Highly Resolved Reference Projections of Building Energy Use for the Contiguous United States: Building Sector Energy Baselines, Projection Methods, and Results

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National Renewable Energy Laboratory

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Acronyms

ACS	American Community Survey
AEO	Annual Energy Outlook
AHS	American Housing Survey
AMY	actual meteorological year
ATUS	American Time Use Survey
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	balancing authority
CBECS	Commercial Building Energy Consumption Survey
DOE	Department of Energy
EIA	Energy Information Agency
EPW	EnergyPlus weather
EUI	energy use intensity, defined as energy consumption per unit of floor area
HSIP	Homeland Security Infrastructure Program
NEMS	National Energy Modeling System
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
IECC	International Energy Conservation Code
ISD	Integrated Surface Database
PBA	Principal Building Activity
PUMA	Public Use Microdata Area
PUMS	Public Use Microdata Samples
RBSA2	Residential Building Stock Assessment II
RECS	Residential Energy Consumption Survey
ReEDS	Regional Energy Deployment System
Resdb	Residential Diagnostic Database
TEMPO	Transportation Energy & Mobility Pathway Options model

Executive Summary

This report describes a methodology for projecting energy consumption in the U.S. residential and commercial building sectors using the National Renewable Energy Laboratory (NREL)'s ComStock™ and ResStock™ models combined with growth rates derived from EIA's Annual Energy Outlook (AEO). The impetus for this work is to provide an intermediate method for generating demand-side sectoral energy projections suitable for grid-scale analysis, such as NREL's Standard Scenarios[1]. Using Decomposition Analysis, the energy demand for each building sector is described as a function of several components, e.g., number of dwelling units, energy use intensity. For each component, an annual exponential growth rate is extracted from the 2021 AEO projection datasets. Growth rates are differentiated by census division, building type, and fuel-specific end use to capture variations in load growth due to demographic, economic, and technological factors. Following the decomposition formula, the growth rates are applied to the energy baselines from ComStock and ResStock to produce the sectoral load forecasts at the county level. The method is a more resolved, detailed, and extensible projection framework than the common practice of applying a single, perhaps regional, growth rate to historical load shapes. This method was used in NREL's grid planning models until a few years ago and is still common practice in some organizations.

For the commercial sector, total demand is formulated as the product of total floor area and the end use energy intensity by fuel type. Growth rates for each of the components are differentiated by building type and census division to reflect the diversity of growth along these dimensions. Residential load is partitioned into two load groups: end use loads that scale with the number of households (e.g., major appliances) and end uses that scale with dwelling floor area (e.g., lighting, space heating, and space cooling). The total load is broken into the number of dwelling units and energy use per dwelling unit for the former load group, and into the number of dwelling units, floor area per dwelling unit, and energy use intensity (energy consumed per unit of floor area) for the latter. For each of these components, a growth rate is extracted relative to fuel type and end use. No distinction is made to geography or building type as the component growth rates do not vary significantly across these dimensions in the AEO projections.

ComStock and ResStock are physics-based and statistically representative building stock models of the U.S. commercial and residential sector, respectively. The sectoral energy baselines are simulated using hundreds of thousands of building energy models and weather data from the 2012 actual meteorological year (AMY). The resulting hourly energy profiles are aggregated by county, building type, and end use, and then scaled by the corresponding annual growth rates derived from the 2021 AEO Reference scenario to produce energy projections through 2050. The compiled result is a demand-side grid model (dsgrid) dataset suitable for use in large-scale grid planning models, i.e., capacity expansion and production cost models.

While the growth rates extracted from the AEO can be modified to account for other assumptions, the growth rates used in this report are unchanged so that the modeled projections reflect AEO's Reference scenario's assumptions for the future. Most notably, the projections do not reflect large-scale electrification – the conversion of most space heating, water heating,

[1] The NREL Standard Scenarios (https://www.nrel.gov/analysis/standard-scenarios.html) also make use of demand projections from the Electrification Futures Study (https://www.nrel.gov/analysis/electrification-futures.html), however, those data are not being regularly updated.

clothes drying, and cooking from the direct use of natural gas and other fossil fuels to electricity. The projections result in 25% more dwelling units, 38% more floor area, and 5% more total energy consumption for the residential sector in 2050 compared to 2018. During this same period, the commercial sector is expected to increase 37% in floor area and 7% in total energy consumption. Overall, electric end uses are expected to grow by 30% and 15% in the residential and commercial sector, respectively while fuel end uses decrease slightly. (That is, the projection reflects a small amount of electrification and some energy efficiency improvements.) The overall growth in energy use for both sectors is consistent with the published growth projections from 2021 AEO's Reference scenario.

The 2021 Standard Scenarios and their previous versions were based on load forecasts constructed using historical load shapes and economy-wide, regionally aggregated AEO load growth rates. The low resolution obfuscates how sector- or end-use-specific load shapes could change over time or over finer geospatial scale. The approach presented represents an improvement on this load forecasting process by allowing growth rates to be disaggregated and applied to capture the range of growth across sector, building type, end use, and census division. In one way, this approach represents a method to downscale AEO load growth to county level using the sectoral baselines. In another, the approach is an extensible framework in which the components of the load growth can be independently estimated and refined to reflect different assumptions about the future.

This study presents growth rates derived from the AEO Reference scenario as a demonstration of the capability. The method can be leveraged to formulate multiple growth rate scenarios to represent, e.g., high electrification and high energy efficiency, scenarios in addition to the AEO reference scenario described herein. It can also be extended by developing and applying a methodology to generate data for multiple weather years to refine the energy forecasts. This projection method does not endogenously represent how the building stock could evolve through time. Technological, policy, and behavioral shifts can be disruptive and may not follow a smooth curve or an exponential one. Instead, these changes may be more effectively modeled from the bottom-up using system dynamics models. Exploratory work is currently underway on new sectoral load forecasting models that focus on the nexus of building stock turnover and technology adoption driven by market conditions, consumer behavior, and policy.

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1 Introduction

According to the U.S. Energy Information Agency (EIA), the United States consumed nearly 100 quadrillion Btu (quad) in primary energy in 2021 (U.S. EIA, 2022). Buildings represent 28% of the total end-use sector energy (excluding electrical system energy losses), with the residential sector accounting for 16% and the commercial sector the other 12%. In terms of electricity, the building sector accounts for nearly two-thirds of the retail sales and thus represents a key determinant of load forecasts used in power system modeling and resource planning.

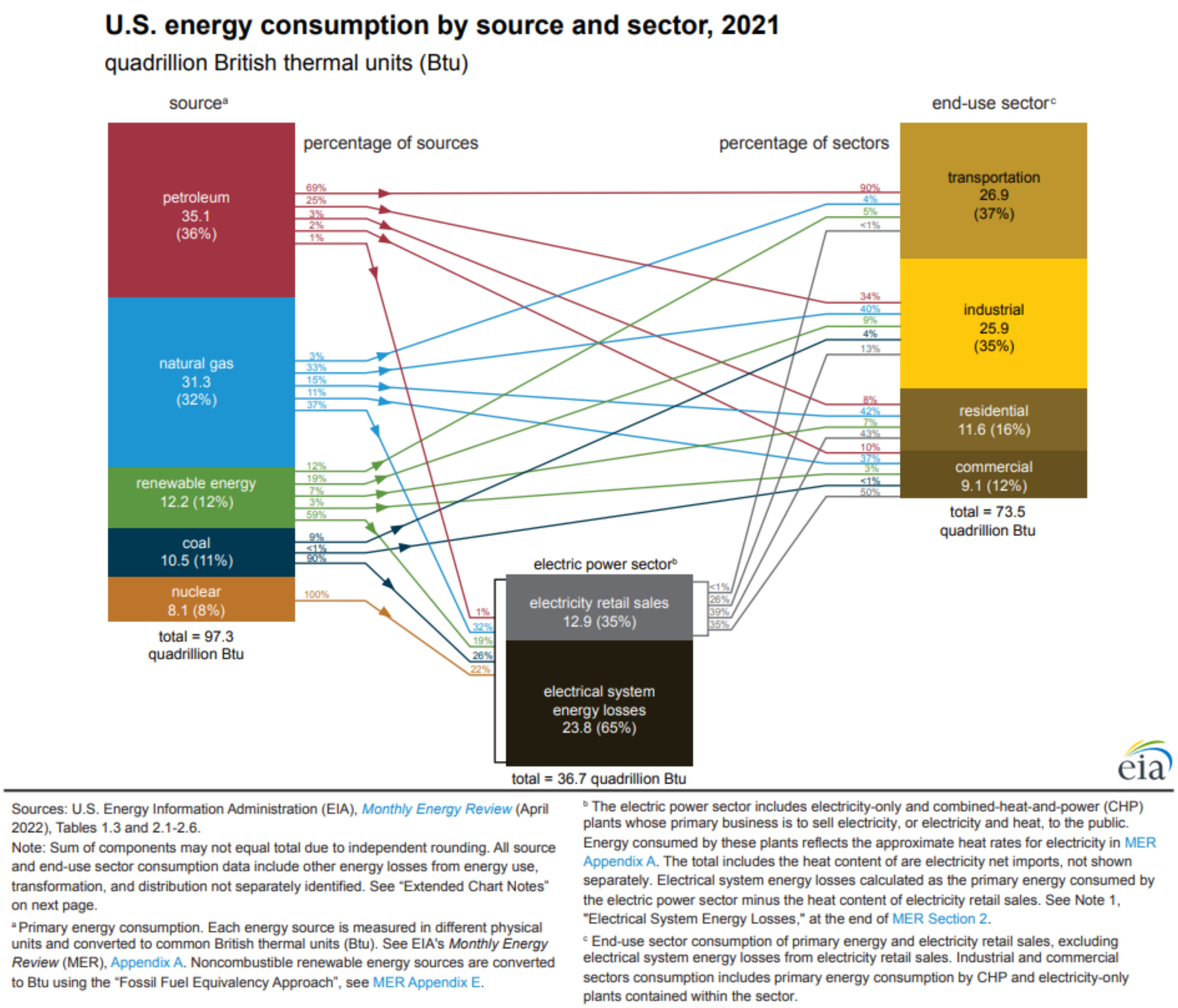

Figure 1. Flow of U.S. economy-wide energy from production sources to end use sectors (Image source: https://www.eia.gov/energyexplained/us-energy-facts/, retrieved April 2022)

While today's buildings sector energy landscape is sufficiently described by both data collection, such as that by EIA, and large-scale bottom-up energy models, there is a growing need for forward-looking research to help understand the long-term impacts of the investment and policy decisions being made today. In addition to more data collection and method development for load forecasts, there is a mounting interest to coordinate data-sharing and standardize assumptions between modeling tools to increase their application and to enable an ecosystem of models that can interconnect to provide a more holistic view of the U.S. energy system. The tools and modeling capability at the National Renewable Energy Laboratory (NREL) are being developed with this objective in mind.

NREL's suite of tools for modeling energy futures includes energy models for both the demand side and supply side. On the energy supply side, the Standard Scenarios provides a suite of future scenarios of the U.S. power sector that cover a wide range of technology cost, fuel cost, and policy assumptions, which result in a wide range of renewable energy shares. These scenarios are simulated using a set of forward-looking technology cost and performance data from the Annual Technology Baseline as well as Regional Energy Deployment System (ReEDS) and Distributed Generation Market Demand capacity expansion models. On the demand side, sectoral energy demand is modeled in detail by ComStock™, ResStock™, and the Transportation Energy & Mobility Pathway Options (TEMPO) model, which are a commercial building stock model, a residential building stock model, and a techno-economic demand model for the transportation sector, respectively. The development of the industrial sector energy modeling capability is underway. The demand-side grid (dsgrid) toolkit combines energy use data from these sectoral models and future projections thereof with estimates of energy losses and gaps to make up a full, highly resolved data description of current and future electricity demand, time-synchronized with variable renewable energy supplies (e.g. wind and solar), and thus suitable for grid analysis.

Demand projection based on the bottom-up sector models is an area currently under active development at NREL. This report presents a simple top-down projection method for the commercial and residential energy sectors by leveraging the widely used demand projection data from EIA's Annual Energy Outlook (AEO). This method represents an intermediate step to fill a data gap until a bottom-up projection modelling framework becomes available for each of the sector models.

The AEO from EIA is a set of annually updated energy projections out to 2050 that explores the long-term energy trends in the U.S. based on specific assumptions and methodologies (U.S. EIA, 2021). The projections are generated by the National Energy Modeling System (NEMS), an integrated economic model that aims to capture the interactions between energy supply, demand, and prices. NEMS has a native resolution at census division and makes use of EIA's Residential and Commercial Building Energy Consumption Surveys, which are administered every 5-6 years to estimate the saturation of enclosure and end use technologies in the building sectors across all U.S. states. The AEO has a Reference scenario and several side cases exploring different future possibilities. In addition to serving as a benchmark for the side cases, the Reference scenario serves to model business-as-usual energy trends based on the status quo. This includes relevant laws and environmental regulations expected to start or continue from the time of analysis, market-driven techno-economic improvements to end use technologies, and established views on economic and demographic forecasts.

In the next two sections, the models used for simulating the residential and commercial energy baseline are described in detail, including data input such as building stock characteristics and weather data. Then the method for projecting end use energy using AEO's Reference scenario is presented, followed by summary results of the projection, discussion, and conclusions.

2 Demand Model Baselines

The ComStock and ResStock models are used to generate commercial and residential building energy baselines, respectively, and are the foundations for future energy use projections. The models' energy end uses have undergone extensive calibration and validation using several benchmark data sources, including Form EIA-861 electricity and Form EIA-176 natural gas sales reporting, utilities load research data, sub-metering datasets, and smart metered data collected from different regions of the U.S. For more detail on the calibration process as well as a comparison of the modeled energy end uses to benchmark data, refer to the 2022 End-Use Load Profiles (EULP) study (Wilson, et al., 2022).

ComStock and ResStock are physics-based, bottom-up models that statistically describe the U.S. commercial and residential building stocks with large probabilistic databases of building characteristics. These characteristics are sampled to produce hundreds of thousands of statistically representative models that together paint a highly resolved picture of the residential and commercial building sectors. In this way, building prototypes with typical characteristics are modeled rather than specific individual buildings found in real-life. The process of model articulation is done using U.S. Department of Energy (DOE) physics-based building energy modeling frameworks – the sampled building characteristic sets are translated by OpenStudio® into building energy models that are then fed into EnergyPlus™ for simulation. The simulations are carried out in batches using distributed computing resources to produce sub-hourly end use load timeseries along with meta-data and scalar summary results for each representative building or housing unit. All software tools described in this section are actively evolving. The specific software versions used to create the energy baselines in this report are outlined in Appendix A.

