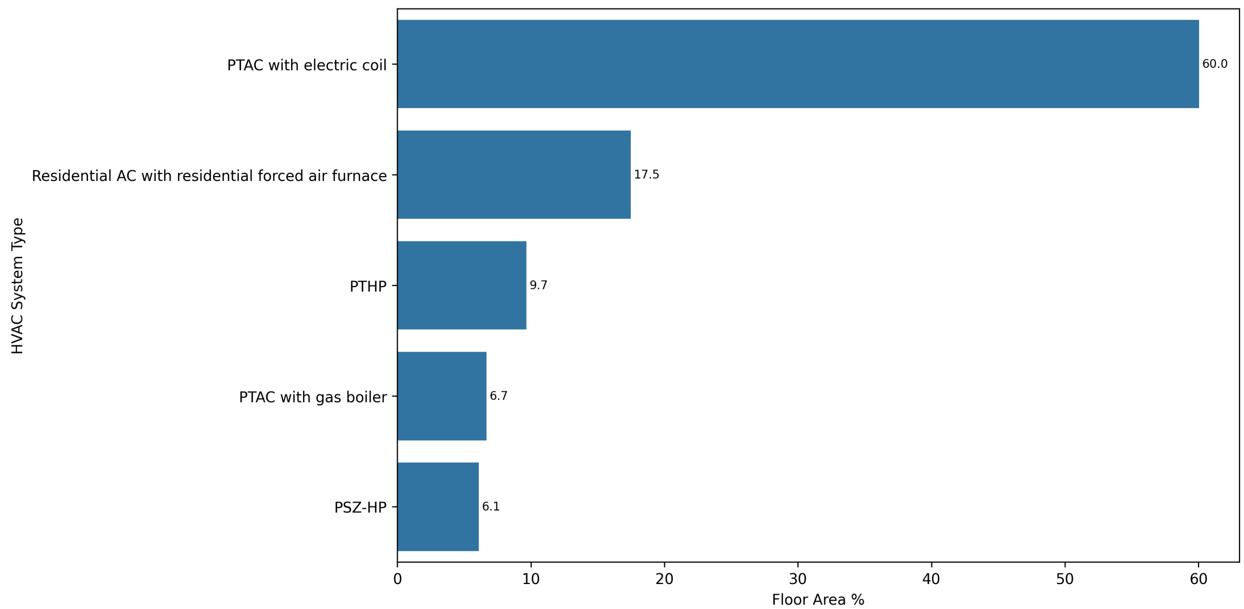

Figure 97. Prevalence of ComStock HVAC system types by total stock floor area; small hotels.

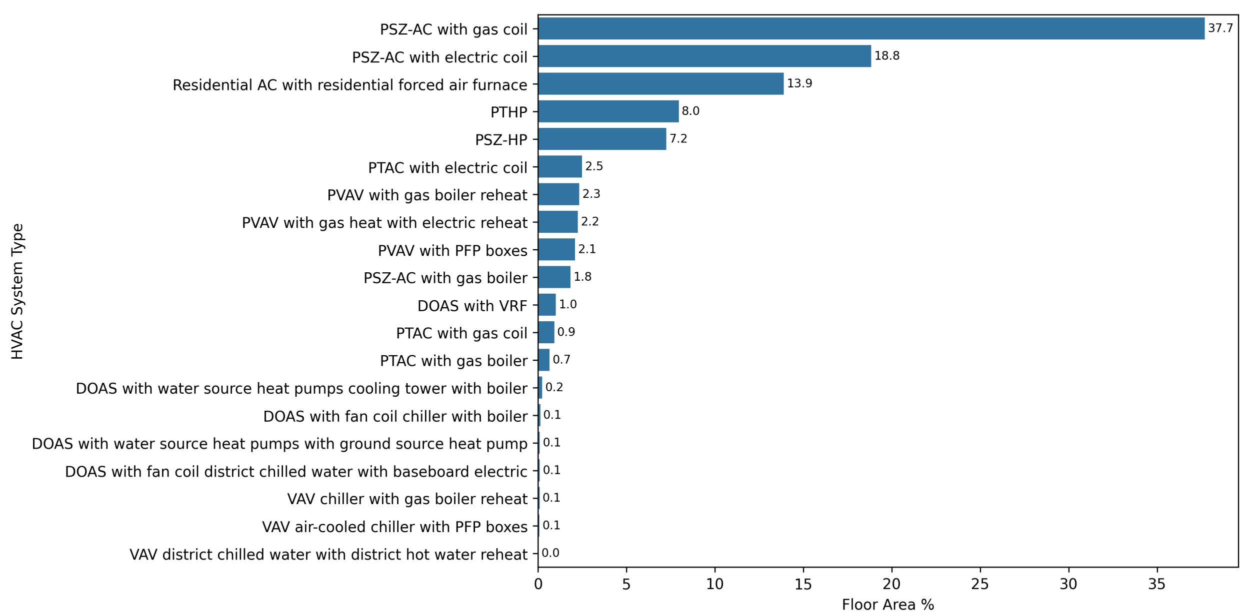

Figure 98. Prevalence of ComStock HVAC system types by total stock floor area; small offices.

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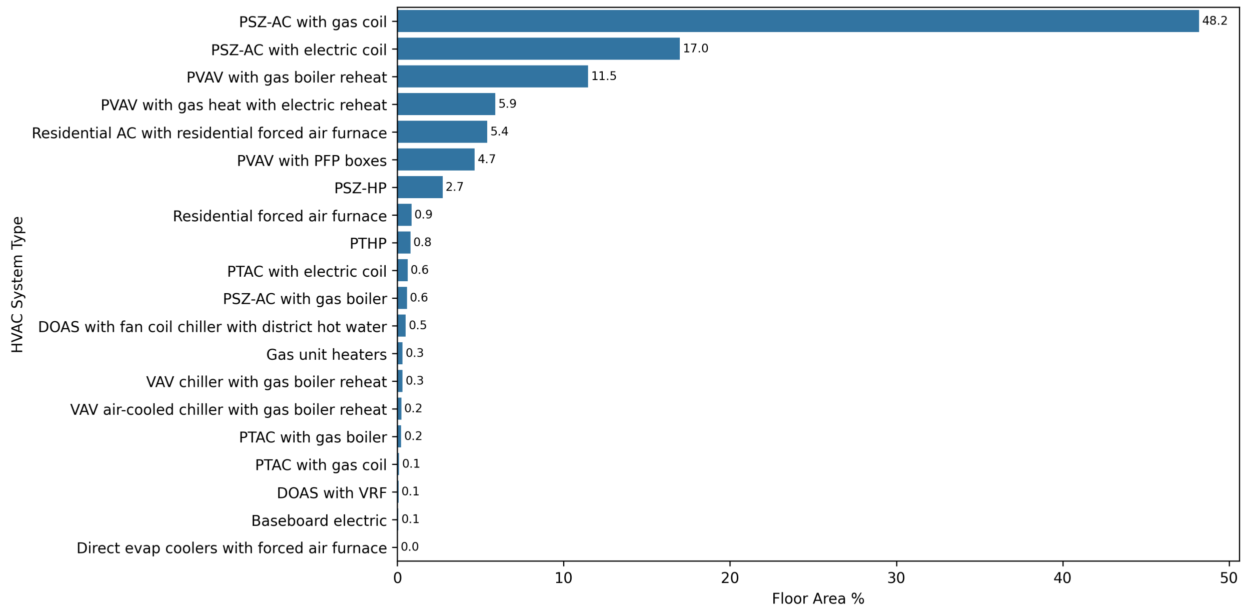

Figure 99. Prevalence of ComStock HVAC system types by total stock floor area; warehouses.

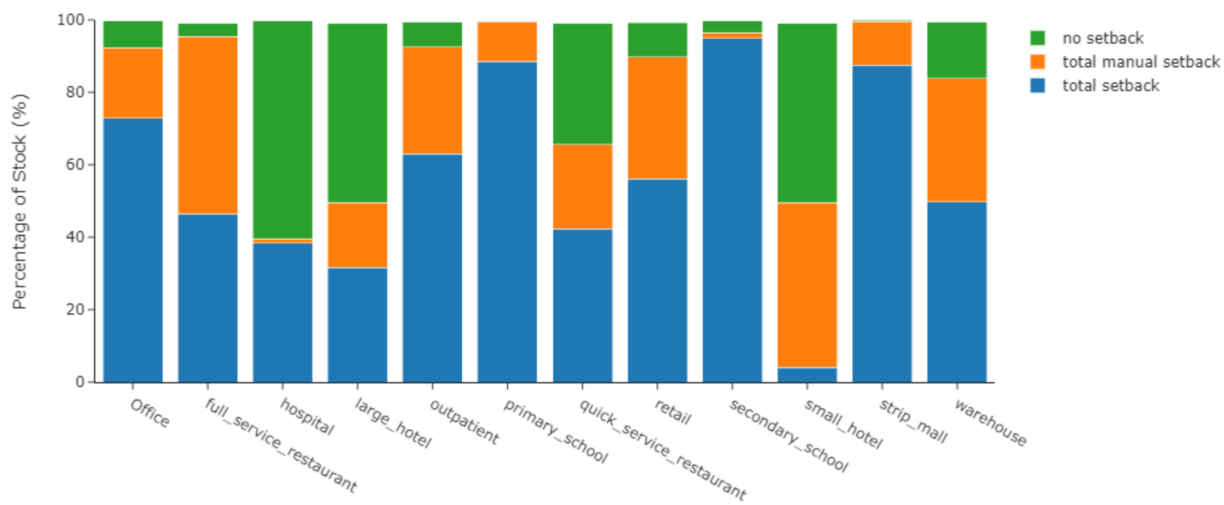

Figure 100. Percentage of buildings with thermostat setbacks by building type from the CBECS 2012 survey.

