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RENEWABLE ENERGY

End-Use Load Profiles for the U.S. Building Stock

Market Needs, Use Cases, and Data Gaps

November 2019

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List of Acronyms

AMI	advanced metering infrastructure
AMY	Actual Meteorological Year
CBECS	Commercial Buildings Energy Consumption Survey
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EPRI	Electric Power Research Institute
EULP	end-use load profile
FSEC	Florida Solar Energy Center
GIS	geographic information systems
HVAC	heating, ventilating, and air conditioning
HVAC&R	heating, ventilating, air conditioning, and refrigeration
ISO	independent system operator
ISO-NE	ISO New England
LBNL	Lawrence Berkeley National Laboratory
LIDAR	Light Detection and Ranging
MELs	miscellaneous electric loads
MGLs	miscellaneous gas loads
NREL	National Renewable Energy Laboratory
RASS	California Residential Appliance Saturation Survey
RBSA	Residential Building Stock Assessment
RBSAM	Residential Building Stock Assessment Metering
RECS	Residential Energy Consumption Survey
RTO	regional transmission organization
TAG	technical advisory group

Executive Summary

States and utilities are developing increasingly ambitious energy goals. Part of the solution to meeting these goals is improving electric grid flexibility. This includes shifting electric demand to align with grid needs. Thus, identifying and using building energy efficiency and other distributed energy resources to produce the highest grid value requires highly resolved, accurate and accessible electricity end-use load profiles (EULPs).

EULPs quantify *how* and *when* energy is used. Currently, few accurate and accessible end-use load profiles are available for utilities, public utility commissions, state energy offices and other stakeholders to use to prioritize investment and value energy efficiency, demand response, distributed generation and energy storage. High-quality EULPs are also critical for determining the time-sensitive value of efficiency[1] and other distributed energy resources, and the widespread adoption of grid-interactive efficient buildings (GEBs).[2] For example, EULPs can be used to accurately forecast energy savings in buildings or identify energy activities that can be shifted to different times of the day.

This report serves as the first-year deliverable for a multiyear U.S. Department of Energy-funded project, *End-Use Load Profiles for the U.S. Building Stock,* that intends to produce a set of highly resolved EULPs of the U.S. residential and commercial building stock. The project team, made up of researchers from the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), and Argonne National Laboratory,[3] ultimately will use calibrated physics-based building energy models to create these EULPs.

There are several advantages to using calibrated building energy models rather than a pure end-use submetering approach; primarily, this approach allows for multiregional coverage at a fraction of the cost of a statistically representative submetered sample. Furthermore, models can be extrapolated to climates, regions, or building types with poor metered data coverage. This approach is similar to what was proposed by KEMA (2009)/DNV GL (2014) and versions of it—such as the California Energy Commission's 2006 Commercial End-Use Survey (California Energy Commission 2006) and most recently ADM Associates (2019)—have been implemented.

Furthermore, a co-product of this approach is a suite of calibrated building energy models that can be used for "what-if" policy and technical analysis. The profiles and the calibrated models will be published along with a user guide for utilities, policymakers, technology developers, and researchers.

Figure ES-1 provides an overview of the project components. The two primary milestones for the project's first year are to identify: (1) market needs for EULPs and (2) data needed to build (*model input data*) and calibrate (*model calibration data*) the project's building energy models. As this is a first-of-its-kind effort to assemble national data for model input and calibration data, the project team is working with regional energy efficiency organizations, the Electric Power Research Institute (EPRI), electric utility companies, and other stakeholders to collect and evaluate end-use and whole-building load profile data from a wide range of existing sources and address critical gaps with additional data collection.

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[1] See LBNL's Time- and Location-Sensitive Value research at https://emp.lbl.gov/projects/time-value-efficiency.

[2] Office of Energy Efficiency and Renewable Energy. Grid-Interactive Efficient Buildings. https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings.

[3] Argonne will support the sensitivity analysis and uncertainty propagation in Years 2 and 3 of the project.