In the rest of this section, the modeling assumptions for ComStock and ResStock along with their modeled energy baselines describing the U.S. building sectors as of 2018 are presented. The differences between the energy baselines and the 2018 modeled energy from 2021 AEO are highlighted, with potential sources of discrepancy discussed. Note both baselines are modeled, and each can be independently compared against actual energy records (e.g., EIA Form 861) for accuracy by sectoral total and utility ID but not by energy end use. The 2018 modeled energy varies between versions of AEO due to periodic updates to NEMS. Compared to the actual records, sectoral energy for 2018 has been underestimated in AEO of the past decade between 3-9% for commercial and 5-10% for residential (U.S. EIA, 2022). Meanwhile, ComStock's baseline is underestimated for both electricity and natural gas; ResStock's baseline compares well with EIA Form 861 reported annual electricity sales and slightly underestimates annual sales of natural gas according to EIA Form 176. See the End Use Load Profiles report (Wilson, et al., 2022) for more details. These caveats should be noted when looking at the baseline energy comparison between ComStock, ResStock and their AEO counterparts in Sections 2.1 and 2.2, respectively.

2.1 ComStock Energy Baseline and Assumptions

ComStock is a granular, bottom-up model of the U.S. commercial building stock. To create the commercial sector energy baseline, ComStock samples conditional probability distributions to define the type, size, shape, equipment, and schedules of 350,000 commercial building archetypes. In this way, these modeling archetypes represent generic typical buildings rather than specific buildings found in the real world. This analysis used a special run of the ComStock End Use Load Profiles release of October 21st, 2021, using 2012 AMY weather data.

The single largest assumption in the version of the ComStock model referenced in this analysis is that commercial buildings are built in accordance with a recognized ASHRAE building code (or typical historic construction practice for buildings built before ASHRAE 90.1 2004 was adopted in the relevant jurisdiction). Most commercial buildings are assumed to follow the ASHRAE 90.1 standard version current at the time of construction, with individual building systems being replaced over time and assumed to follow the energy code enforced in that location at the time of retrofit. The main data sources for this version of ComStock include the Commercial Building Energy Consumption Survey (CBECS), CoStar, and HSIP Gold 2012 Database. More information about these data sources, including vintage and how the dataset is used in ComStock is provided in Table 1. For more detail on ComStock, see the ComStock Reference Documentation (Parker, et al., 2023).

Table 1. ComStock Data Sources.

Data Source	Year	Data	Reference
Commercial Building Energy Consumption Survey (CBECS)	2012	Coarse geospatial resolution: Building type, vintage, floor area, conditioned floor space, number of stories, energy sources, HVAC, water heating equipment, and hours of operation ** CBECS does not have enough samples for our desired geospatial level of detail	https://www.eia.gov/consumption/commercial/data/2012/
CoStar	2017	Fine geospatial resolution for buildings that are part of an active real estate market: Location, building type, vintage, floor area, and number of stories	http://www.costar.com/products/costar-property-professional
Homeland Security Infrastructure Program (HSIP) Gold 2012 Database	2012	Fine geospatial resolution for buildings that are *not* part of an active real estate market (i.e., hospital, schools): Building type, number of beds (hospitals), enrollment (schools), and location	https://sdrgc.org/Documents/Docs/docs_20150408/HSIPgoldFreedom2015.pdf
ASHRAE 90.1		Nominal efficiency levels for lighting, HVAC, and envelope properties	https://www.ashrae.org/technical-resources/bookstore/standard-90-1

ComStock models 11 end uses, 4 fuel types, and 14 building types. Warehouse is the predominant building type and electricity interior equipment represents the largest energy end use. Although ComStock and the Commercial Demand Module of NEMS (AEO's underlying model) share CBECS as a major data source, their end use and building type definitions do not align completely with each other. NEMS's commercial building types are based on the CBECS Principal Building Activity (PBA) grouping, whereas ComStock building types are curated using the PBAplus definitions, which are partitions of PBA. To enable a comparison between the two models, we unified the building types and end uses between the models and rescale their loads such that they represent the same total floor area by building type. Table 3 and Table 2 provide the mapping used to consolidate and align the building types and end-use categories, respectively. As ComStock does not model all building types available in NEMS's commercial module, its unmodeled building types – assembly, food sales, other, and unspecified – were removed from the comparison, thus they are not shown in Table 2.

Table 2. Consolidation of ComStock and 2021 AEO commercial building types into aligned building categories. The AEO commercial building types – assembly, food sales, others, and unspecified – were removed from the analysis as they were not modeled in ComStock.

Commercial Building Type	ComStock Building Type	AEO Commercial Building Type
Education	Primary School, Secondary School	Education
Food Service	Full Service Restaurant, Quick Service Restaurant	Food Service
Health Care	Hospital	Health Care
Lodging	Large Hotel, Small Hotel	Lodging
Mercantile Service	Retail, Strip Mall	Mercantile Service
Office	Large Office, Medium Office, Outpatient, Small Office	Large Office, Small Office
Warehouse	Warehouse	Warehouse

Table 3. Consolidation of ComStock and 2021 AEO commercial end uses into aligned categories.

Commercial End Use	ComStock End Use	AEO Commercial End Use
Electricity Cooling	District Cooling, Electricity Cooling, Electricity Heat Rejection, Electricity Pumps (50%)	Electricity Cooling

Commercial End Use	ComStock End Use	AEO Commercial End Use
Electricity Heating	Electricity Heat Recovery, Electricity Heating, Electricity Pumps (50%)	Electricity Heating
Electricity Interior Equipment	Electricity Interior Equipment	Electricity Cooking, Electricity Office Equipment – PCs, Electricity Office Equipment – Non-PCs Electricity Others
Electricity Lighting	Electricity Exterior Lighting, Electricity Interior Lighting	Electricity Lighting
Electricity Refrigeration	Electricity Refrigeration	Electricity Refrigeration
Electricity Ventilation	Electricity Fans	Electricity Ventilation
Electricity Water Heating	Electricity Water Systems	Electricity Water Heating
Natural Gas Cooling		Natural Gas Cooling
Natural Gas Heating	District Heating, Natural Gas Heating	Natural Gas Heating
Natural Gas Interior Equipment	Natural Gas Interior Equipment	Natural Gas Cooking, Natural Gas Others
Natural Gas Lighting		Natural Gas Lighting
Natural Gas Water Heating	District Heating Water Systems, Natural Gas Water Systems	Natural Gas Water Heating
Other Fuel Cooling		Fuel Oil Cooling
Other Fuel Heating	Fuel Oil Heating, Propane Heating	Fuel Oil Heating
Other Fuel Interior Equipment		Fuel Oil Others
Other Fuel Water Heating	Fuel Oil Water Systems, Propane Water Systems	Fuel Oil Water Heating
Unspecified		Electricity Unspecified, Natural Gas Unspecified, Fuel Oil Unspecified, LPG Unspecified, Other Unspecified

LPG: Liquefied Petroleum Gas, another name for propane

Figure 2 and Figure 3 compare the ComStock modeled floor area, electric load, and natural gas consumption with AEO's commercial sector in base year 2018 by building type (denoted by marker color) and census division (denoted by marker shape). The parity line (a dark diagonal dash line in the figures) provides a reference for how well aligned the data is between the two models. Data below the parity line indicate overrepresentation in ComStock compared to AEO and vice versa for data above the line. Additional lines (in a lighter color) representing percent deviations from parity are provided to assist with result interpretation. In Figure 2, the disaggregated floor area in ComStock perfectly matches AEO because of normalization. For electricity and gas loads in Figure 3, the deviations can vary significantly, reflecting the difference in modeling scope, assumption, and approach between the two models.

While both ComStock and NEMS are designed to assess the energy use of the commercial building stock, they differ in their approach to do so. ComStock uses physics-based building energy models, which can better capture the interaction between systems, whereas NEMS uses inventories from the consumption surveys and average efficiencies by technology to estimate energy end uses. The electric end uses of ComStock have been calibrated to several measured data sources in the End Use Load Profiles project, including Advanced Metering Infrastructure data from four U.S. regions, utilities load research data, and EIA Form 861 electricity sales reporting. On the other hand, ComStock's natural gas end uses did not undergo the same rigorous process due to a lack of timeseries data for benchmarking and is an area under active development. As shown in Figure 3, ComStock's electric loads match better with AEO (within ±75% of discrepancy with AEO's) than its natural gas loads (within -75% to over +200% deviation compared to AEO).

Overall, the ComStock modeled energy is lower than AEO by17% for all fuels. When broken out by fuel type, the difference is +5% for electricity, -44% for natural gas and -55% for other fuels. In addition to different modeling approaches, ComStock does not model all end uses or technology types covered by NEMS, which contributes to the underrepresentation of loads in ComStock. As shown in Table 3, some broad categories are missing from ComStock (e.g., natural gas cooling[2], and natural gas lighting), though they represent less than 1% of the total load in AEO. Additionally, ComStock modeled some end uses in a limited scope or by assuming a different technology saturation. For example, refrigeration in ComStock is restricted to commercial-style hardwired refrigeration, whereas in NEMS, the end use covers all refrigeration equipment types, including plug-in freezers, refrigerators, and refrigerated warehouses. These unmodeled technologies lead to a 93% difference in refrigeration energy use. The differences highlighted are intended to show alignment between ComStock and NEMS's commercial module, not a judgement of accuracy, as both models have some discrepancies compared to EIA Form 861 and 176. It should be noted that any discrepancies in the baseline will be propagated into the projection, which will be discussed in Section 4.3.

[2] Example: gas-generated steam used to drive an AC compressor

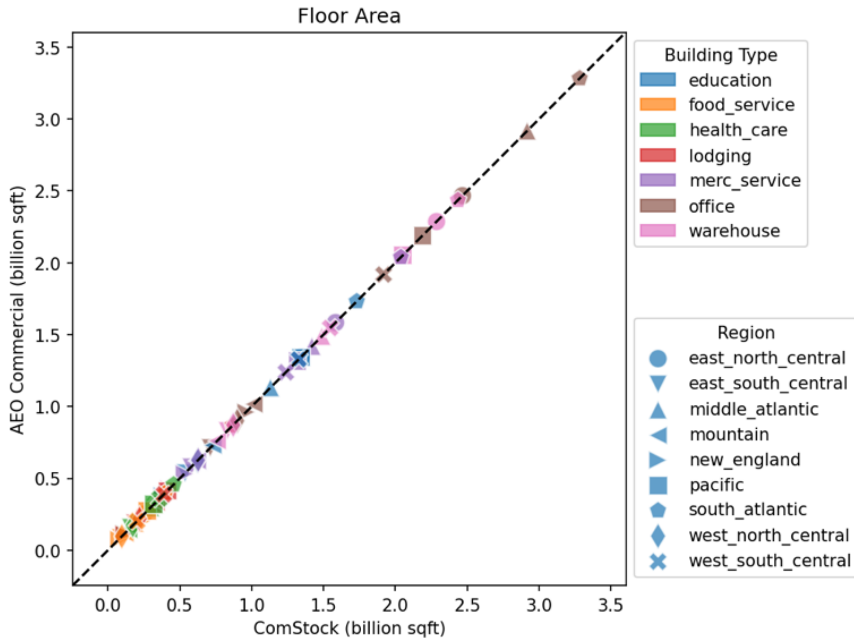

Figure 2. Comparison of ComStock and 2021 AEO commercial floor area in the base year 2018. (The ComStock floor areas are calibrated to align with AEO in this report.)

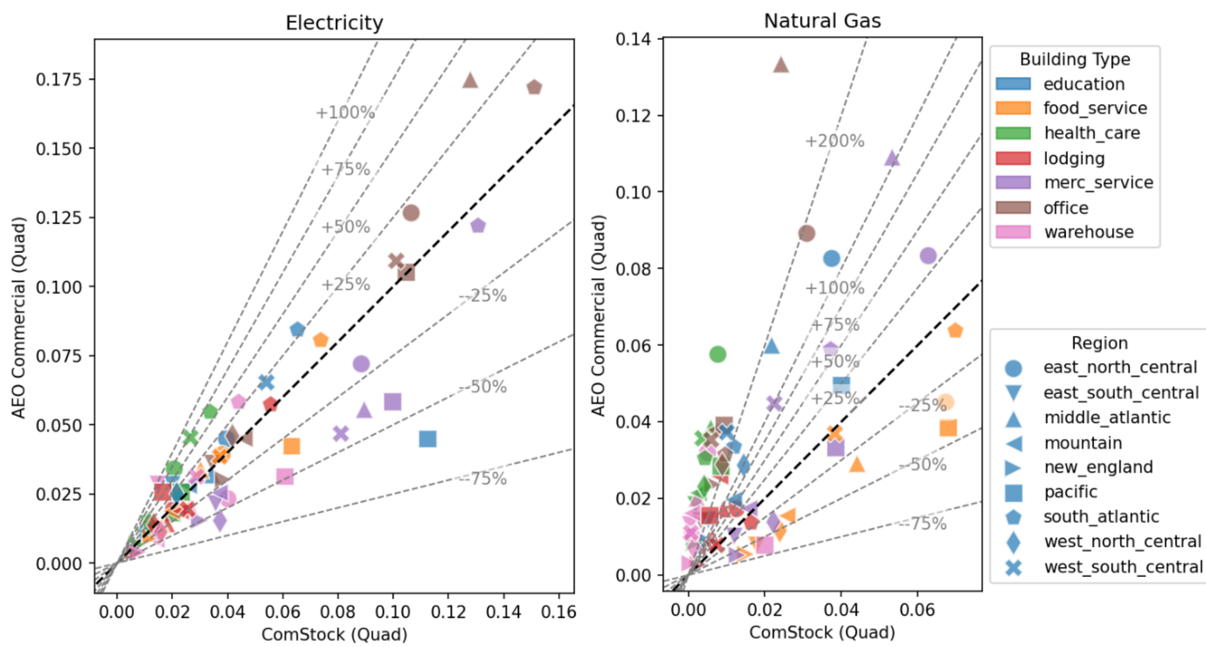

Figure 3. Comparison of ComStock and 2021 AEO commercial electricity (left) and natural gas (right) consumption in the base year 2018.

2.2 ResStock Energy Baseline and Assumptions

ResStock is a granular, bottom-up model of the U.S. housing stock. Using mostly publicly available and census-based data, such as EIA's Residential Energy Consumption Survey (RECS) and the U.S. Census Bureau's American Community Survey (ACS), as well as some proprietary datasets, ResStock defines more than 100 housing characteristics for a building energy model, including climate zone, vintage, dwelling type, floor area, and heating fuel, in the form of conditional probability distributions. Table 4 provides a detailed list of data sources used by ResStock to characterize the housing stock for simulation. The probability distributions are sampled to create models that each represent a dwelling unit, i.e., a single-family house or an apartment unit in a multi-family building. That is, in the case of multi-family or attached units, ResStock does not model buildings in their entirety, but rather single units, because those are the statistical population directly sampled in, e.g., RECS and ACS, and studied by the model. ResStock sampled and simulated 550,000 dwelling unit samples to create the residential energy baseline covering the contiguous U.S.