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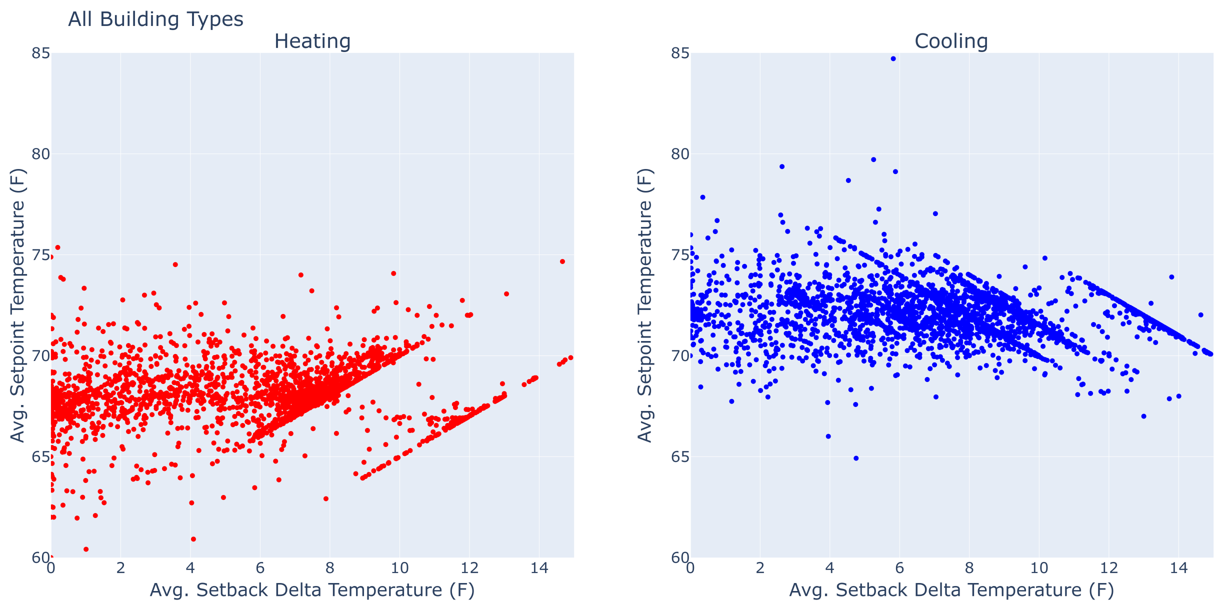

Figure 101. Thermostat heating and cooling set point-setback delta correlation from BAS data sources; all building types.

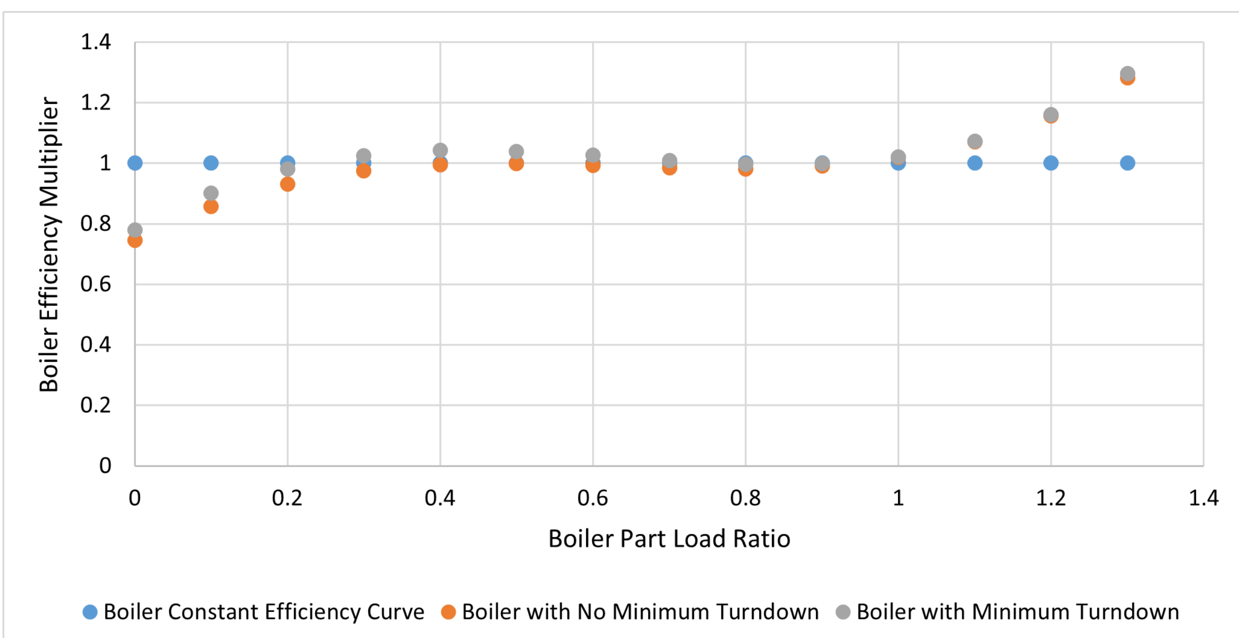

Figure 102. Boiler part load performance curves.

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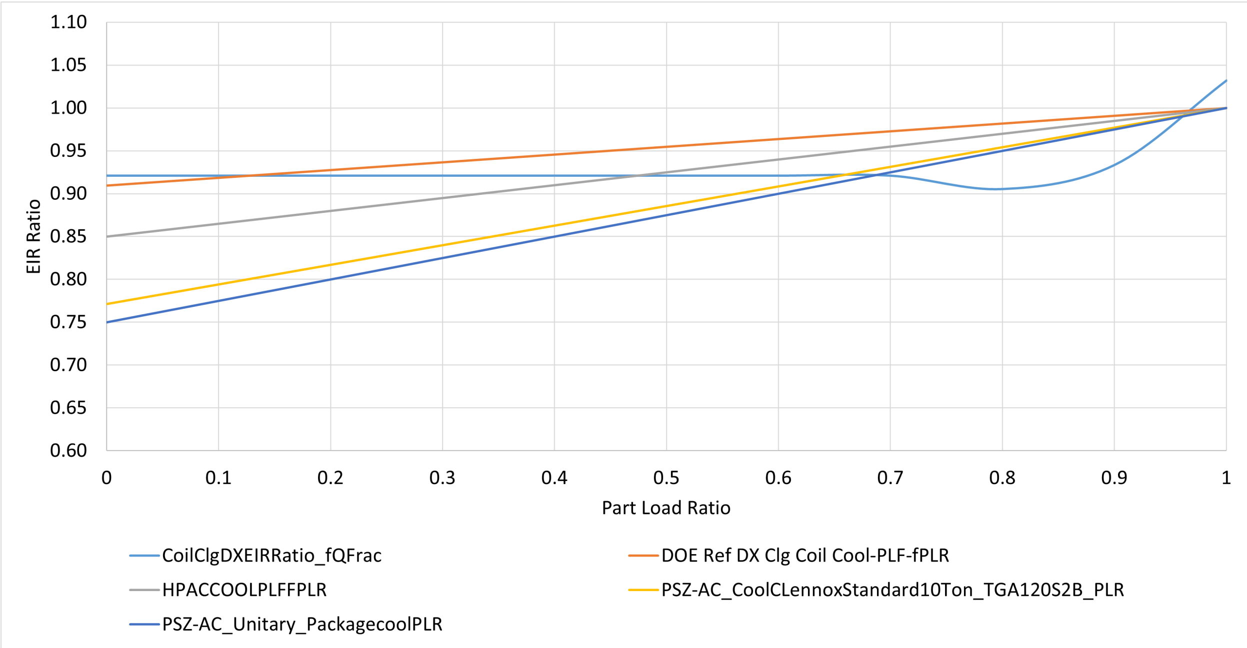

Figure 103. DX cooling energy input ratio as a function of part load ratio performance curves.