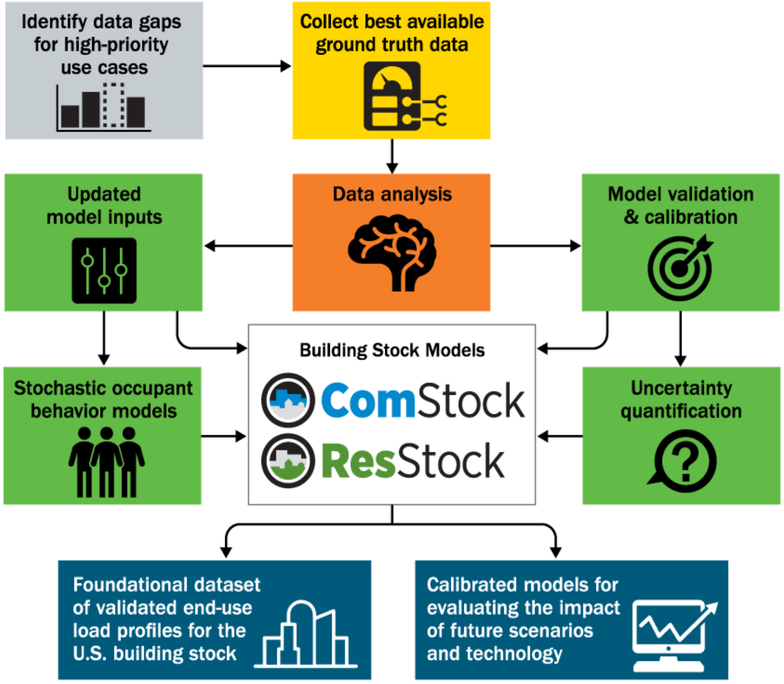

Figure ES-1. Project overview

In the second and third year of this project, these data will be used to refine and calibrate national-scale building stock models (ResStock™ and ComStock™)[4] to produce EULPs at both aggregate and individual building scales. Rather than use the common approach of modeling a few individual prototype building models and scaling the resulting load profiles to reflect the building stock, a stock modeling approach will be used. In the stock modeling approach, hundreds of thousands of building energy models will be used to statistically represent the building stock (one model for every ~200 buildings). The diversity of characteristics of these models will represent the diversity of characteristics in the real building stock to the extent possible. In many stock models, occupant behavior is represented by simple schedules with little or no diversity. This becomes problematic either because (1) all of the schedules stack, creating unrealistic coincident peaks in aggregate or (2) the schedules are average consumption, so they are not representative of actual events occurring within a building (e.g., water draws are averaged over the day instead of discrete events). For this project, to represent the impact of the diversity of occupant behavior, we will incorporate stochastic behavioral modeling for each building in the simulation, which will capture this diversity of behavior-driven events. Figure ES-1 presents an overview of the project approach.

Market Needs

A key focus for the project's first year was a comprehensive identification of EULP market needs based on a review of publicly available EULPs and interactions with stakeholders. A technical advisory group (TAG) was formed to help guide the project, ensure support for the project approach and analysis, and assist with the EULP dissemination at project completion.

Selection of the TAG

To create the TAG, we reached out to experts in the field, considering several criteria:

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[4] ResStock and ComStock are trademarked by NREL.

- *Robust geographic representation* to assist with identifying and acquiring EULP input and calibration data, and ensure regional (and national) support for the project approach and analysis

- *Strong utility and public utility commission staff representation* to ensure that the primary users of our EULPs understand and are supportive of our approach

- *Diverse organizations* that represent a variety of expertise and experience creating and using EULPs.

Currently, the TAG comprises more than 70 individuals representing more than 50 organizations, including utilities, independent system operator (ISO)/regional transmission organizations (RTOs), public utility commissions, state and local government, consulting firms, software companies, academic institutions, nongovernmental organizations representing utilities and regional efficiency groups, and the U.S. Department of Energy (DOE). Geographically, our TAG members are located in 20 states that cover seven of the eight North American Electric Reliability Corporation regions, with many members conducting work regionally or nationally. A full list of TAG members can be found in Appendix A.