Table 4. ResStock Data Sources from the End-Use Load Profiles project.

Data Source	Year	Data	Source
Residential Energy Consumption Survey (RECS)	2015	National survey performed by EIA in 2015 that provides the most comprehensive overview of building characteristics, HVAC system, and appliance saturation, efficiency levels, and usage of the residential building stock. This survey is used by ResStock to specify plug loads and window frames and number of panes.	https://www.eia.gov/consumption/residential/data/2015/
RECS	2009	National survey performed by EIA in 2009 that provides the most comprehensive overview of building characteristics, HVAC system, and appliance saturation, efficiency levels, and usage of the residential building stock. This survey is used to specify the saturation and efficiency levels of pool pumps, extra freezers, refrigerators, and hot tubs, the number of stories of the building, HVAC heating and cooling types, HVAC system efficiencies, and water heater characteristics.	https://www.eia.gov/consumption/residential/data/2009/
American Community Survey (ACS)	2012-2016	National survey performed by U.S. Census Bureau that provides high-level building characteristics. PUMS is an anonymized reduction of ACS. ResStock uses the dwelling unit counts by census tract to spatially allocate the dwelling units across the U.S.	https://www.census.gov/acs/www/data/data-tables-and-tools/data-profiles/2016/
American Housing Survey (AHS)	2017	National survey performed by the U.S. Census Bureau in 2017 that provides ResStock with distributions for residential floor area, number of bedrooms, clothes washer, and clothes dryer saturation for the 15 largest metropolitan statistical areas and the census divisions.	https://www.census.gov/programs-surveys/ahs/data.2017.html
AHS	2013	National survey performed by the U.S. Census Bureau in 2013 that provides ResStock with distributions for residential floor area, number of bedrooms, clothes washer, and clothes dryer saturation for the 15 largest metropolitan statistical areas and the census divisions.	https://www.census.gov/programs-surveys/ahs/data.2013.html
Public Use Microdata Samples (PUMS)	2019	An anonymized version of the ACS that allows for cross-tabulation of high-level housing characteristics for every Public Use Microdata Area (PUMA) in the U.S. Some of the characteristics are Building Type, Vintage, Heating Fuel, Vacancy Status, and Number of Occupants.	https://www.census.gov/programs-surveys/acs/microdata/access.html

Data Source	Year	Data	Source
ASHRAE Standard 169	2013	Definition of climate zones in the U.S, that drives many of the building energy codes (ASHRAE 90.1 and 90.2). The climate zones are used to specify distributions of the location of the water heater, foundation types, HVAC system types and setpoints, and infiltration rate	https://www.ashrae.org/technical-resources/bookstore/weather-data-center
Residential Diagnostic Database (resdb)	N/A	Database created by Lawrence Berkeley National Laboratory of over 147,000 envelope leakage experiments. These data are used to inform air leakage distributions in ResStock.	https://resdb.lbl.gov/
International Energy Conservation Code (IECC)	2004	Climate zones used to help map weather stations to nearby counties and constrained to the IECC climate and moisture zone.	https://codes.iccsafe.org/content/document/286?site_type=public
Residential Building Stock Assessment II (RBSA2)	2016-2017	A survey of the Pacific Northwest that has the best data on window-to-wall ratio of dwelling units.	https://neea.org/resources/rbsa-ii-combined-database
EIA Form 861	2018	Mandatory survey of utilities, their retail sales, revenue, number of customers, service territory. ResStock uses these data to assign counties to independent system operator/ regional transmission operators and for validation of loads at the utility scale.	https://www.eia.gov/electricity/data/eia861/
Regional Energy Deployment System (ReEDS)	2011	A model developed by NREL that projects electricity generation technologies and transmission infrastructure across the contiguous U.S. ResStock uses the same geographic identifiers as ReEDS to easily map ResStock results.	https://www.nrel.gov/docs/fy12osti/46534.pdf
American Time Use Survey (ATUS)	2013-2017	National survey recording in 15-min increments the activities and locations of respondents' typical 24-hour day.	https://www.bls.gov/tus/database.htm

ResStock models 32 end uses, 5 fuel types, and 5 building types. The building types are aligned with RECS's definitions, and thereby with NEMS's Residential Demand Module. Single-family detached is the predominant housing type and the largest residential end uses include natural gas heating and electric cooling. Table 5 and Table 6 provide the mapping used to consolidate and align the residential end use categories and building types, respectively, between ResStock and NEMS (AEO's underlying model). Some end use categories are modeled in much more detail in ResStock than NEMS, e.g., space heating, cooling, and ventilation. On the other hand, ResStock models all plug loads as a single category and relies on RECS to provide the geographic diversity in total plug load. ResStock does not model other fuels such as wood and coal. Aligning the end uses and building types allow the datasets to be compared in Figure 4 and Figure 5 and is also necessary for projecting the ResStock dataset using AEO-derived growth factors.

Table 5. Consolidation of ResStock and 2021 AEO residential building types into aligned building categories.

Residential Building Type	ResStock Building Type	AEO Residential Building Type
Mobile Home	Mobile Home	Mobile Home
Multi-Family	Multi-Family with 2 - 4 Units, Multi-Family with 5+ Units	Multi-Family
Single-Family	Single-Family Attached, Single-Family Detached	Single-Family

Table 6. Consolidation of ResStock and 2021 AEO residential end uses into aligned end use categories.

Residential End Use	ResStock End Use	AEO Residential End Use
Electricity Heating, Cooling, and Ventilation	Electricity Bath Fan, Electricity Ceiling Fan, Electricity Cooling, Electricity Fans Cooling, Electricity Fans Heating, Electricity Heating, Electricity Heating Supplemental, Electricity Pumps Cooling, Electricity Pumps Heating, Electricity Range Fan	Electricity Ceiling Fan, Electricity Space Cooling, Electricity Dehumidifier, Electricity Furnace Fans, Electricity Space Heating, Electricity Secondary Heating
Electricity Lighting	Electricity Exterior Lighting, Electricity Garage Lighting, Electricity Interior Lighting	Electricity Lighting
Electricity Major Appliances	Electricity Clothes Dryer, Electricity Clothes Washer, Electricity Cooking Range, Electricity Dishwasher,	Electricity Cooking, Electricity Coffee Maker, Electricity Clothes Washer, Electricity Dryer,

Residential End Use	ResStock End Use	AEO Residential End Use
	Electricity Hot Tub Heater, Electricity Hot Tub Pump, Electricity Hot Water, Electricity Pool Heater, Electricity Pool Pump, Electricity Well Pump	Electricity Dishwasher, Electricity Hot Water, Electricity Pool Heater, Electricity Spa
Electricity Plug Loads / Others	Electricity Plug Loads	Electricity Monitors, Electricity Rechargeable Devices, Electricity Desktop / PC, Electricity DVD, Electricity Home Theater, Electricity Laptop, Electricity Microwave, Electricity Network Equipment, Electricity Other Electronics, Electricity Security System, Electricity Set Top Box, Electricity Television, Electricity Video Game Console, Electricity WCL
Electricity Refrigeration	Electricity Extra Refrigerator, Electricity Freezer, Electricity Refrigerator	Electricity Freezer, Electricity Refrigerator
Fuel Oil Heating, Cooling, and Ventilation	Fuel Oil Heating	Fuel Oil Space Heating, Fuel Oil Secondary Heating
Fuel Oil Major Appliances	Fuel Oil Hot Water	Fuel Oil Hot Water
Fuel Oil Plug Loads / Others		Fuel Oil Other Appliances
LPG Heating, Cooling, and Ventilation	Propane Heating	LPG Space Heating, LPG Secondary Heating
LPG Major Appliances	Propane Clothes Dryer, Propane Cooking Range, Propane Hot Water	LPG Cooking, LPG Hot Water
LPG Plug Loads / Others		LPG Other Appliances
Natural Gas Heating, Cooling, and Ventilation	Natural Gas Heating	Natural Gas Space Cooling, Natural Gas Space Heating, Natural Gas Secondary Heating
Natural Gas Lighting	Natural Gas Lighting	
Natural Gas Major Appliances	Natural Gas Clothes Dryer, Natural Gas Cooking Range,	Natural Gas Cooking, Natural Gas Dryer,

Residential End Use	ResStock End Use	AEO Residential End Use
	Natural Gas Fireplace, Natural Gas Grill, Natural Gas Hot Tub Heater, Natural Gas Hot Water, Natural Gas Pool Heater	Natural Gas Hot Water
Natural Gas Plug Loads / Others		Natural Gas Other Appliances
Other Fuel Heating, Cooling, and Ventilation		Other Fuel Space Cooling, Other Fuel Space Heating, Other Fuel Secondary Heating
Other Fuel Major Appliances		Other Fuel Hot Water

LPG: Liquefied Petroleum Gas, another name for propane.

Both ResStock and NEMS's residential module make use of RECS as a major data source. To understand how well these two models align in load estimates for AEO's 2018 base year, Figure 4 and Figure 5 compare their modeled dwelling unit count and floor area, electric load and natural gas consumption, respectively, differentiated by building type (denoted by marker color) and census division (denoted by marker shape). The plots show general agreement between ResStock and AEO in both the size of the housing stock and energy consumption. Both the modeled dwelling unit count and total floor area are aligned with AEO's within ±20% of discrepancy. Most of the modeled electricity uses are within ±25% of AEO's. The modeled natural gas uses for single-family homes are lower by 10-75% compared to AEO but comparable for other housing types.

Similar to ComStock, the calibration of ResStock's natural gas end uses was limited by the availability of ground truth data. As such, the natural gas comparison in Figure 5 shows slightly greater dissimilarity than the electricity comparison. Of note, the natural gas estimate for the East North Central and Middle Atlantic census divisions has the highest discrepancies and are both lower relative to AEO. In Figure 4, the housing stock in East North Central is higher in terms of unit count but lower in terms of floor area, suggesting that the modeled dwelling units are on average smaller in footprint than what is modeled in NEMS. Meanwhile, the housing stock estimate for Middle Atlantic is somewhat consistent between the two models. This suggests that the discrepancy in natural gas consumption for both census divisions is more related to a lower estimate of natural gas appliance saturation, usage, or efficiency than to the size of the housing stock in those areas.

Compared to AEO's baseline, the total dwelling unit count and total floor area modeled by ResStock is overall higher by 8% and 7%, respectively. The modeled energy is lower by 16% overall, 4% for electricity, 20% for natural gas, and 43% for other fuels. The differences highlighted are intended to show alignment between ResStock and AEO, not a judgement of accuracy, as both models have some discrepancies compared to EIA Form 861 and 176. Note the discrepancy in the baseline will be propagated into the projection, which will be discussed in Section 4.4.

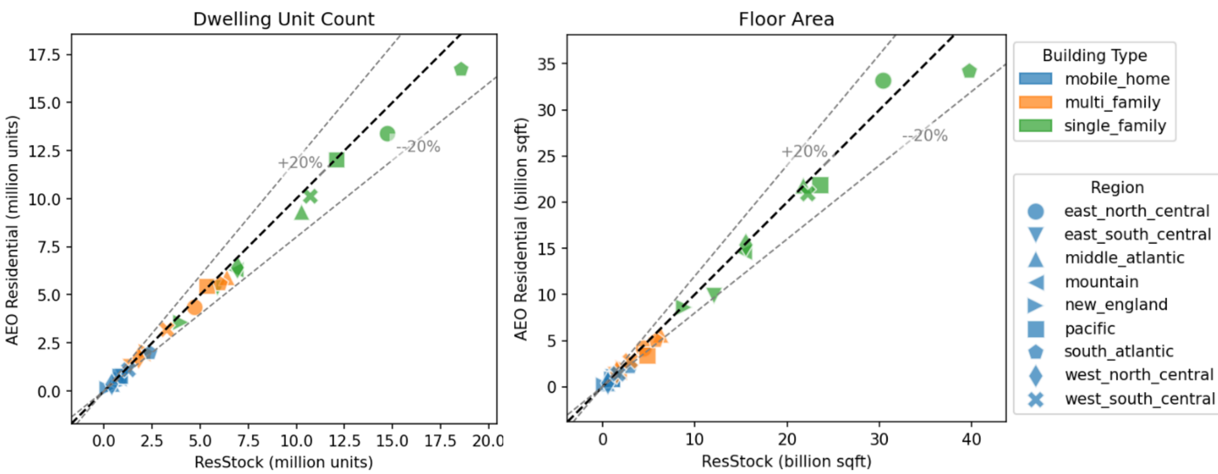

Figure 4. Comparison of ResStock and 2021 AEO residential dwelling unit count (left) and floor area (right) in the base year 2018.

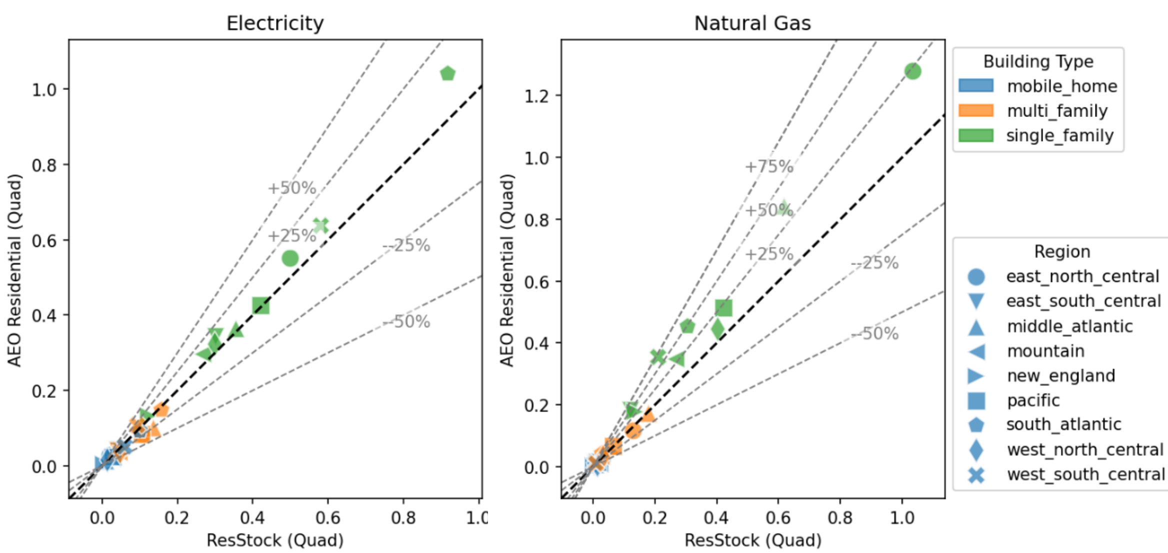

Figure 5. Comparison of ResStock and 2021 AEO residential electricity (left) and natural gas (right) consumption in the base year 2018.