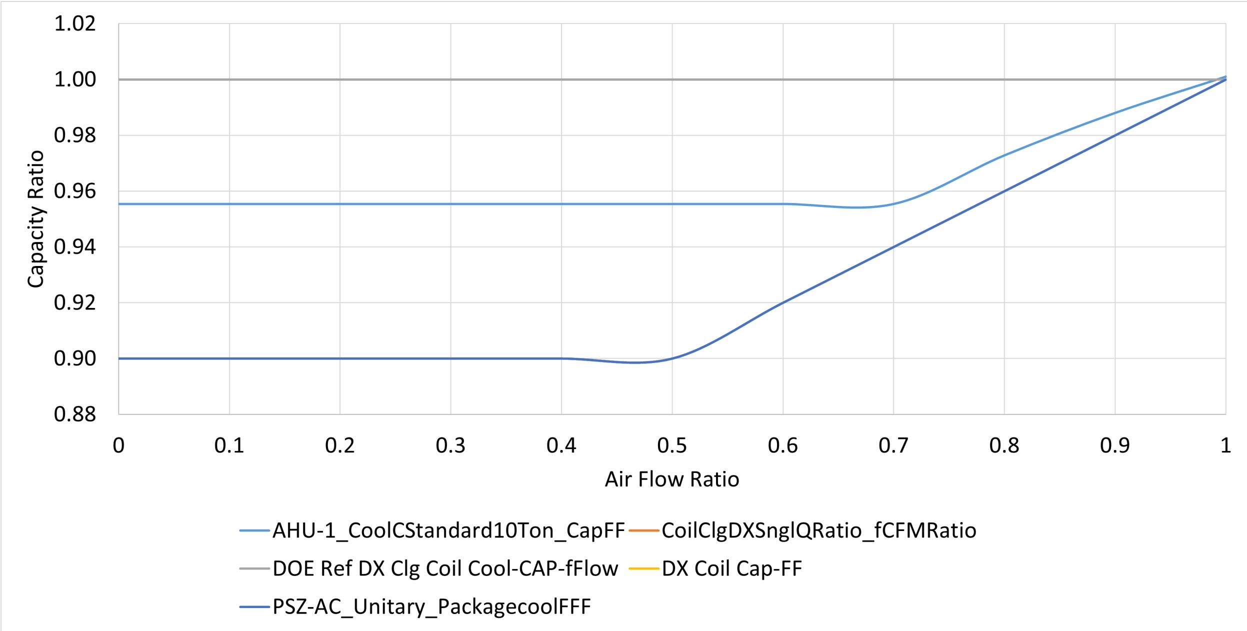

Figure 104. DX cooling capacity as a function of airflow performance curves.

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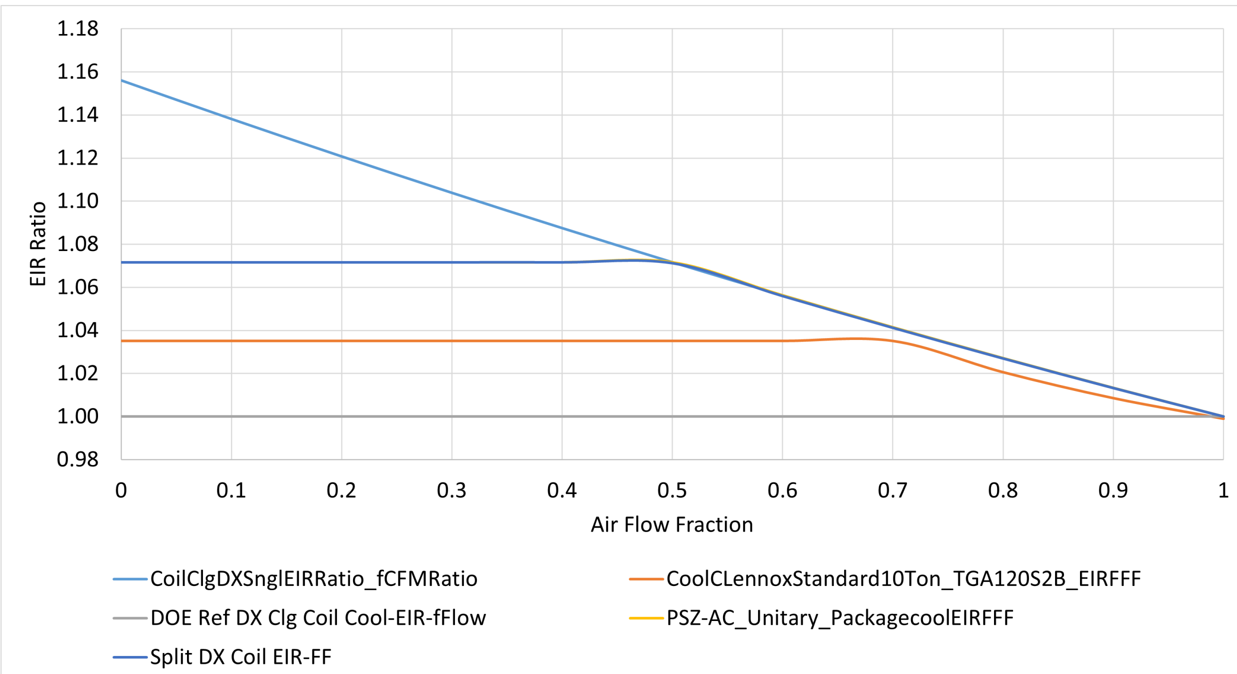

Figure 105. DX cooling energy input ratio as a function of airflow performance curves.

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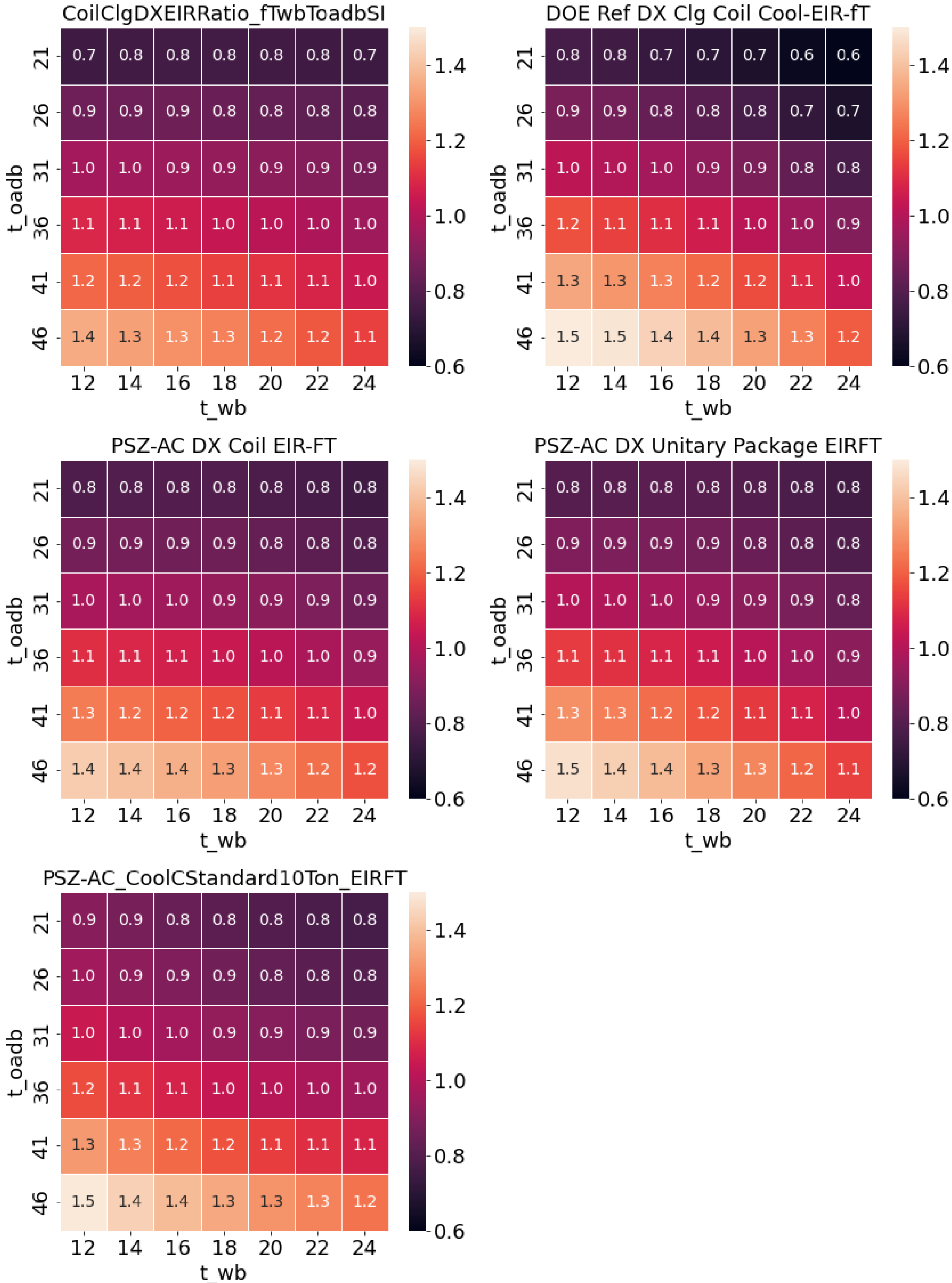

Figure 106. DX cooling energy input ratio as a function of temperature performance curves. Independent variables are outdoor air dry bulb temperature (y-axis, degrees Celsius) and wet bulb temperature entering the cooling coil (x-axis, degrees Celsius).