Inventory of Existing End-Use Load Profiles

In addition to stakeholder feedback, a review of existing publicly available EULPs was completed, to both understand the existing EULP approaches and to identify what end-use metered data are available. This effort also provided data on the regional and building type coverage of existing studies. The TAG's feedback was solicited to ensure comprehensive coverage of all existing studies, and the complete inventory is now available on LBNL's website.[5]

Use Case Identification and Data Fidelity Requirements

The main focus of defining market needs was identifying EULP use cases and the associated data requirements. First, the TAG helped identify and prioritize use cases. Then the project team determined the data fidelity required to meet the prioritized use cases. The use case fidelity requirements, shown in Table ES-1, will be used as a guide for the EULP target time resolution (15 minutes), geographic resolution (utility territory), and electrical characteristics (real power).[6] The bold text in Table ES-1 highlights where the data currently being used are typically insufficient, and where this project will make material improvements to the data for the use case.

Market Acceptance of Proposed Approach

As a final step in determining market needs, expert feedback was solicited through multiple channels on our proposed modeling approach, data inputs, model output resolution, and usefulness and acceptance of the EULPs. The project team interviewed TAG member subject matter experts (e.g., previous developers of EULPs), potential users of our EULPs, and additional experts that are contributing data to the project. Key subject matter experts are supportive of the modeling approach and proposed data collection process, and are supportive of using the EULPs (and models). In addition, there is general agreement that the fidelity of the models is appropriate, and the level of accuracy we are proposing is useful and relevant for their applications.[7]

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[5] The inventory can be found at: https://emp.lbl.gov/publications/end-use-load-profile-inventory.

[6] *Real power* is the portion of electricity that supplies energy to the load. *Reactive power* is the portion of electricity that establishes and sustains the electric and magnetic fields of alternating-current equipment.

[7] See the End-Use Load Profiles for the U.S. Building Stock project website at https://www.nrel.gov/buildings/end-use-load-profiles.html and Technical Advisory Group meeting materials for project updates.

Table ES-1. Use Case Data Requirements

Use Case	Time Resolution	Geographic Resolution	Electrical Characteristics
Electricity Resource Planning	Hourly, peak day, monthly peak	**Service territory**	Real power
Energy Efficiency Planning	Hourly, peak day, seasonal peak and off peak	**Service territory**	Real power
Policy and Rate Design	**15 min, hourly**	**City, climate zone, or state**	**Depends on application**
Transmission and Distribution System Planning	**15 min or smaller, hourly**	**Distribution feeder, or substation**	**Real and reactive power**
Program Impact Evaluation	Hourly	**Service territory**	Real power
Demand-Response Planning	15 min, hourly, peak day	**Service territory**	Real power
Improved Building Energy Modeling	15 min, hourly	Region	Real power
Electrification Planning	**Hourly, peak day, seasonal peak and off peak**	**Service territory or smaller**	**Real power**
Emissions Analysis	Hourly	Service territory or larger	Real power
Photovoltaics Planning	**1 min**	**Weather station**	**Real power**

Data Needs

ResStock and ComStock are currently calibrated to annual energy consumption values from the Energy Information Administration's Residential Energy Consumption Survey (RECS) and the Commercial Buildings Energy Consumption Survey (CBECS), respectively, at both a national and regional level. One of the primary objectives of this project is to improve the spatial and temporal resolution of ResStock and ComStock. As the models are calibrated, the project team will determine what additional data sources are necessary to update model inputs and to provide EULPs at 15-minute increments for utility territories. Figure ES-2 provides an overview of the workflow for updating ResStock and ComStock inputs and highlights that time-series data sets can provide both input and calibration information for the models by leveraging different features of the data sets.