3 Weather Data

Weather files are generated using data from three major sources: Integrated Surface Database (ISD) from the National Oceanic and Atmospheric Administration (NOAA), Synoptic (a company that was used to download data from MesoWest), and National Solar Radiation Database (NSRDB). The code is written and maintained by the ComStock team. The automated process described below has been used to create weather files for about 1,200 weather stations distributed across the contiguous United States for actual meteorological years 2010-2020. The team also maintains a map of weather stations to counties—for counties without a weather station, the weather station closest to the county population centroid is selected. This project uses the AMY files for 2012.

The first step in assembling a weather file is to retrieve five key variables in the ISD – dry bulb temperature, relative humidity, wind speed, wind direction, and atmospheric pressure. The ISD contains data for many weather stations and is thus used as the primary data source. For stations and years where the ISD does not provide data or the data it provides are incomplete or not reliable, Synoptic data are used instead. Synoptic data are also used selectively for locations that are not serviced by the NWS. At this point in the process, data selection is complete and all relevant weather stations have assigned timeseries data. The data are then resampled to the hourly frequency and undergo additional processing for data gap-filling and quality control.

In the quality control step, each variable is processed separately. If the timeseries contain gaps of less than 4 consecutive hours, they are filled with linear interpolation. If the gap is larger than 3h, but smaller than 100h, a naïve gap filling method is applied, using data from the 3 days before the gap and from the 3 days after the gap. If any gap larger than 100h is present, the data for the selected station and year are discarded. Similarly, if more than 300h total across the whole year timeseries are missing, the data are discarded. Individual values for each hour for each variable are analyzed to see if they are in a reasonable range. If an anomalous value is spotted, it is removed and filled in with linear interpolation. Finally, a check is applied to make sure that all the variables together respect psychrometric relationships.

At this point, five variables are retrieved from the NREL National Solar Radiation Database (NSRDB) for each location (defined at a 5km x 5km grid scale) and year – global horizontal irradiation, diffuse horizontal irradiation, direct normal irradiation, sky cover, and surface albedo. These data are modeled data (not measured data like the NOAA and Synoptic data) and quality control steps are applied during the dataset creation, so there is no need to further inspect the downloaded data. All variables are then merged into a single EnergyPlus Weather (EPW) file. It is important to note that EPW files require 29 variables, as mentioned in their documentation. For the 19 variables not retrieved from NOAA, ISD, Synoptic, or NSRDB, default values are used, as indicated by the EPW documentation. Doing so assumes that the 10 data-driven variables are the main drivers of building energy consumption and that default variables are sufficient for the remainder.[3]

[3] The literature (e.g., https://doi.org/10.1016/j.enbuild.2012.01.033) generally shows that dry bulb temperature and relative humidity (or wet bulb temperature) are the two most important variables, followed by solar irradiation (two of global horizonal, diffuse horizontal and direct normal irradiation), followed by wind speed.

4 End Use Projection

4.1 Projection Method Overview

To construct building sector energy use projections to 2050, we decomposed the baseline ComStock and ResStock results presented in Section 3 into load components that are then scaled up using growth rates derived from AEO. This is known as a Decomposition and Recomposition Analysis. Using the 2021 AEO Reference scenario, exponential annual growth rates were extracted to describe overall stock growth and end use-differentiated energy use growth between 2018 and 2050. In the residential sector, these growth factors are used to scale the number of dwelling units in the housing stock, the average size (floor area) of the units, and then either the energy use intensity (per floor area) or energy per dwelling unit depending on end use. For the commercial sector, total floor area and end use energy intensity are projected based on the building type and census division. For the method used to extract the annual growth rates, see Appendix A. Detailed projection methods for ComStock and ResStock are presented below.

Our projections have been developed with an eye toward supporting NREL grid planning tools. Currently, ReEDS, NREL's flagship capacity expansion model for the power sector, has access to two sets of load data. One load data option is historical load shapes grown over time using AEO electricity growth rates at the census division level. The historical load shapes cover various geographies, some quite coarse (e.g., multiple states), that are downscaled to the ReEDS balancing authority (BA) level using fixed fractions. The other option is state-level load projections produced by Evolved Energy Research (EER). These projections are also downscaled to the ReEDS BA level with fixed fractions. The method described in this report provides absolute improvement in geographic resolution compared to both incumbent methods, as it starts from the county level. This is a good fit for ReEDS modeling, because ReEDS BAs are an aggregation of CONUS counties. It also enables more granular mappings to the transmission nodes of production cost (operational) models that are often used to verify the reliability of power system buildouts produced by models like ReEDS. The application of different growth rates by building type, end-use, and census division described in this report is also an absolute advantage over the historical load shape option because the latter does not differentiate growth rates across sectors (i.e., buildings, transportation, and industry), let alone sub-sectors and end uses, and thus does not capture how load shapes could change over time. The EER load projections do not have this issue and are also available for multiple scenarios and weather years. Evolving the method described in this report into an obvious drop-in substitute for ReEDS modeling relative to the EER data would thus require both formulating multiple growth rate scenarios to represent, e.g., high electrification and high energy efficiency, scenarios in addition to the AEO Reference scenario described herein as well as developing and applying a methodology (e.g., brute force or regression/machine learning models) to construct data for multiple weather years.

4.2 Projection Method and AEO Limitations

EIA's AEO consists of large-scale techno-economically driven sectoral projection datasets that are balanced between the demand-side and the supply-side. The datasets are comprehensive and provide breakdowns of energy and stock quantities at a level of detail that few other datasets or models can match. This allows for an easy extraction of growth rates that are differentiated by building type, energy end use, and census division, which the presented method leverages to improve the energy forecast of the building sectors. However, the method is still relying on exogenously determined projections that may not fully align with ComStock and ResStock's underlying assumptions and analysis needs. Moreover, the limitations that exist in the AEO extend into the sector projections via the growth rates.

EIA's NEMS, which produces the AEO, models consumer adoption of new technologies by considering trends in market behaviors, technologies, and demographics. However, due to the extensive coverage of the NEMS model, the underlying data can be limited, and the no-new-policy mandate of EIA can lead to conservative assumptions. The type of changes simulated in NEMS are often extensions of existing trends in technology and consumer behaviors (U.S. EIA, 2021), which lead to low electrification of space heating and water heating and low shares of new technologies that could otherwise bring about disruptive changes. For example, the AEO Reference scenario only considers existing policies, including for energy efficiency (U.S. EIA, 2021), and the policies are modeled to expire without extension, based on current law (U.S. EIA, 2022), even though they often get renewed prior to expiring (Gilbert & Sovacool, 2016). Additionally, the technology models in NEMS do not capture all the technical details that will meaningfully influence energy. A couple examples are: 1) equipment can maintain the same overall efficiency rating while seeing improvement in part-load performance over time, and 2) heat pumps with improved cold climate capacity retention and backup heating switchover setting can influence HVAC sizing, the use of backup heating, and overall energy use. These simplified assumptions, combined with conservative assumptions on consumer adoption and behaviors, may limit the extent to which AEO projections can capture the range of building efficiency and electrification futures.

4.3 Commercial Sector Projection

Commercial buildings vary widely in floor area and energy consumption from building type to building type and from one region to the next. Therefore, energy consumption from the commercial sector is often characterized by floor area and Energy Use Intensity (EUI) – energy consumed per square foot of conditioned floor area. To develop projections for the Commercial end uses, growth rates were extracted separately for floor area and EUI to understand: 1) how fast the commercial sector is expanding, and 2) how energy-efficient commercial spaces are becoming, which counters the growth in floor area. These growth rates were differentiated by building types and census division to account for the diversity in the building stock. To illustrate, Figure 6 through Figure 9 show how the floor area and space cooling electricity EUI are projected to grow in the 2021 AEO Reference scenario. It is worth noting that in Figure 8 the cooling EUI for large offices increases by nearly 30% in 2050 from 2018. There is a substantial growth in cooling demand for large offices, particularly in the South and Mountain regions. This increase in demand outpaces the growth in floor area and likely offsets the efficiency improvements in many types of equipment, resulting in a net increase in cooling EUI for large offices.

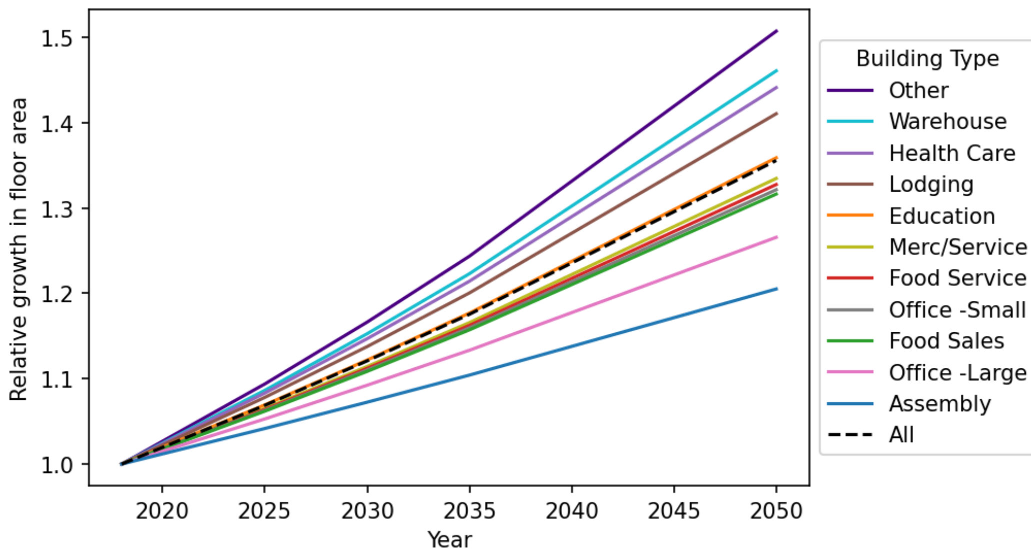

Figure 6. Growth (relative to the 2018 level) in commercial floor area by building type, based on growth rates estimated from the 2021 AEO Reference scenario

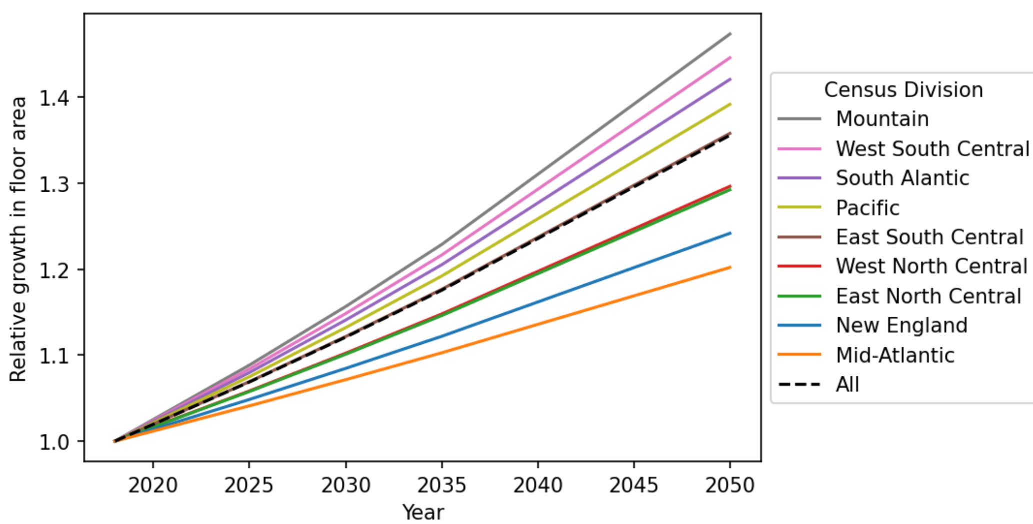

Figure 7. Growth (relative to the 2018 level) in commercial floor area by census division, based on growth rates estimated from the 2021 AEO Reference scenario

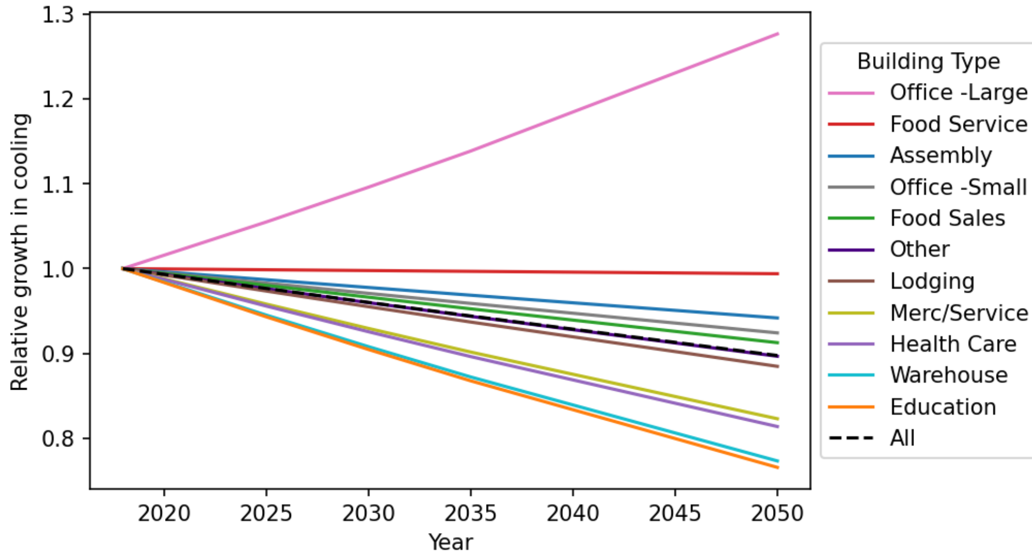

Figure 8. Growth (relative to the 2018 level) in commercial space cooling EUI (energy per sqft) by building type, based on 2021 AEO Reference Scenario