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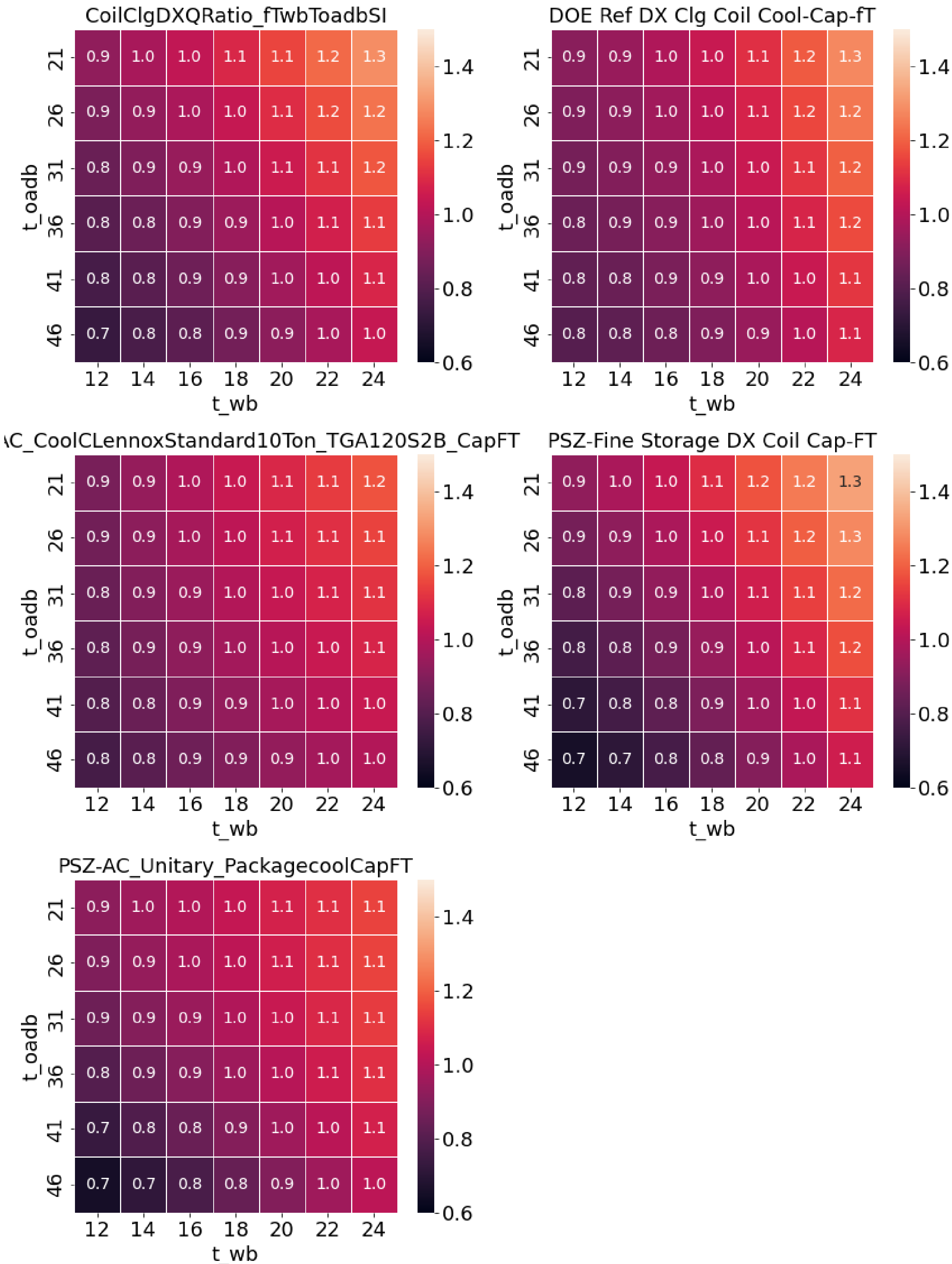

Figure 107. DX cooling capacity as a function of temperature performance curves. Independent variables are outdoor air dry bulb temperature (y-axis, degrees Celsius) and wet bulb temperature entering the cooling coil (x-axis, degrees Celsius).

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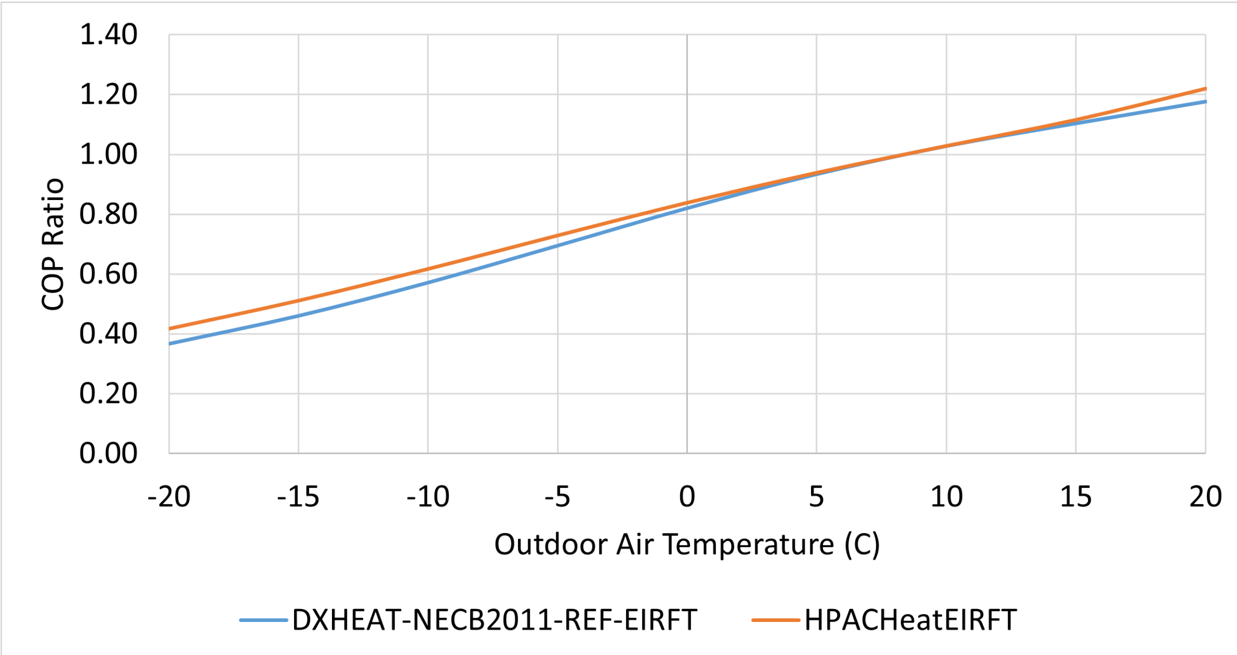

Figure 108. Air-source heat pump COP ratio as a function of outdoor air dry bulb temperature.