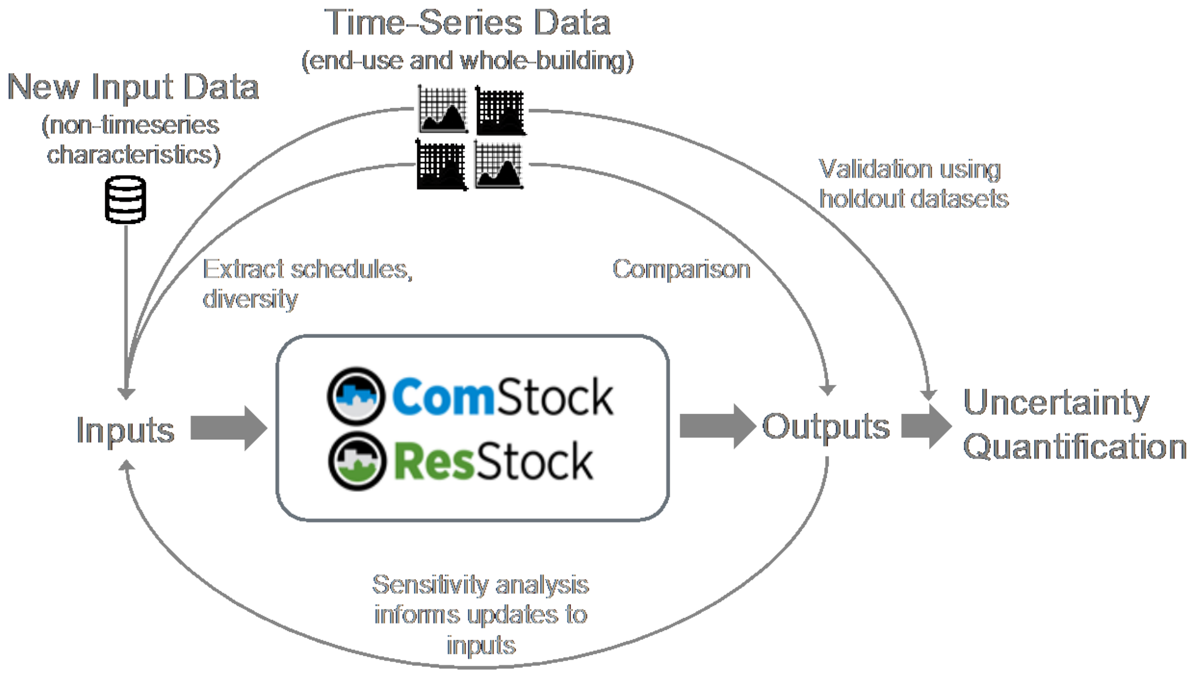

Figure ES-2. End-use load profiles modeling workflow

Model Input Data

There are three major categories of inputs for ResStock and ComStock:

1. *Schedule-related inputs* (e.g., business hours, lighting on/off schedules) directly affect the timing of energy use; these are directly related to human behavior or scheduled operations. This category of inputs also involves understanding the variability and saturation of different behavior types across the building stock.
2. *Characteristic inputs* (e.g., floor area; lighting power density; heating, ventilating, and air-conditioning [HVAC] system cooling type) indirectly affect the magnitude and timing of energy use. These are the physical descriptions of the building, its equipment, and the saturation of these components across the stock.
3. *Environmental inputs* (e.g., humidity, temperature) directly affect the timing and magnitude of energy use; these are external to the building.

The project team reviewed all 657 inputs of ResStock and ComStock and identified a subset of 78 inputs that are relevant to the time-series outputs needed for the top-priority use cases. For this subset, the project team identified additional data sources that could be used to update models. As we calibrate our models, region-by-region, to develop individual and aggregate EULPs, the project team will conduct ongoing sensitivity analyses to identify the parameters most significant to ResStock and ComStock time-series outputs. These sensitivity analyses will directly inform the calibration procedure and determine which inputs should be improved.

Model Calibration Data

To determine how accurate the models are and to help identify areas where model inputs need refinement, metered ground truth data (*model calibration data*) are needed. To determine data needs, the project team collected calibration data and identified data gaps.