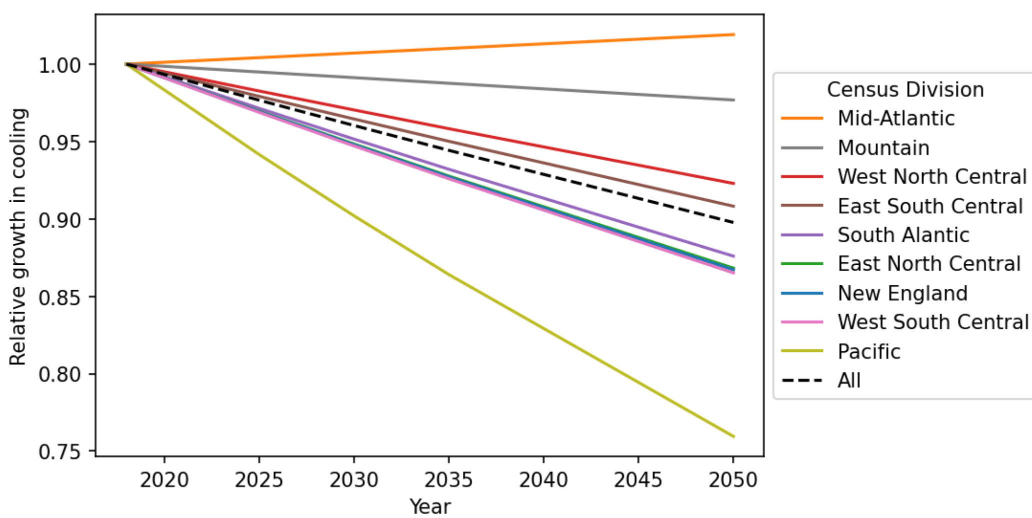

Figure 9. Growth (relative to 2018 level) in commercial space cooling EUI (energy per sqft) by census division based on 2021 AEO Reference Scenario

The total energy use for a given fuel type k at year t for the commercial sector is described by the equation below:

$$E_{t,k} = \sum_{n \in CenDiv} \sum_{m \in BldgTypes} \left(G_{m,n} \left(1 + \gamma_{m,n}\right)^{t-2018} \sum_{i \in EndUses} C_{i,k,m,n} \left(1 + \delta_{i,k,m,n}\right)^{t-2018} \right)$$

$$k \in FuelTypes, \qquad t = 2018, 2019, \dots, 2050$$

Where:

- $E_{t,k}$: total energy use in year t of $FuelType\ k$
- $G_{m.n}$: total floor area for $BldgType\ m$ in $CenDiv\ n$ and base year 2018
- $\gamma_{m,n}$: floor area exponential growth factor for $BldgType\ m$ in $CenDiv\ n$
- $C_{i,k,m,n}$: average EUI for $EndUse\ i$ of $FuelType\ k$ and $BldgType\ m$ in $CenDiv\ n$ and base year 2018
- $\delta_{i,k,m,n}$: EUI exponential growth factor for $EndUse\ i$ of $FuelType\ k$ and $BldgType\ m$ in $CenDiv\ n$

$FuelTypes$ consist of electricity, natural gas, and other fuels. $G_{m.n}$ and $C_{i,k,m,n}$ are data aggregates from the ComStock energy baseline. $\gamma_{m.n}$ and $\delta_{i,k,m,n}$ are the average exponential or annual growth factor between 2018 and 2050 derived from the AEO. The full list of these factors is available in Appendix C.

Table 7 summarizes the modeled floor area and energy differences between ComStock and AEO in the energy baseline (2018) and projection (2050). Since the floor areas in ComStock have been calibrated to match AEO in the baseline year, they also match in the projection as the same growth rates are applied to both models. However, the difference in the total energy projection increases to 20% from 17% in the baseline and is driven by the augmented discrepancy in the baseline EUI aggregates (since the floor areas are calibrated to be the same). Any differences in the baseline data aggregates are augmented by their respective exponential growth rates, with larger growth rates in magnitude widening the discrepancy faster than their smaller counterparts. In addition to growing at different rates, the difference in each data aggregate can be positive or negative, leading offsets and a net difference that changes from the baseline to the project. For example, ComStock's total electricity goes from slightly higher than AEO in 2018 to slightly lower than AEO in 2050, which amounts to a 12% change in difference. This is driven by a subset of EUI aggregates for which Comstock is lower than AEO and those aggregates have large growth rates, thus widening the gap in the downward direction. Meanwhile the discrepancy in both natural gas and other fuels slightly improve. However, their baseline differences are large and will be investigated in future projects.

Table 7. Summary of difference between modeled baseline and projection by ComStock and 2021 AEO Reference scenario, downselected to ComStock building types only.

	2018			2050		
	ComStock	**AEO**	**Difference**	**ComStock**	**AEO**	**Difference**
Total floor area (billion sqft)	55.4	55.4	0%	75.4	75.4	0%
Total energy (trillion Btu)	3796.2	4592.7	-17%	4051.9	5081.4	-20%

	2018			2050		
	ComStock	AEO	Difference	ComStock	AEO	Difference
Total electricity (trillion Btu)	2677.4	2555.0	5%	2735.9	2950.1	-7%
Total natural gas (trillion Btu)	1054.8	1894.5	-44%	1260.6	2021.4	-38%
Total other fuels (trillion Btu)	64.0	143.2	-55%	55.4	110.0	-50%

Figure 10 and Figure 11 show the fuel-specific end use consumption projected from ComStock and AEO, grouped by census division and building type, respectively. In terms of census division, ComStock projection is generally estimating lower total fuel use by 11-36% except for Pacific, which is estimating higher use by 11%, compared to AEO. These discrepancies can be attributed to differences of 50% or more in estimates of electric lighting, refrigeration, and water heating; natural gas cooling, heating, and water heating; and end uses of other fuels. In terms of building type, the ComStock projection is estimating higher total fuel use for food service by 23% and lower use for all other building types, except Mercantile Service, by 20-60%. While the individual fuel end uses may differ significantly, sometimes by an order of magnitude, the total energy stacks generally align across census divisions, and to a lesser degree across building types, where the estimates are lower for education and healthcare in ComStock.

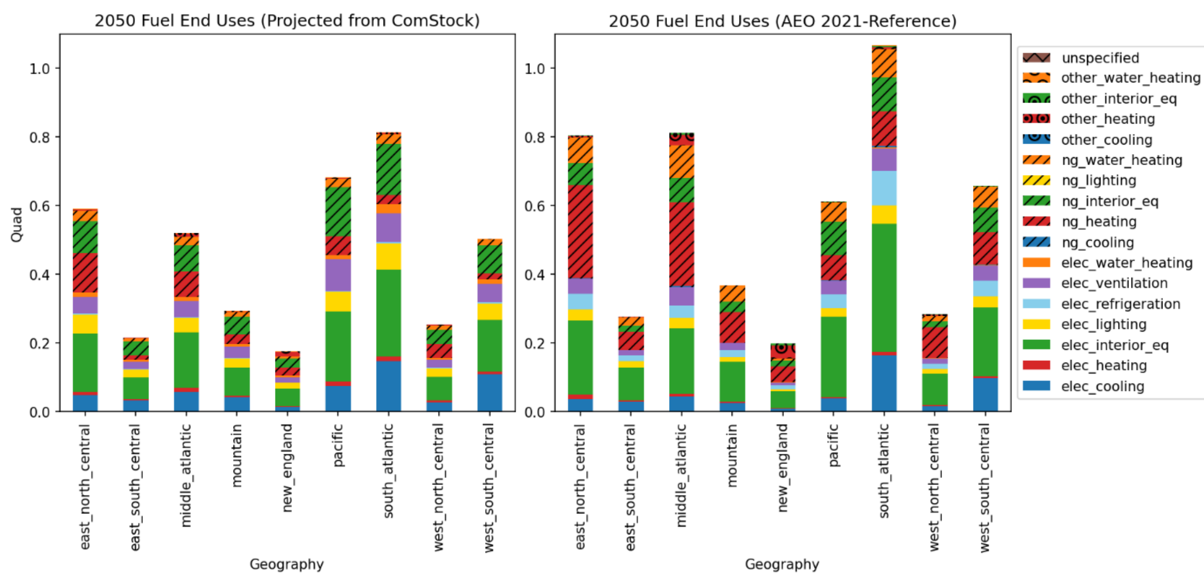

Figure 10. 2050 total commercial fuel end use breakdown by census division projected from ComStock (left) and 2021 AEO Reference scenario (right), downselected to ComStock building types only.

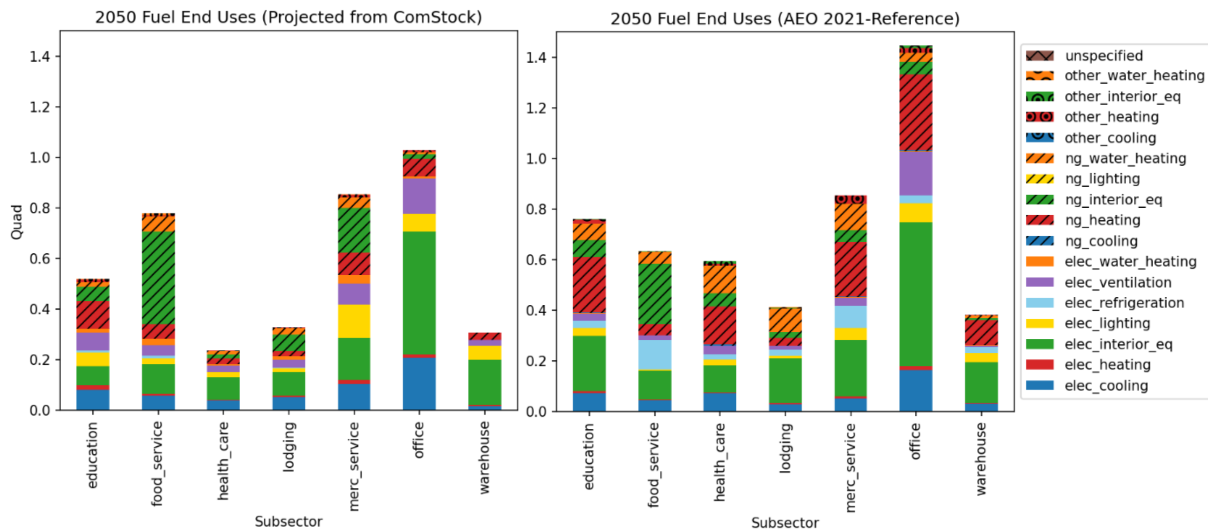

Figure 11. 2050 total commercial fuel end use breakdown by building type projected from ComStock (left) and 2021 AEO Reference scenario (right), downselected to ComStock building types only.

4.4 Residential Sector Projection

Compared to the commercial sector, there is less variability between residential buildings' physical and operational characteristics. In general, the residential building stock is characterized by the number of dwelling units (e.g., in ResStock) or households (e.g., in AEO). Households are assumed to be synonymous to the number of occupied dwelling units. There are cases where there are multiple households that live in a dwelling unit, but these cases are small compared to the total number of households and occupied dwellings. Dwellings include both occupied and vacant homes. Applying estimates of household growth rates derived from the AEO to the ResStock dwelling unit counts implies that both the occupied and vacant housing segments are growing proportionally to the population growth assumed in AEO.

For residential energy, some end uses are correlated with floor area, while others are more proportional to the number of dwellings. For example, end uses such as heating, cooling, and lighting tend to scale with the square footage of a building, while other end uses, such as laundry machines, dishwashers, and other major appliances, are more proportional to household count as there tends to be one of those appliances per dwelling. Therefore, four key drivers of residential energy use growth are identified: number of households, floor area per household, energy use intensity (energy per floor area), and energy per dwelling. Table 8 shows how the end uses are divided based on their scalability to square footage and number of dwellings.

Table 8. Residential End Use Categorization

AEO Residential End Use (Aggregated)	ResStock End Use	Function of
Space Heating and Cooling	Heating	Square Footage
	Cooling	Square Footage
	HVAC Fan Pump	Square Footage

AEO Residential End Use (Aggregated)	ResStock End Use	Function of
	Vent Fans	Square Footage
	Ceiling Fan	Square Footage
Plug Loads and Other	Plug Loads	Square Footage
Lighting	Exterior Lighting	Square Footage
	Interior Lighting	Square Footage
Major Appliances	Cooking Range	Unit Count
	Dishwasher	Unit Count
	Clothes Dryer	Unit Count
	Clothes Washer	Unit Count
	Hot Water	Unit Count
	Pool Hot Tub	Unit Count
	Well Pump	Unit Count
Refrigeration	Freezer	Unit Count
	Extra Refrigerator	Unit Count
	Refrigerator	Unit Count

The total energy use for a given fuel type *k* at year *t* for the residential sector is described by the equation below:

$$E_{t,k} = A(1+\alpha)^{t-2018}\left(B(1+\beta)^{t-2018}\sum_{i\in EndUses_{FA}} C_{i.k}\left(1+\delta_{i,k}\right)^{t-2018} + \sum_{j\in EndUses_{HU}} D_{j,k}\left(1+\mu_{j,k}\right)^{t-2018}\right)$$

$$k \in FuelTypes, \qquad t = 2018, 2019, \dots, 2050$$

Where:

- $E_{t,k}$: total energy use in year t of $FuelType\ k$
- A: Total number of dwellings in base year 2018
- α: Number of dwelling exponential growth factor
- B: Average floor area per dwelling in base year 2018

- β: Floor exponential growth factor
- $C_{i,k}$: average EUI for $EndUse_{FA}$ i of $FuelType$ k in base year 2018
- $\delta_{i,k}$: EUI exponential growth factor for $EndUse_{FA}$ i of $FuelType$ k
- $EndUse_{FA}$: End uses whose energy tends to scale with floor area
- $D_{j,k}$: average energy per dwelling for $EndUse_{HU}$ j of $FuelType$ k in base year 2018
- $\mu_{j,k}$: energy per dwelling exponential growth factor for $EndUse_{HU}$ j of $FuelType$ k
- $EndUse_{HU}$: End uses whose energy tends to scale with dwelling count

$FuelTypes$ consist of electricity, natural gas, fuel oil, liquefied propane gas, and other fuels. A, B, $C_{i,k}$ and $D_{j,k}$ are data aggregates from the ResStock energy baseline. α, β, $\delta_{i,k}$ and $\mu_{j,k}$ are the average exponential or annual growth factor between 2018 and 2050 derived from the AEO. Although AEO provides growth projections by building type and region, the projections do not vary significantly. Therefore, to simplify the modelling, we calculate a single growth rate per end use and fuel type combination. The full list of residential annual growth factors is available in Appendix C.

Table 9 summarizes the modeled floor area and energy differences between ResStock and AEO in the energy baseline (2018) and projection (2050). As explained under Section 4.3, the discrepancy in the projection is primarily a reflection of the disaggregated discrepancies in the baseline and is driven by those augmented by larger magnitude growth rates. Since the data aggregates in ResStock generally align with those of AEO's 2018 baseline, such as electricity and natural gas shown in Figure 5, its projection is also generally consistent with AEO. However, the discrepancy in other fuels, which include fuel oil and LPG, is nearly 50% and will be investigated in future projects.

Table 9. Summary of difference between modeled baseline and projection by ResStock and 2021 AEO Reference scenario.