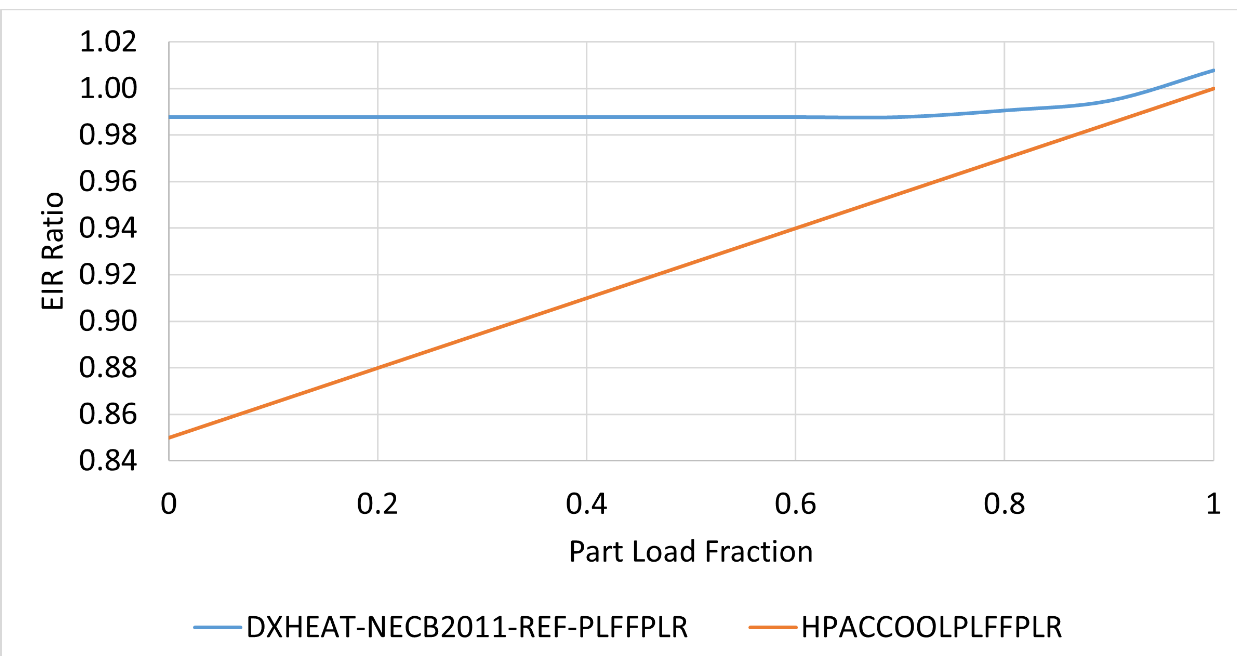

Figure 109. Air-source heat pump EIR ratio as a function of part load ratio.

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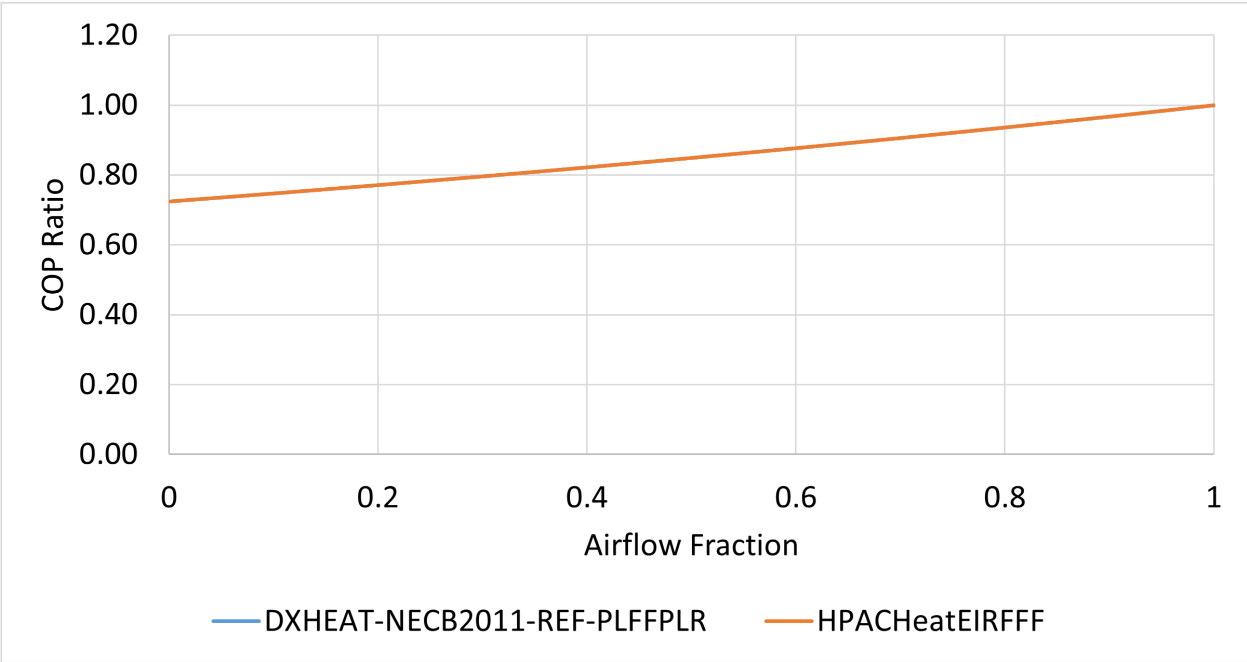

Figure 110. Air-source heat pump EIR ratio as a function of airflow fraction.

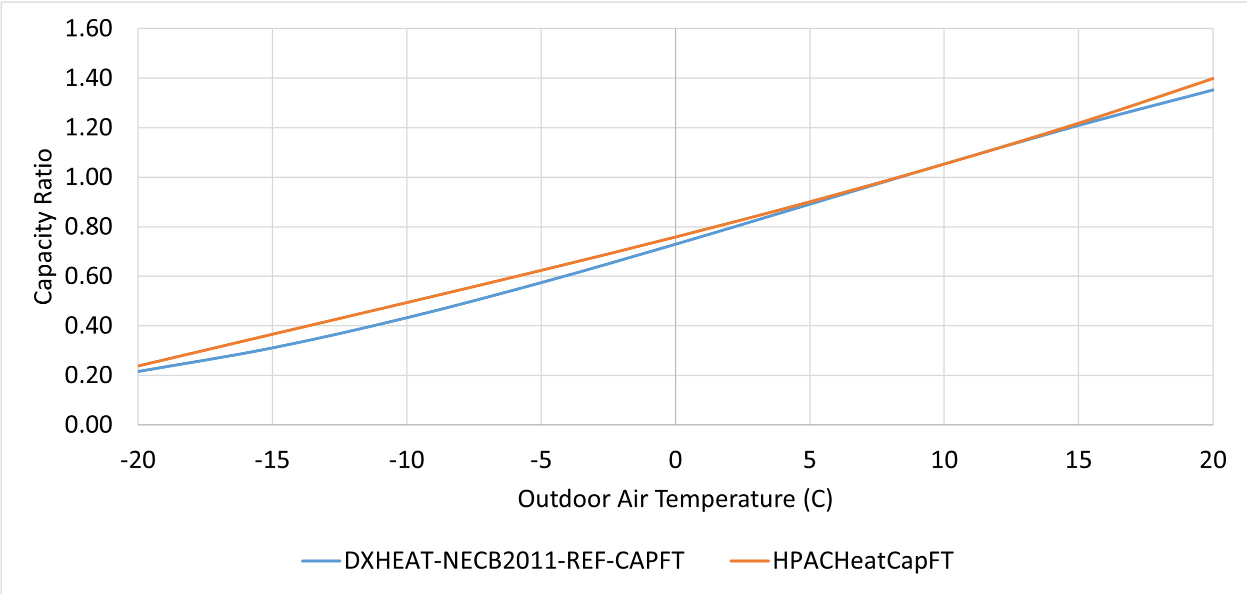

Figure 111. Air-source heat pump capacity as a function of outdoor air dry bulb temperature.

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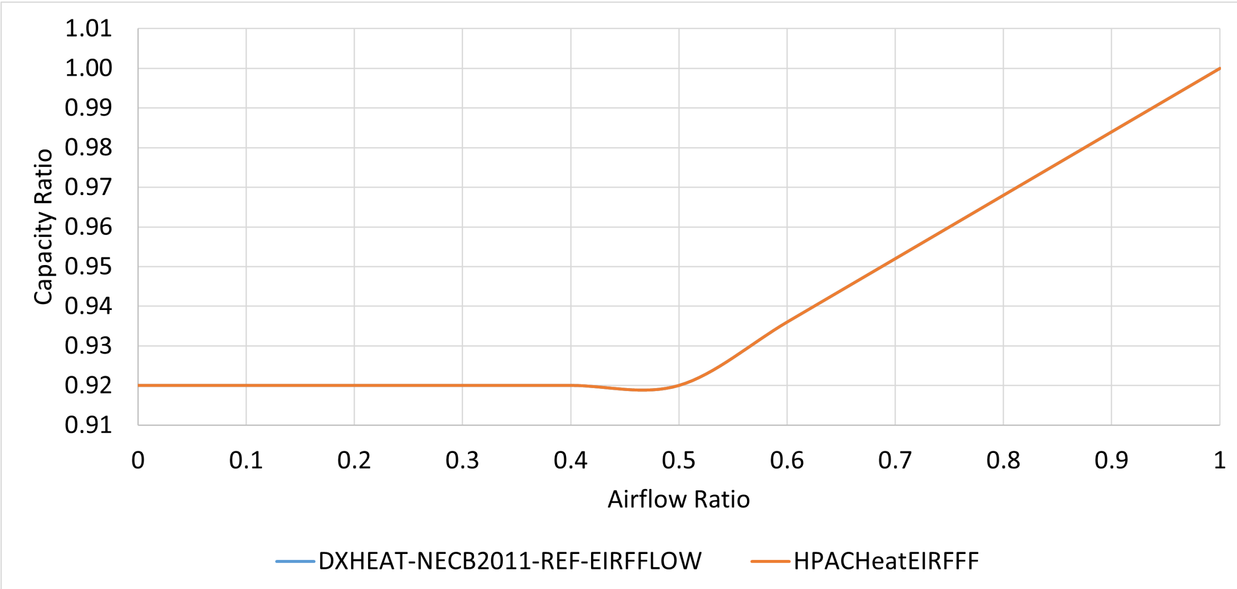

Figure 112. Air-source heat pump capacity as a function of airflow ratio.

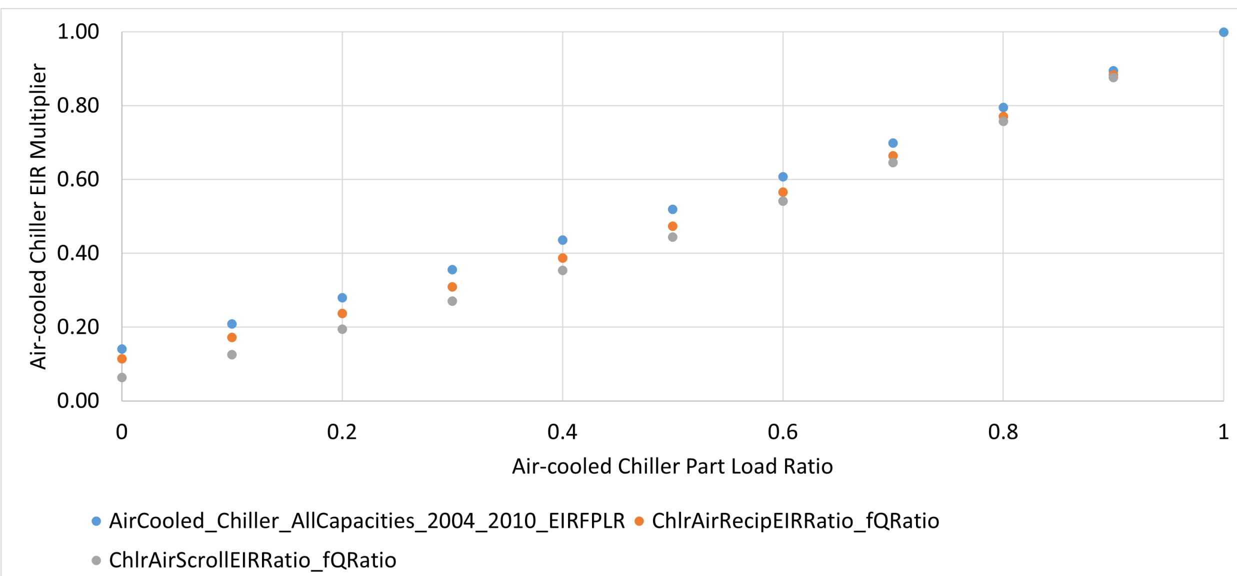

Figure 113. Air-cooled chiller EIR as a function of part load ratio performance curves. Independent variables beyond the curve limits will use the bound of the curve limit during simulation.

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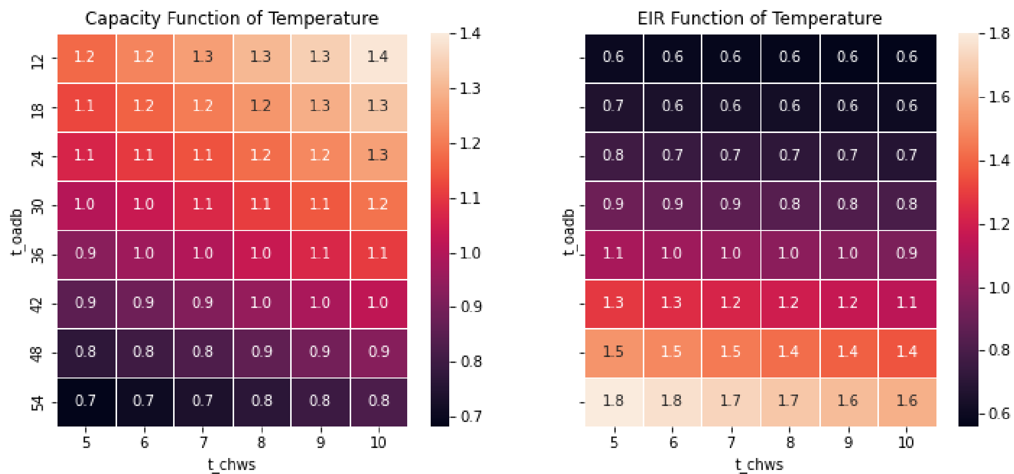

Figure 114. "AirCooledChiller2010PathA" modifier performance curves; capacity as a function of temperature and EIR as a function of temperature. Independent variables beyond the curve limits will use the bound of the curve limit during simulation.

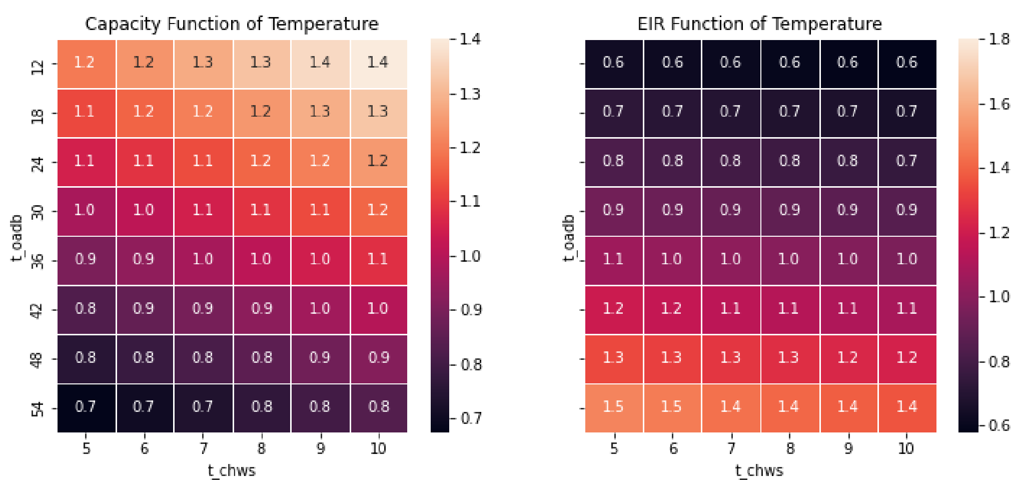

Figure 115. "ChlrAirRecip" modifier performance curves; capacity as a function of temperature and EIR as a function of temperature. Independent variables beyond the curve limits will use the bound of the curve limit during simulation.

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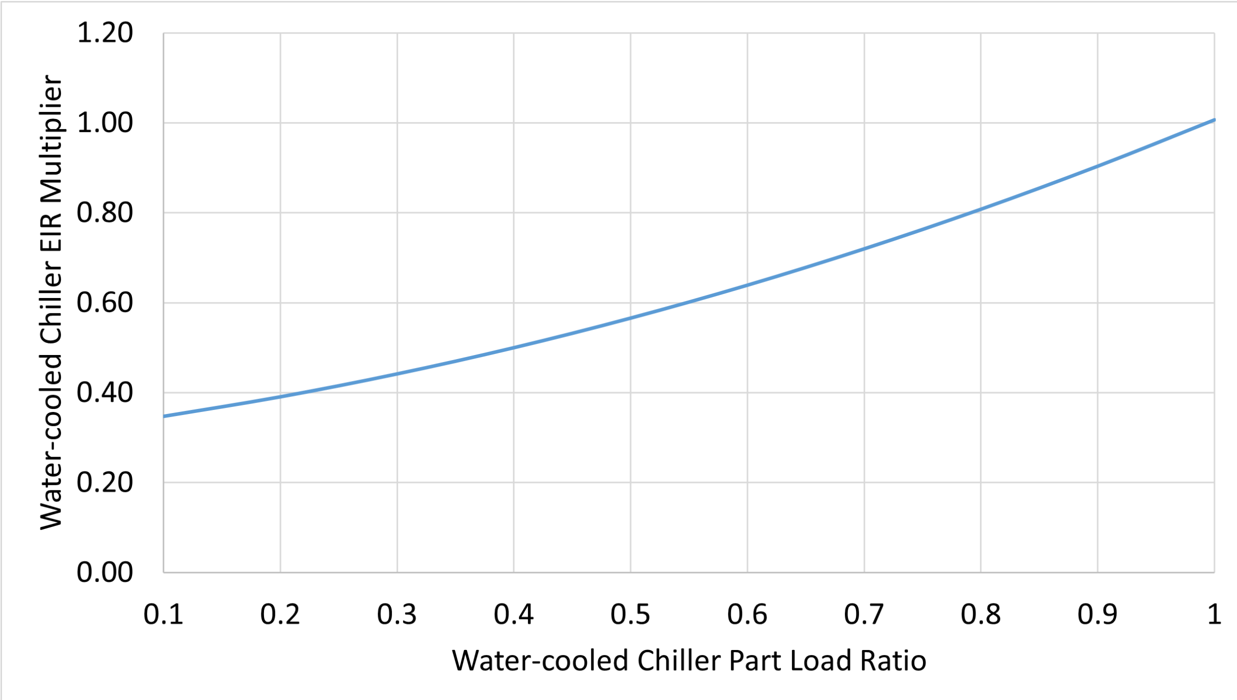

Figure 116. Energy input ratio modifier as a function of water-cooled chiller part load ratio.