	2018			2050		
	ResStock	AEO	Difference	ResStock	AEO	Difference
Total floor area (billion sqft)	231.0	215.5	7%	318.4	297.1	7%
Total dwelling units (million units)	131.1	121.2	8%	164.0	151.6	8%
Total energy (trillion Btu)	9928.0	11858.0	-16%	10429.2	12561.5	-17%
Total electricity (trillion Btu)	4856.5	5068.5	-4%	6000.8	6609.0	-9%

	2018			2050		
	ResStock	AEO	Difference	ResStock	AEO	Difference
Total natural gas (trillion Btu)	4160.1	5200.4	-20%	3895	4823.3	-19%
Total other fuels (trillion Btu)	911.5	1589.1	-43%	533.4	1129.2	-53%

As shown in Figure 12 and Figure 13, the fuel-specific end use consumption projected from ResStock is in general agreement with AEO with a few noted differences. In terms of census division, the ResStock projection predicts a lower total fuel use by 8-31% primarily due to electric plug loads and natural gas heating. In terms of building type, the ResStock projection predicts a higher total fuel use by 4% and 26% for multi-family and mobile home, respectively, and a lower total fuel use by 22% for single-family. These differences are due in part to missing end use categories in ResStock (e.g., plug loads or others of fuel oil and natural gas, end uses of other fuels), which amount to 0.8 quad or 6% of the total AEO fuel use. Nevertheless, the total energy stacks are generally aligned across census divisions and building types between the two models.

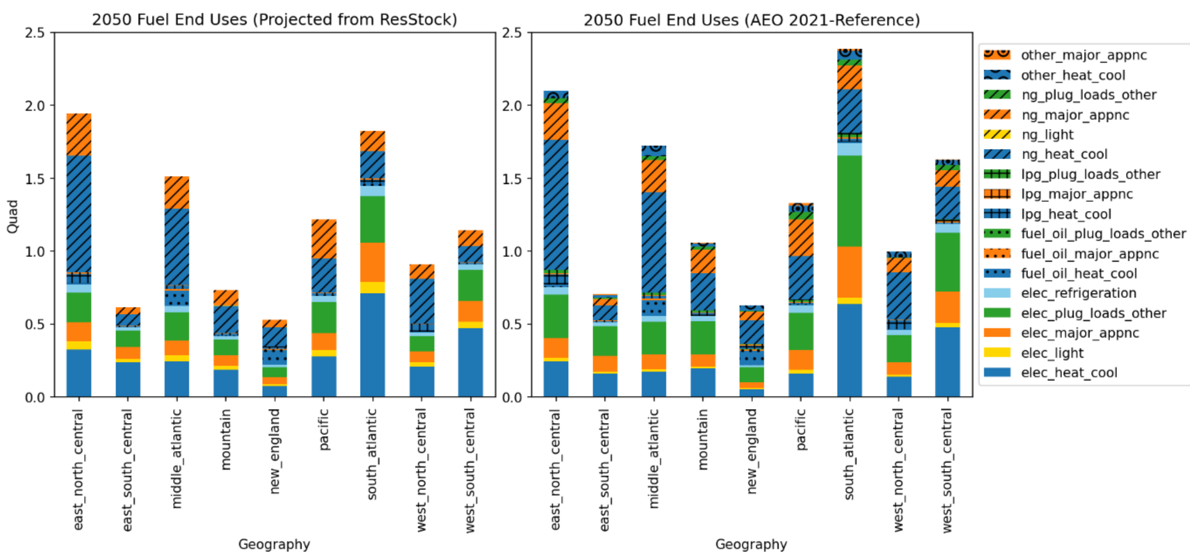

Figure 12. 2050 total residential fuel end use breakdown by census division projected from ResStock (left) and 2021 AEO Reference scenario (right).

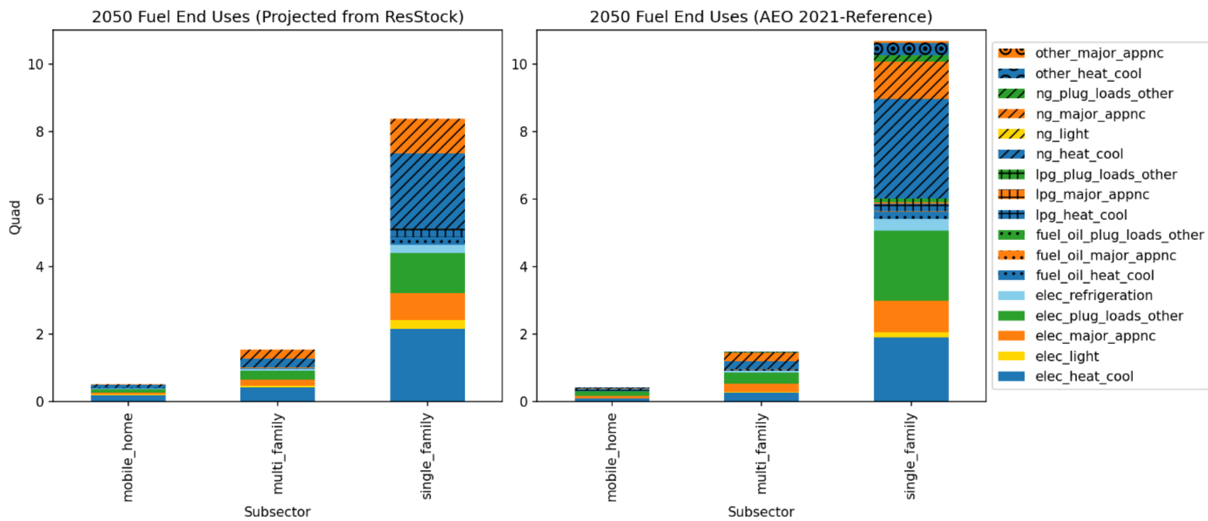

Figure 13. 2050 total residential fuel end use breakdown by building type projected from ResStock (left) and 2021 AEO- Reference scenario (right).

5 Discussion

Section 4 describes a simple projection method that extends the ComStock and ResStock modeled energy baselines out to 2050 using segmented growth rates derived using EIA's Annual Energy Outlook. The method described here does not endogenously represent how the building stock could evolve through time but aims to improve upon an existing approach for applying AEO growth rates to historical or modeled baseline load data by: 1) identifying key drivers of demand growths and 2) establishing these drivers as separate growth factors that can be controlled independently to model different growth scenarios.

For the commercial sector, only total floor area and energy use intensity were identified as key drivers for demand growth. These end use growth rates are distinguished by building type and census division to reflect the diversity in growth along those dimensions. For the residential sector, four key drivers of demand growth are identified: number of households, floor area per household, energy use intensity (energy per unit floor area), and energy use per household. Throughout the projection period certain residential end uses scale linearly with the number of households, whereas others scale with both the floor area and household count.

The annual growth rates used in the compilation of the dsgrid data set are derived directly from the 2021 AEO Reference scenario without any modification. The compiled projection shows that the residential sector is expected to grow by 25% in the number of households (and dwelling unit count), 38% in floor area, and 5% in total energy consumption from 2018 to 2050. The commercial sector is expected to increase 37% in floor area and 7% in total energy consumption from 2018 to 2050. During this time, electric end uses are expected to grow by 30% and 15% in the residential and commercial sector, respectively while end uses of other fuel types decrease slightly due to electrification. While these overall growth percentages are consistent with AEO's growth projections, the projected 2050 loads from ComStock and ResStock are generally lower compared to AEO. This is largely due to known differences in the energy baselines between NREL's sector models and EIA's NEMS, e.g., the lower estimate of natural gas and other fuels in ComStock and ResStock and the large growth rates associated with them, which widen the gap in the projection.

As with the status quo method, this projection approach reduces AEO's projection data into simple exponential growth rates. As such, the projection is simplified and exogenous with no dynamic feedback. Notably, the growth rates only serve to affect future loads in magnitude and their impact on the shape of the loads is hence limited to how the rescaled end use loads stack up to the total energy. The growth rates cannot capture demand-side temporal variability brought upon by future weather patterns, human behavior change, demand response, load controls or technology change. While the segmented growth rates improve the alignment of modeling assumptions between ComStock, ResStock, and NEMS's sectoral demand modules, they do not eliminate their modeling differences. Finally, as with the AEO Reference scenario, the compiled projection represents a future with minimal electrification, owing to a lack of major electrification measures in existing legislation as of September 2020 (analysis cutoff date for 2021 AEO).

While it is possible to quickly explore or include other future scenarios under this new projection paradigm, for example, by modifying the reference growth rates according to new assumptions or deriving new growth rates from AEO’s side cases, a more robust and extensible approach is to develop a bottom-up stock turnover model that is endogenous with ComStock and ResStock. This is planned for future work and could add to NREL’s existing tool suite to produce long-term projections that are highly parametrizable and internally consistent across sectors.

6 Conclusion

This report describes the compilation of a residential and commercial buildings sector energy baseline from the ComStock and ResStock models of U.S. building stock and how those data are combined with growth rates derived from EIA's 2021 AEO Reference scenario to produce projections out to 2050. The energy baselines use 2012 AMY weather data to support the compilation of a demand-side grid model data set suitable for use in NREL's large-scale grid models.

The methodology presented in this report serves to improve upon an existing load projection method used for developing NREL's Standard Scenarios. Rather than applying a single growth rate to a sector's total demand, growth rates are disaggregated by end use, floor area, energy use intensity, and other dimensions identified to be key drivers of demand growth. In this way, the separated growth factors can be manipulated independently and quickly to produce a new scenario. The method could be evolved to include multiple growth rate scenarios and multiple weather years to construct data for ReEDS. In the long run however, a bottom-up stock turnover model endogenous to ComStock and ResStock is better suited to address this data gap by allowing for easy parametrization and integration with NREL's exiting tools, such as the Annual Technology Baseline, to produce highly resolved and internally consistent projections for a wide range of future scenarios.

7 References

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Appendix A. Software versions

As described in Section 2, ResStock, ComStock, and the software used in the model simulation process are under active development. This includes buildstockbatch, a tool suite for running and managing batches of simulations on distributed computing resources, such as NREL's High Performance Computer. The ComStock and ResStock git repositories are public and provide a full description of the input data structures, probability distributions, and assumptions used for modeling the commercial and residential building stock, respectively.

The specific version of the software used in this report is accessible either as a standard release or by instantiating the relevant git repositories with the correct secure hash algorithm (SHA) references. They are shown below:

Commercial Energy Baseline:

- ComStock SHA: 00a3f79bab74d7fb8b71e7897486eb54b51277fc
- Buildstockbatch SHA: 9e00b5649c96ad18bc6336ba9b24c81156f8fd2d
- OpenStudio version: 2.9.1

Residential Energy Baseline:

- ResStock version: https://github.com/NREL/resstock/releases/tag/eulp_final
- Buildstockbatch: https://github.com/NREL/buildstockbatch/releases/tag/eulp_res_final
- OpenStudio version: 3.2.1

Appendix B. Method for Extracting Annual Growth Rates

Exponential growth can be described as a simple growth rate imposed annually on a principal value as follows:

$$p_2 = p_1(1 + r)^{t_2 - t_1}$$

Where p_1 and p_2 represent the principal value at time t_1 and t_2 respectively, and r is the annual growth rate.

To extract the annual growth rate r from the AEO projected end use data, we take the value at the base year 2018 to be P_1 and the projected value at the future year 2050 to be P_2, and then calculate:

$$r = e^{\frac{\ln\left(\frac{p_1}{p_2}\right)}{t_2 - t_1}} - 1 = e^{\frac{\ln\left(\frac{p_{2050}}{p_{2018}}\right)}{32}} - 1$$

The following can be used to combine two annual growth rates, e.g., *r1* and *r2*. An application of this is obtaining the annual growth rate for a particular end use by combining the growth rate for that end use in energy per sqft and the growth rate for floor area.

$$r_{combined} = (1 + r_1)(1 + r_2) - 1$$

Appendix C. End Use Annual Growth Factors from 2021 AEO Reference Scenario

ComStock Growth Factors

Table 10. Simple annual growth factors (2018-2050) for commercial floor area

Census Division	Assembly	Education	Food Sales	Food Service	Health Care	Lodging	Office -Large	Office -Small	Merc/Service	Warehouse	Other
New England	0.000	0.008	0.006	0.006	0.010	0.010	0.005	0.005	0.007	0.009	0.012
Mid-Atlantic	-0.002	0.005	0.006	0.006	0.008	0.010	0.004	0.004	0.006	0.008	0.013
East North Central	0.005	0.009	0.006	0.006	0.011	0.010	0.005	0.006	0.007	0.011	0.014
West North Central	0.005	0.010	0.007	0.007	0.012	0.011	0.006	0.007	0.008	0.007	0.013
South Atlantic	0.009	0.010	0.010	0.010	0.013	0.011	0.011	0.011	0.010	0.014	0.013
East South Central	0.006	0.010	0.010	0.010	0.012	0.011	0.007	0.008	0.010	0.012	0.014
West South Central	0.008	0.013	0.011	0.011	0.014	0.012	0.010	0.011	0.011	0.012	0.013
Mountain	0.011	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.013	0.013
Pacific	0.007	0.008	0.009	0.009	0.012	0.010	0.009	0.010	0.010	0.013	0.012

Table 11. Simple annual growth factors (2018-2050) for commercial electricity end use energy use intensity

Census Division	Building Type	Heating	Cooling	Water Heating	Ventilation	Cooking	Lighting	Refrigeration	Office Equip - PCs	Office Equip - NonPCs	Other
New England	Assembly	-0.023	-0.003	-0.026	-0.021	-0.013	-0.030	-0.004	-0.008	0.017	-0.003
New England	Education	-0.023	-0.010	-0.030	-0.020	-0.020	-0.023	-0.007	-0.008	0.017	-0.008
New England	Food Sales	-0.023	-0.003	-0.018	-0.021	-0.011	-0.023	-0.004	-0.008	0.017	-0.005
New England	Food Service	-0.026	-0.002	-0.027	-0.022	-0.012	-0.022	-0.009	-0.008	0.017	-0.004
New England	Health Care	-0.024	-0.008	-0.030	-0.017	-0.014	-0.023	-0.007	-0.008	0.017	0.001
New England	Lodging	-0.020	-0.005	-0.027	-0.021	-0.015	-0.028	-0.006	-0.008	0.017	-0.003
New England	Office - Large	-0.017	0.006	-0.020	-0.009	-0.008	-0.022	-0.006	-0.008	0.017	0.020
New England	Office - Small	-0.023	-0.002	-0.020	-0.021	-0.008	-0.025	-0.005	-0.008	0.017	0.001
New England	Merc/Service	-0.022	-0.007	-0.017	-0.020	-0.009	-0.025	-0.007	-0.008	0.017	-0.005
New England	Warehouse	-0.020	-0.004	-0.021	-0.022	0.000	-0.027	-0.009	-0.008	0.017	0.003
New England	Other	-0.020	-0.005	-0.023	-0.021	-0.012	-0.024	-0.005	-0.008	0.017	-0.002
Mid-Atlantic	Assembly	-0.023	-0.001	-0.021	-0.021	-0.013	-0.030	-0.005	-0.008	0.017	-0.005
Mid-Atlantic	Education	-0.025	-0.007	-0.026	-0.020	-0.019	-0.025	-0.008	-0.008	0.017	-0.009
Mid-Atlantic	Food Sales	-0.022	-0.002	-0.020	-0.022	-0.012	-0.025	-0.004	-0.008	0.017	-0.005
Mid-Atlantic	Food Service	-0.026	0.000	-0.026	-0.022	-0.013	-0.023	-0.009	-0.008	0.017	-0.004
Mid-Atlantic	Health Care	-0.024	-0.006	-0.028	-0.018	-0.014	-0.023	-0.007	-0.008	0.017	-0.011
Mid-Atlantic	Lodging	-0.023	-0.003	-0.025	-0.021	-0.015	-0.028	-0.006	-0.008	0.017	-0.003
Mid-Atlantic	Office - Large	-0.018	0.008	-0.016	-0.009	-0.009	-0.022	-0.006	-0.008	0.017	0.018
Mid-Atlantic	Office - Small	-0.024	-0.001	-0.019	-0.021	-0.009	-0.026	-0.005	-0.008	0.017	0.000
Mid-Atlantic	Merc/Service	-0.021	-0.005	-0.016	-0.021	-0.009	-0.027	-0.008	-0.008	0.017	-0.005
Mid-Atlantic	Warehouse	-0.020	-0.006	-0.020	-0.022	-0.008	-0.028	-0.010	-0.008	0.017	0.002
Mid-Atlantic	Other	-0.020	-0.003	-0.020	-0.022	-0.013	-0.024	-0.005	-0.008	0.017	-0.003
East North Central	Assembly	-0.019	-0.002	-0.018	-0.020	-0.013	-0.030	-0.004	-0.008	0.017	-0.003
East North Central	Education	-0.020	-0.010	-0.022	-0.019	-0.019	-0.022	-0.007	-0.008	0.017	-0.007
East North Central	Food Sales	-0.020	-0.005	-0.014	-0.021	-0.010	-0.022	-0.003	-0.008	0.017	-0.004

Census Division	Building Type	Heating	Cooling	Water Heating	Ventilation	Cooking	Lighting	Refrigeration	Office Equip - PCs	Office Equip - NonPCs	Other
East North Central	Food Service	-0.017	-0.002	-0.022	-0.020	-0.011	-0.023	-0.007	-0.008	0.017	-0.004
East North Central	Health Care	-0.021	-0.008	-0.024	-0.017	-0.014	-0.022	-0.006	-0.008	0.017	-0.007
East North Central	Lodging	-0.020	-0.004	-0.020	-0.019	-0.013	-0.027	-0.006	-0.008	0.017	-0.002
East North Central	Office - Large	-0.015	0.006	-0.012	-0.007	-0.008	-0.021	-0.005	-0.008	0.017	0.016
East North Central	Office - Small	-0.017	-0.003	-0.014	-0.020	-0.007	-0.025	-0.004	-0.008	0.017	0.001
East North Central	Merc/Service	-0.016	-0.007	-0.011	-0.020	-0.008	-0.024	-0.006	-0.008	0.017	-0.004
East North Central	Warehouse	-0.018	-0.009	-0.016	-0.020	-0.011	-0.026	-0.008	-0.008	0.017	0.004
East North Central	Other	-0.017	-0.005	-0.016	-0.020	-0.011	-0.023	-0.004	-0.008	0.017	-0.001
West North Central	Assembly	-0.023	-0.001	-0.016	-0.019	-0.013	-0.030	-0.004	-0.008	0.017	-0.004
West North Central	Education	-0.023	-0.009	-0.019	-0.018	-0.018	-0.021	-0.007	-0.008	0.017	-0.007
West North Central	Food Sales	-0.019	-0.004	-0.007	-0.020	-0.010	-0.022	-0.003	-0.008	0.017	-0.003
West North Central	Food Service	-0.019	-0.001	-0.021	-0.020	-0.011	-0.023	-0.007	-0.008	0.017	-0.004
West North Central	Health Care	-0.017	-0.007	-0.024	-0.017	-0.013	-0.021	-0.005	-0.008	0.017	-0.007
West North Central	Lodging	-0.018	-0.004	-0.018	-0.019	-0.013	-0.026	-0.005	-0.008	0.017	-0.002
West North Central	Office - Large	-0.015	0.007	-0.010	-0.006	-0.007	-0.021	-0.005	-0.008	0.017	0.016
West North Central	Office - Small	-0.018	-0.002	-0.013	-0.020	-0.009	-0.024	-0.004	-0.008	0.017	0.002
West North Central	Merc/Service	-0.017	-0.006	-0.010	-0.019	-0.007	-0.024	-0.006	-0.008	0.017	-0.005
West North Central	Warehouse	-0.016	-0.007	-0.013	-0.019	-0.007	-0.026	-0.008	-0.008	0.017	0.003
West North Central	Other	-0.016	-0.003	-0.012	-0.019	-0.010	-0.022	-0.004	-0.008	0.017	-0.002
South Atlantic	Assembly	-0.029	-0.003	-0.018	-0.021	-0.015	-0.031	-0.004	-0.008	0.017	-0.004
South Atlantic	Education	-0.027	-0.008	-0.022	-0.019	-0.019	-0.022	-0.007	-0.008	0.017	-0.007
South Atlantic	Food Sales	-0.021	-0.003	-0.014	-0.021	-0.011	-0.023	-0.003	-0.008	0.017	-0.004
South Atlantic	Food Service	-0.021	0.000	-0.021	-0.022	-0.012	-0.024	-0.007	-0.008	0.017	-0.004
South Atlantic	Health Care	-0.024	-0.006	-0.023	-0.017	-0.014	-0.022	-0.006	-0.008	0.017	-0.007
South Atlantic	Lodging	-0.020	-0.004	-0.021	-0.020	-0.014	-0.028	-0.006	-0.008	0.017	-0.002
South Atlantic	Office - Large	-0.022	0.007	-0.013	-0.008	-0.008	-0.022	-0.005	-0.008	0.017	0.017
South Atlantic	Office - Small	-0.023	-0.003	-0.016	-0.021	-0.009	-0.025	-0.004	-0.008	0.017	0.001
South Atlantic	Merc/Service	-0.020	-0.006	-0.014	-0.020	-0.009	-0.025	-0.006	-0.008	0.017	-0.004
South Atlantic	Warehouse	-0.024	-0.009	-0.015	-0.021	-0.010	-0.027	-0.008	-0.008	0.017	0.002
South Atlantic	Other	-0.020	-0.003	-0.015	-0.020	-0.011	-0.023	-0.004	-0.008	0.017	-0.002
East South Central	Assembly	-0.030	0.000	-0.016	-0.019	-0.013	-0.029	-0.003	-0.008	0.017	-0.003
East South Central	Education	-0.027	-0.008	-0.021	-0.017	-0.018	-0.021	-0.006	-0.008	0.017	-0.006
East South Central	Food Sales	-0.017	-0.003	-0.015	-0.019	-0.010	-0.021	-0.003	-0.008	0.017	-0.003
East South Central	Food Service	-0.018	0.000	-0.019	-0.019	-0.011	-0.021	-0.007	-0.008	0.017	-0.004
East South Central	Health Care	-0.022	-0.006	-0.019	-0.015	-0.013	-0.020	-0.005	-0.008	0.017	-0.007
East South Central	Lodging	-0.020	-0.002	-0.019	-0.018	-0.012	-0.025	-0.005	-0.008	0.017	-0.002
East South Central	Office - Large	-0.017	0.009	-0.009	-0.006	-0.006	-0.019	-0.004	-0.008	0.017	0.019
East South Central	Office - Small	-0.021	-0.002	-0.014	-0.019	-0.007	-0.024	-0.004	-0.008	0.017	0.001
East South Central	Merc/Service	-0.019	-0.005	-0.013	-0.019	-0.007	-0.023	-0.006	-0.008	0.017	-0.004
East South Central	Warehouse	-0.019	-0.008	-0.013	-0.019	0.000	-0.025	-0.007	-0.008	0.017	0.001
East South Central	Other	-0.018	-0.002	-0.014	-0.018	-0.010	-0.021	-0.004	-0.008	0.017	-0.001
West South Central	Assembly	-0.025	-0.003	-0.019	-0.021	-0.016	-0.032	-0.004	-0.008	0.017	-0.004
West South Central	Education	-0.027	-0.010	-0.024	-0.020	-0.021	-0.023	-0.007	-0.008	0.017	-0.007
West South Central	Food Sales	-0.023	-0.004	-0.016	-0.022	-0.012	-0.024	-0.003	-0.008	0.017	-0.004
West South Central	Food Service	-0.024	-0.001	-0.022	-0.023	-0.013	-0.025	-0.008	-0.008	0.017	-0.004
West South Central	Health Care	-0.027	-0.007	-0.024	-0.018	-0.015	-0.023	-0.006	-0.008	0.017	-0.010
West South Central	Lodging	-0.025	-0.005	-0.023	-0.020	-0.015	-0.029	-0.006	-0.008	0.017	-0.003
West South Central	Office - Large	-0.024	0.007	-0.013	-0.009	-0.009	-0.022	-0.005	-0.008	0.017	0.015
West South Central	Office - Small	-0.024	-0.003	-0.017	-0.021	-0.009	-0.026	-0.004	-0.008	0.017	0.001
West South Central	Merc/Service	-0.021	-0.006	-0.015	-0.021	-0.010	-0.027	-0.007	-0.008	0.017	-0.005
West South Central	Warehouse	-0.026	-0.010	-0.016	-0.021	-0.012	-0.027	-0.009	-0.008	0.017	0.002
West South Central	Other	-0.023	-0.004	-0.016	-0.021	-0.012	-0.024	-0.005	-0.008	0.017	-0.002
Mountain	Assembly	-0.034	0.002	-0.019	-0.020	-0.015	-0.030	-0.004	-0.008	0.017	-0.004
Mountain	Education	-0.031	-0.007	-0.023	-0.019	-0.020	-0.022	-0.007	-0.008	0.017	-0.008
Mountain	Food Sales	-0.021	-0.002	-0.015	-0.021	-0.011	-0.022	-0.003	-0.008	0.017	-0.004

Census Division	Building Type	Heating	Cooling	Water Heating	Ventilation	Cooking	Lighting	Refrigeration	Office Equip - PCs	Office Equip - NonPCs	Other
Mountain	Food Service	-0.023	0.001	-0.021	-0.021	-0.012	-0.023	-0.007	-0.008	0.017	-0.004
Mountain	Health Care	-0.021	-0.005	-0.022	-0.017	-0.014	-0.022	-0.005	-0.008	0.017	-0.008
Mountain	Lodging	-0.018	-0.001	-0.021	-0.019	-0.014	-0.027	-0.005	-0.008	0.017	-0.002
Mountain	Office - Large	-0.021	0.009	-0.012	-0.007	-0.008	-0.021	-0.005	-0.008	0.017	0.017
Mountain	Office - Small	-0.024	0.001	-0.015	-0.020	-0.008	-0.025	-0.004	-0.008	0.017	0.001
Mountain	Merc/Service	-0.022	-0.005	-0.014	-0.020	-0.008	-0.024	-0.006	-0.008	0.017	-0.004
Mountain	Warehouse	-0.021	-0.007	-0.014	-0.019	-0.013	-0.026	-0.008	-0.008	0.017	0.003
Mountain	Other	-0.019	0.000	-0.013	-0.019	-0.013	-0.023	-0.004	-0.008	0.017	-0.002
Pacific	Assembly	-0.033	-0.009	-0.033	-0.020	-0.015	-0.031	-0.010	-0.008	0.017	-0.004
Pacific	Education	-0.030	-0.015	-0.031	-0.017	-0.019	-0.025	-0.013	-0.008	0.017	-0.008
Pacific	Food Sales	-0.023	-0.006	-0.026	-0.020	-0.012	-0.026	-0.014	-0.008	0.017	-0.007
Pacific	Food Service	-0.023	-0.004	-0.030	-0.020	-0.013	-0.023	-0.013	-0.008	0.017	-0.006
Pacific	Health Care	-0.025	-0.011	-0.032	-0.016	-0.015	-0.025	-0.011	-0.008	0.017	-0.009
Pacific	Lodging	-0.020	-0.010	-0.030	-0.018	-0.014	-0.028	-0.010	-0.008	0.017	-0.002
Pacific	Office - Large	-0.024	0.003	-0.024	-0.010	-0.009	-0.024	-0.010	-0.008	0.017	0.017
Pacific	Office - Small	-0.026	-0.008	-0.024	-0.020	-0.009	-0.027	-0.009	-0.008	0.017	0.000
Pacific	Merc/Service	-0.024	-0.012	-0.021	-0.019	-0.009	-0.028	-0.012	-0.008	0.017	-0.005
Pacific	Warehouse	-0.023	-0.011	-0.026	-0.021	-0.013	-0.029	-0.013	-0.008	0.017	0.002
Pacific	Other	-0.020	-0.010	-0.027	-0.019	-0.012	-0.026	-0.010	-0.008	0.017	-0.001

Table 12. Simple annual growth factors (2018-2050) for commercial natural gas end use energy use intensity