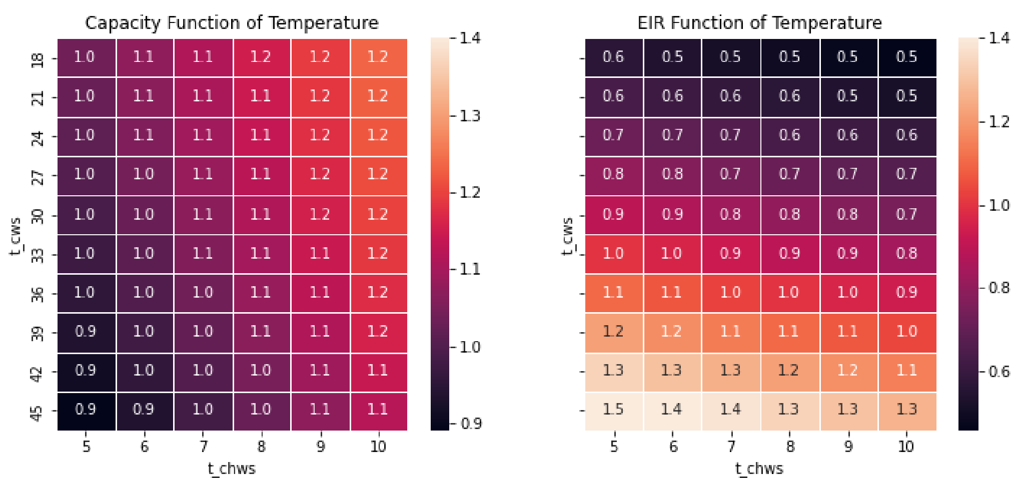

Figure 117. Performance curves for "WaterCooled PositiveDisplacement Chiller LT150 2010 Modifiers" WCC.

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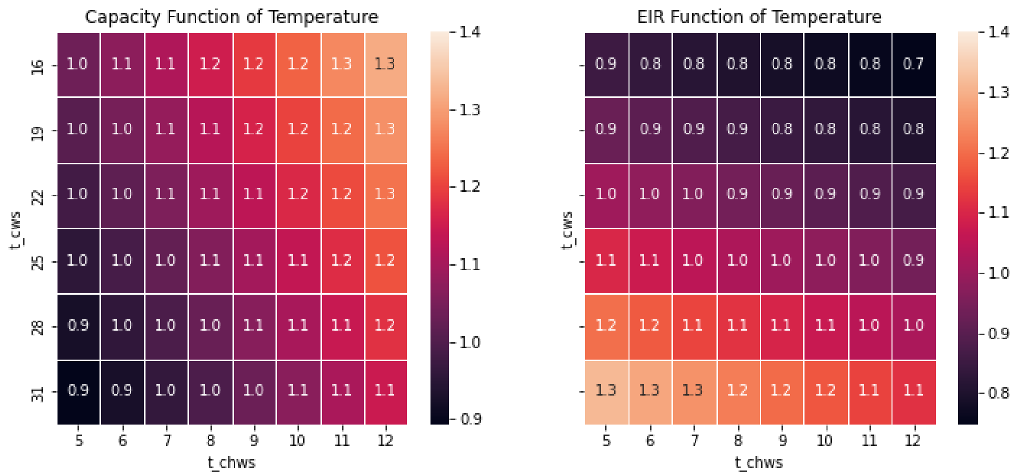

Figure 118. Performance curves for “ChlrWtrPosDispPathAAll Modifiers” WCC.

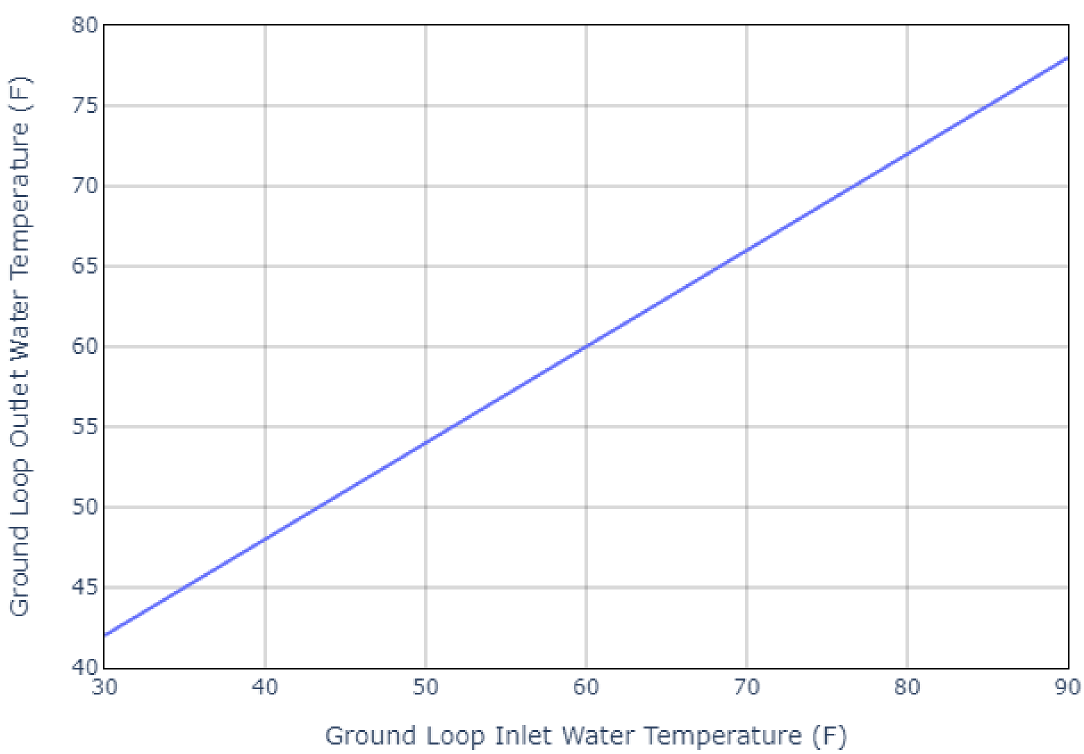

Figure 119. Ground loop outlet vs. inlet temperature relationship for GSHPs.

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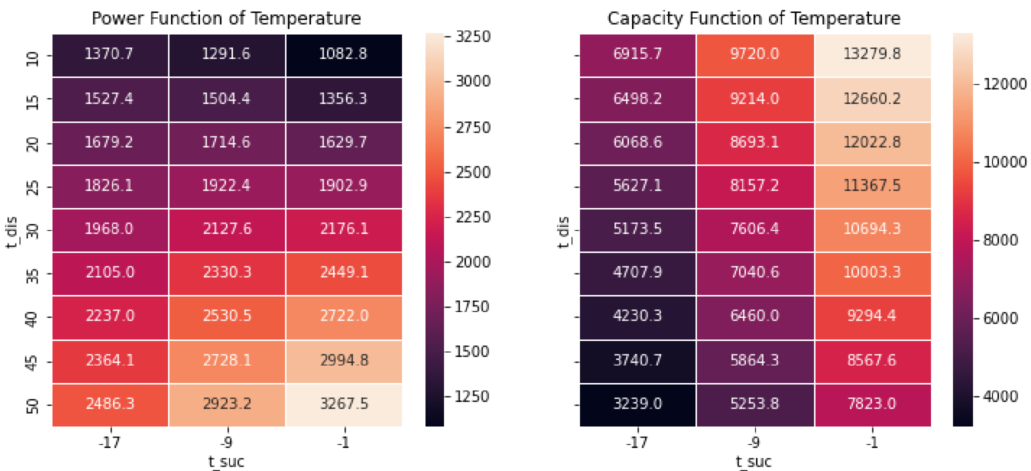

Figure 120. Power and capacity values as a function of suction and discharge temperature for small, old, medium-temperature compressors.

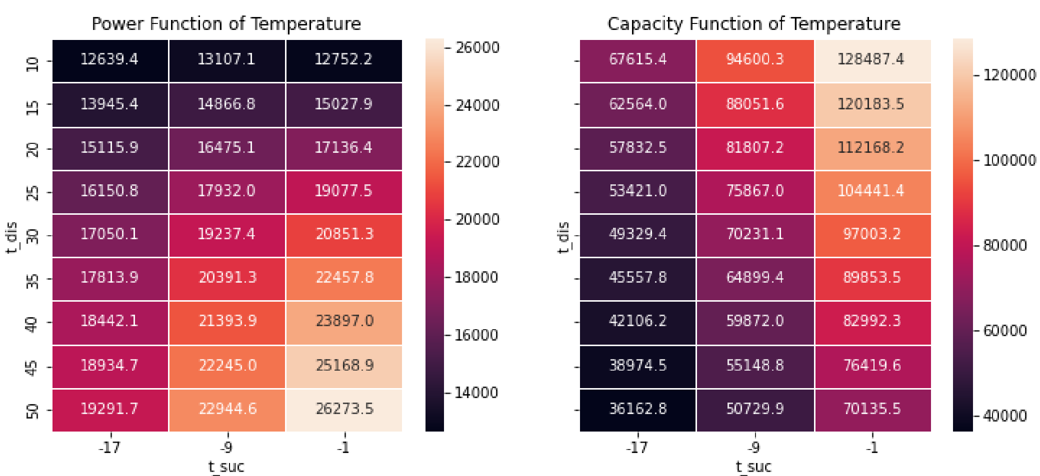

Figure 121. Power and capacity values as a function of suction and discharge temperature for large, new, medium-temperature compressors.

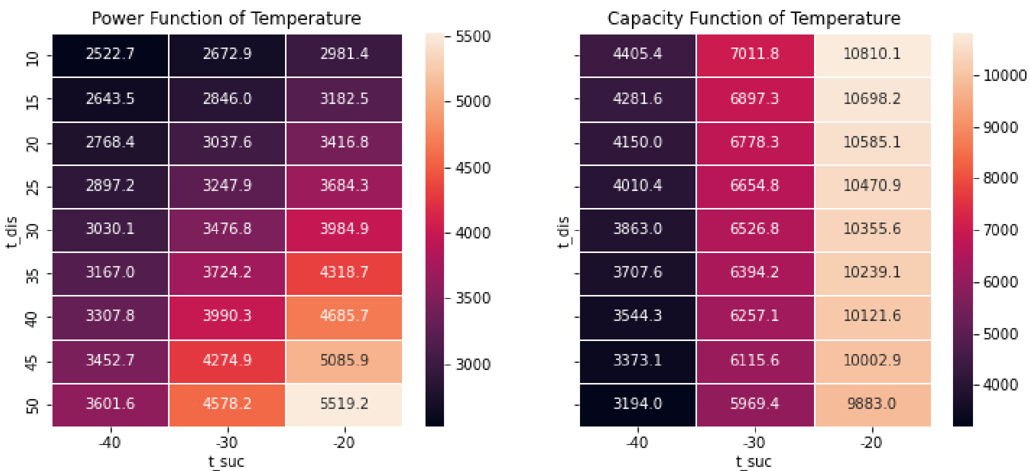

Figure 122. Power and capacity values as a function of suction and discharge temperature for small, old, low-temperature compressors.

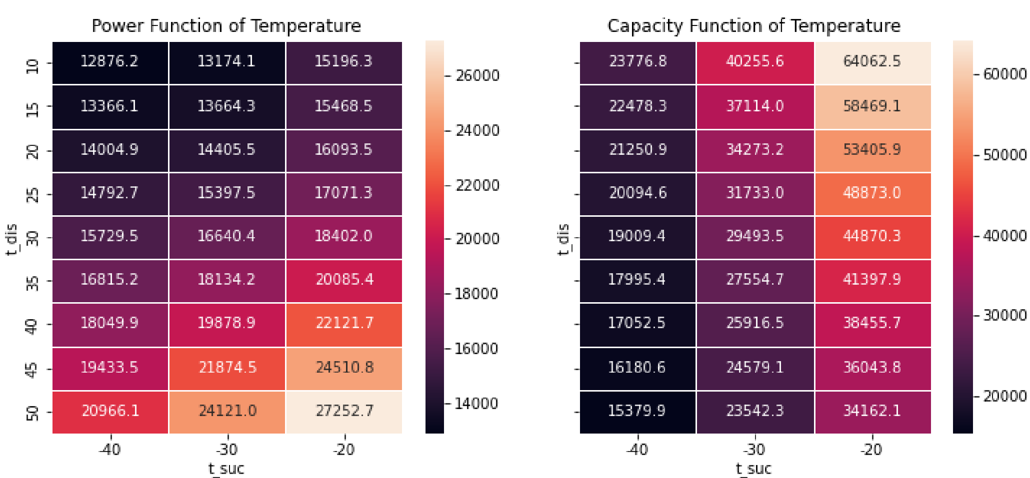

Figure 123. Power and capacity values as a function of suction and discharge temperature for large, new, low-temperature compressors.

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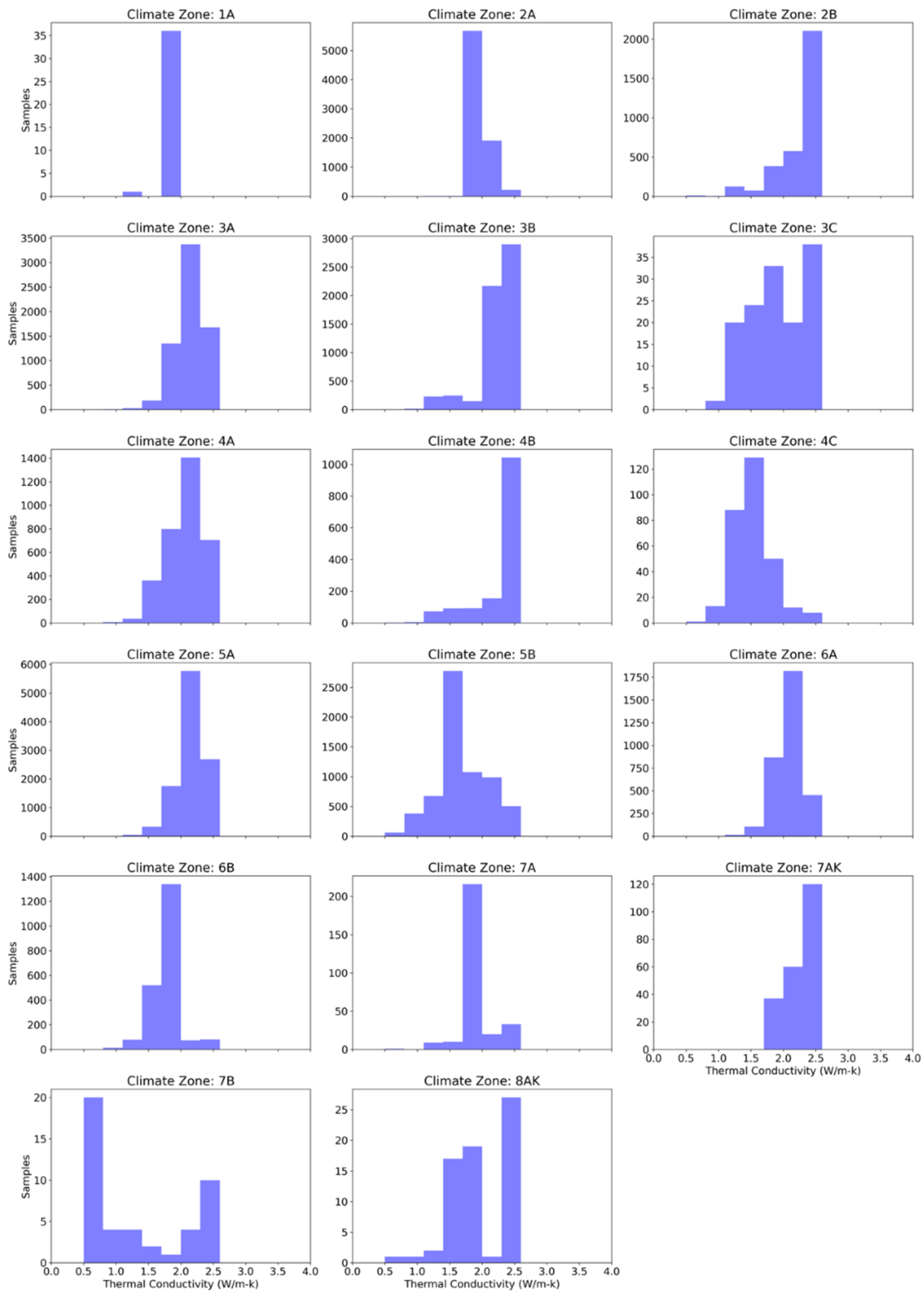

Figure 124. Soil thermal conductivity distributions by climate zone.

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