Census Division	Building Type	Heating	Cooling	Water Heating	Ventilation	Cooking	Lighting	Refrigeration	Office Equip - PCs	Office Equip - NonPCs	Other
New England	Assembly	-0.007	0.049	0.002	0.000	0.016	0.000	0.000	0.000	0.000	0.001
New England	Education	0.013	-0.013	-0.002	0.000	0.002	0.000	0.000	0.000	0.000	-0.007
New England	Food Sales	-0.006	0.000	-0.001	0.000	0.008	0.000	0.000	0.000	0.000	0.006
New England	Food Service	0.000	0.000	-0.004	0.000	0.001	0.000	0.000	0.000	0.000	0.076
New England	Health Care	0.012	-0.002	-0.001	0.000	0.005	0.000	0.000	0.000	0.000	-0.009
New England	Lodging	0.000	0.000	-0.004	0.000	0.007	0.000	0.000	0.000	0.000	-0.004
New England	Office -Large	-0.006	0.003	0.000	0.000	0.003	0.000	0.000	0.000	0.000	-0.001
New England	Office -Small	-0.004	0.000	-0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.041
New England	Merc/Service	-0.004	-0.007	-0.004	0.000	0.003	0.000	0.000	0.000	0.000	0.033
New England	Warehouse	-0.011	-0.010	-0.005	0.000	-0.009	0.000	0.000	0.000	0.000	0.041
New England	Other	-0.007	0.000	0.001	0.000	0.020	0.000	0.000	0.000	0.000	0.003
Mid-Atlantic	Assembly	-0.009	0.008	-0.003	0.000	0.002	0.000	0.000	0.000	0.000	0.009
Mid-Atlantic	Education	-0.006	-0.012	-0.003	0.000	0.003	0.000	0.000	0.000	0.000	-0.005
Mid-Atlantic	Food Sales	-0.008	-0.024	-0.005	0.000	0.017	0.000	0.000	0.000	0.000	0.016
Mid-Atlantic	Food Service	-0.004	-0.028	-0.004	0.000	0.002	0.000	0.000	0.000	0.000	0.006
Mid-Atlantic	Health Care	-0.006	-0.002	-0.002	0.000	0.004	0.000	0.000	0.000	0.000	-0.004
Mid-Atlantic	Lodging	-0.005	0.007	-0.001	0.000	0.006	0.000	0.000	0.000	0.000	0.008
Mid-Atlantic	Office -Large	-0.009	0.008	-0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.005
Mid-Atlantic	Office -Small	-0.010	-0.009	-0.003	0.000	0.005	0.000	0.000	0.000	0.000	0.026
Mid-Atlantic	Merc/Service	-0.008	-0.016	-0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.005
Mid-Atlantic	Warehouse	-0.011	-0.007	-0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.051
Mid-Atlantic	Other	0.004	0.000	0.001	0.000	0.005	0.000	0.000	0.000	0.000	0.014
East North Central	Assembly	-0.014	0.016	-0.004	0.000	0.003	0.000	0.000	0.000	0.000	0.054
East North Central	Education	-0.010	-0.037	-0.005	0.000	0.010	0.000	0.000	0.000	0.000	-0.009
East North Central	Food Sales	-0.009	-0.040	-0.005	0.000	0.009	0.000	0.000	0.000	0.000	0.068
East North Central	Food Service	-0.008	-0.040	-0.005	0.000	0.003	0.000	0.000	0.000	0.000	0.147
East North Central	Health Care	-0.006	-0.012	-0.004	0.000	0.008	0.000	0.000	0.000	0.000	-0.012
East North Central	Lodging	-0.008	0.000	-0.004	0.000	0.010	0.000	0.000	0.000	0.000	-0.001

Census Division	Building Type	Heating	Cooling	Water Heating	Ventilation	Cooking	Lighting	Refrigeration	Office Equip - PCs	Office Equip - NonPCs	Other
East North Central	Office -Large	-0.011	0.004	-0.004	0.000	0.002	0.000	0.000	0.000	0.000	0.002
East North Central	Office -Small	-0.012	-0.022	-0.004	0.000	0.007	0.000	0.000	0.000	0.000	0.041
East North Central	Merc/Service	-0.011	-0.017	-0.005	0.000	-0.002	0.000	0.000	0.000	0.000	0.067
East North Central	Warehouse	-0.013	0.000	-0.003	0.000	0.005	0.000	0.000	0.000	0.000	0.053
East North Central	Other	-0.009	-0.008	-0.002	0.000	0.032	0.000	0.000	0.000	0.000	0.009
West North Central	Assembly	-0.014	-0.008	-0.004	0.000	0.002	0.000	0.000	0.000	0.000	-0.005
West North Central	Education	-0.009	-0.042	-0.003	0.000	0.014	0.000	0.000	0.000	0.000	-0.003
West North Central	Food Sales	-0.011	-0.033	-0.007	0.000	0.019	0.000	0.000	0.000	0.000	-0.001
West North Central	Food Service	-0.009	-0.041	-0.006	0.000	0.003	0.000	0.000	0.000	0.000	-0.001
West North Central	Health Care	-0.010	-0.014	-0.004	0.000	0.009	0.000	0.000	0.000	0.000	-0.015
West North Central	Lodging	-0.006	0.000	-0.002	0.000	0.006	0.000	0.000	0.000	0.000	-0.001
West North Central	Office -Large	-0.014	0.000	-0.005	0.000	0.016	0.000	0.000	0.000	0.000	-0.006
West North Central	Office -Small	-0.014	-0.036	-0.004	0.000	0.015	0.000	0.000	0.000	0.000	-0.001
West North Central	Merc/Service	-0.011	-0.028	-0.005	0.000	-0.001	0.000	0.000	0.000	0.000	0.000
West North Central	Warehouse	-0.013	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.000	-0.001
West North Central	Other	-0.013	0.000	-0.005	0.000	0.024	0.000	0.000	0.000	0.000	0.010
South Atlantic	Assembly	-0.014	-0.035	-0.003	0.000	0.006	0.000	0.000	0.000	0.000	0.022
South Atlantic	Education	-0.007	-0.037	-0.003	0.000	0.011	0.000	0.000	0.000	0.000	-0.006
South Atlantic	Food Sales	0.001	-0.030	-0.006	0.000	0.026	0.000	0.000	0.000	0.000	0.011
South Atlantic	Food Service	-0.009	-0.035	-0.005	0.000	0.001	0.000	0.000	0.000	0.000	0.044
South Atlantic	Health Care	-0.008	-0.011	-0.003	0.000	0.001	0.000	0.000	0.000	0.000	-0.011
South Atlantic	Lodging	-0.006	0.000	-0.001	0.000	0.012	0.000	0.000	0.000	0.000	-0.001
South Atlantic	Office -Large	-0.010	0.004	-0.001	0.000	0.007	0.000	0.000	0.000	0.000	-0.010
South Atlantic	Office -Small	-0.015	-0.033	-0.004	0.000	-0.001	0.000	0.000	0.000	0.000	0.016
South Atlantic	Merc/Service	-0.014	-0.022	-0.006	0.000	-0.003	0.000	0.000	0.000	0.000	0.033
South Atlantic	Warehouse	-0.016	0.000	-0.004	0.000	0.053	0.000	0.000	0.000	0.000	0.151
South Atlantic	Other	-0.013	0.000	-0.002	0.000	0.004	0.000	0.000	0.000	0.000	-0.001
East South Central	Assembly	-0.013	-0.035	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.000
East South Central	Education	-0.008	-0.041	-0.003	0.000	0.013	0.000	0.000	0.000	0.000	-0.013
East South Central	Food Sales	-0.011	-0.034	-0.002	0.000	0.004	0.000	0.000	0.000	0.000	0.000
East South Central	Food Service	-0.010	-0.040	-0.004	0.000	0.004	0.000	0.000	0.000	0.000	0.000
East South Central	Health Care	-0.008	0.000	-0.003	0.000	0.005	0.000	0.000	0.000	0.000	-0.001
East South Central	Lodging	-0.008	0.000	-0.004	0.000	0.012	0.000	0.000	0.000	0.000	-0.005
East South Central	Office -Large	-0.007	0.000	-0.005	0.000	0.019	0.000	0.000	0.000	0.000	-0.001
East South Central	Office -Small	-0.015	-0.036	-0.004	0.000	0.057	0.000	0.000	0.000	0.000	0.000
East South Central	Merc/Service	-0.012	-0.027	-0.005	0.000	-0.002	0.000	0.000	0.000	0.000	-0.001
East South Central	Warehouse	-0.016	0.000	-0.004	0.000	-0.012	0.000	0.000	0.000	0.000	-0.001
East South Central	Other	-0.011	0.000	0.003	0.000	0.005	0.000	0.000	0.000	0.000	0.012

Census Division	Building Type	Heating	Cooling	Water Heating	Ventilation	Cooking	Lighting	Refrigeration	Office Equip - PCs	Office Equip - NonPCs	Other
West South Central	Assembly	-0.013	-0.032	-0.004	0.000	0.004	0.000	0.000	0.000	0.000	0.094
West South Central	Education	-0.012	-0.036	-0.005	0.000	0.002	0.000	0.000	0.000	0.000	-0.009
West South Central	Food Sales	-0.011	-0.030	-0.007	0.000	0.002	0.000	0.000	0.000	0.000	0.030
West South Central	Food Service	-0.008	-0.035	-0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.112
West South Central	Health Care	-0.014	0.003	-0.003	0.000	0.004	0.000	0.000	0.000	0.000	-0.007
West South Central	Lodging	-0.015	0.000	-0.003	0.000	0.010	0.000	0.000	0.000	0.000	0.006
West South Central	Office -Large	-0.021	0.004	-0.005	0.000	0.013	0.000	0.000	0.000	0.000	-0.013
West South Central	Office -Small	-0.019	-0.032	-0.006	0.000	0.001	0.000	0.000	0.000	0.000	0.098
West South Central	Merc/Service	-0.018	-0.014	-0.006	0.000	-0.003	0.000	0.000	0.000	0.000	0.010
West South Central	Warehouse	-0.021	0.000	-0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.050
West South Central	Other	-0.017	0.000	-0.003	0.000	0.029	0.000	0.000	0.000	0.000	0.012
Mountain	Assembly	-0.019	-0.028	-0.005	0.000	0.005	0.000	0.000	0.000	0.000	-0.011
Mountain	Education	-0.010	-0.031	-0.006	0.000	0.007	0.000	0.000	0.000	0.000	-0.011
Mountain	Food Sales	-0.010	-0.033	-0.008	0.000	0.029	0.000	0.000	0.000	0.000	-0.002
Mountain	Food Service	-0.007	-0.035	-0.007	0.000	0.004	0.000	0.000	0.000	0.000	-0.002
Mountain	Health Care	-0.011	-0.011	-0.005	0.000	0.002	0.000	0.000	0.000	0.000	-0.003
Mountain	Lodging	-0.009	0.000	-0.005	0.000	0.004	0.000	0.000	0.000	0.000	-0.011
Mountain	Office -Large	-0.017	0.005	-0.006	0.000	-0.002	0.000	0.000	0.000	0.000	-0.004
Mountain	Office -Small	-0.015	-0.030	-0.005	0.000	0.053	0.000	0.000	0.000	0.000	0.011
Mountain	Merc/Service	-0.015	-0.025	-0.007	0.000	0.001	0.000	0.000	0.000	0.000	0.024
Mountain	Warehouse	-0.018	0.000	-0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.013
Mountain	Other	-0.015	0.000	-0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.017
Pacific	Assembly	-0.019	-0.024	-0.007	0.000	0.001	0.000	0.000	0.000	0.000	0.016
Pacific	Education	-0.011	-0.041	-0.005	0.000	0.003	0.000	0.000	0.000	0.000	-0.007
Pacific	Food Sales	-0.003	-0.032	-0.006	0.000	-0.004	0.000	0.000	0.000	0.000	0.006
Pacific	Food Service	-0.009	-0.037	-0.008	0.000	0.001	0.000	0.000	0.000	0.000	0.041
Pacific	Health Care	-0.011	-0.013	-0.006	0.000	0.001	0.000	0.000	0.000	0.000	-0.011
Pacific	Lodging	-0.007	0.000	-0.007	0.000	0.004	0.000	0.000	0.000	0.000	-0.004
Pacific	Office -Large	-0.021	0.003	-0.008	0.000	-0.002	0.000	0.000	0.000	0.000	-0.008
Pacific	Office -Small	-0.015	-0.033	-0.007	0.000	0.001	0.000	0.000	0.000	0.000	0.047
Pacific	Merc/Service	-0.014	-0.026	-0.008	0.000	-0.004	0.000	0.000	0.000	0.000	-0.001
Pacific	Warehouse	-0.018	0.000	-0.006	0.000	-0.003	0.000	0.000	0.000	0.000	0.045
Pacific	Other	-0.013	0.000	-0.006	0.000	0.002	0.000	0.000	0.000	0.000	-0.014

Table 13. Consolidated commercial end use category details.

Commercial End Use	Equipment Examples
Cooling	Centrifugal chillers, reciprocating chillers, screw chillers, scroll chillers, gas-fired chillers, rooftop air conditioners, gas-fired engine-driven rooftop air conditioners, rooftop heat pumps, ground source heat pumps
Heating	Gas-fired/oil-fired furnaces, gas-fired/oil-fired/electric boilers electric resistance heaters, rooftop heat pumps, ground source heat pumps
Interior Equip	Cooking (gas/electric range with griddle and oven, hot food holding cabinets), office equipment – PCs, office equipment – non-PCs, other (miscellaneous electric loads)
Lighting	General service lamps, reflector lamps, linear lighting systems, low bay lighting systems, high bay lighting systems
Refrigeration	Compressor rack systems, condensers, supermarket display cases, reach-in refrigerators, reach-in freezers, walk-in refrigerators, walk-in freezers, ice machines, beverage merchandisers, refrigerated vending machines
Ventilation	Constant air volume ventilation, variable air volume ventilation, fan coil units
Water Heating	Gas-fired/electric resistance/heat pump/oil-fired/solar water heaters

ResStock Growth Factors

For the residential sector, the growth in dwelling unit count and floor area projected per 2021 AEO does not vary significantly by census division.

Table 14. Simple annual growth factors (2018-2050) for residential dwelling unit count

Average Dwelling unit Growth Rate
0.0070

Table 15. Simple annual growth factors (2018-2050) for average floor area per dwelling unit

Annual Square Footage per Dwelling unit Growth Rate
0.0100

Table 16. Simple annual growth factors (2018-2050) for end use energy per dwelling unit

Fuel Type	End Uses	
	Major Appliances	Refrigeration
Electricity	0.0007	-0.0047
Natural Gas	-0.0016	N/A
Fuel Oil	-0.0301	N/A
Propane	-0.0234	N/A
Other	0.0094	N/A

Table 17. Simple annual growth factors (2018-2050) for residential end use EUI (energy per sqft)

Fuel Type	End Uses		
	Space Heating and Cooling	Plug Loads and Other	Lighting
Electricity	0.0039	0.0046	-0.0190
Natural Gas	-0.0151	-0.0118	N/A
Fuel Oil	-0.0290	-0.0136	N/A
Propane	-0.0219	0.0095	N/A
Other	-0.0201		

Table 18. Consolidated residential end use category details.

Residential End Use	Equipment Examples
Lighting	Lighting
Major Appliances	Clothes washer, cooking, dishwasher, dryer, hot water, pool heater, spa
Plug Loads and Other	Coffee maker, desktop PC, DVD, electric other, home theater, laptop, microwave, monitors, network equipment, other appliance, rechargeable, security system, set top box, TV, video game console, WCL
Refrigeration	Freezer, refrigerator
Space Heating, Cooling, and Ventilation	Ceiling fan, dehumidifier, furnace fans, secondary heating, space cooling, space heating