For this project we utilize a hybrid approach that leverages multiple levels of metered data along with physics-based models, which simulate the physical relationships between heat transfer and energy consumption. This allows for much less data collection than would be required with a pure end-use submetering approach and also provides a way of estimating EULPs where data do not exist. To support the multilevel calibration, we pursued multiple types of calibration data, which are shown in Table ES-2 along with a summary of their availability.[8] Collected calibration data sets were categorized, and a review of coverage was conducted to understand which end uses or building types had limited or poor-quality data. One category of data with limited coverage is submetered data for commercial building end uses.

Table ES-2. Summary of Calibration Data[9]

Type of Calibration Data	Summary of Availability
Utility Sales: Annual sales/consumption data by sector by utility	Universally available from the U.S. Energy Information Administration (EIA)
Load research data: Utility customer class aggregate load shapes	Acquired for ~20 utility companies and the Electric Reliability Council of Texas
Advanced metering infrastructure (AMI): Whole-building AMI data	Acquiring in multiple census divisions, via nondisclosure agreements with utility companies
AMI + Metadata: Building characteristic metadata joined with AMI data	Acquiring for a subset of the AMI data sets
Submetered: End-use metering data, including smart thermostat data	Multiple (3+) strong data sets available for residential; few data sets available for commercial buildings

Each of these types of calibration data can be used in different ways to verify the characterization of both the aggregate profile and the diversity of profiles within a segment. For example, comparisons of model outputs to calibration data informs which inputs (*schedule-related* or *characteristic*) need to be updated based on the timing or magnitude of profiles. Schedule-related inputs can be directly extracted from many of the end-use and whole-building data sets we have collected. Other calibration data sets can be used for validation and to establish model confidence.

Addressing Data Gaps

After identifying the model calibration data gaps, a number of approaches were explored to acquire additional data, transfer data from other stock segments, infer information from nontraditional data sources, and assess the quality and accuracy of the EULPs.

Targeted Data Outreach

The major identified data gap from the first phase of the project is publicly available submetered data for commercial end uses and building types. The project team is exploring data purchase options through outreach to organizations that have data for sale, determining the quality of the data, and understating restrictions on data use if purchased. A complete list of options and the corresponding data needs will be complete by November 2019 to determine if additional steps are needed.[10]

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[8] Project partner EPRI is also pursuing working with utility companies to develop survey instruments for collecting detailed building characteristic data, which can be paired with AMI data to enable conditional demand analysis. Conditional demand analysis is a hybrid approach for statistically inferring EULPs. The resulting survey data and conditional demand analysis results are another potential source for calibration data.

[9] See Appendix D for complete list of calibration data.

[10] See the End-Use Load Profiles for the U.S. Building Stock project website at https://www.nrel.gov/buildings/end-use-load-profiles.html and Technical Advisory Group meeting materials for project updates.

Evaluating Transferability

Some data gaps might be well addressed by transferring data from other building types, end uses, years, or regions. Previous literature has suggested that many non-HVAC EULPs are highly transferrable between regions (KEMA 2009) and that key tools and techniques can "enable the transfer of data across climates and potentially across time" (DNV GL 2014). We posit that our approach of using building stock models calibrated at multiple geographic levels is one such key technique enabling this transferability. For example, we hypothesize that our models capture the physics-based heat transfer relationship between heating, cooling, temperature, and energy consumption. With information on the building composition, heating and cooling equipment types, and temperature, it is likely that different climate zones can be well represented using our stock models even in the absence of large amounts of calibration data. For example, we can test transferability by utilizing inputs from one region and evaluating the stock models' output against AMI or other data sets in another region.

This is the first EULP research project of this scale, so there are still open research questions on which end uses are transferable between locations and building types. The project team anticipates that understanding transferability of data will also yield insights on unanalyzed topics such as the relationship between building stock, equipment and operation by geography. This will be a significant scientific contribution of this project.

In cases where we assume transferability but find through analysis that a segment is not transferable, we will consider purchasing additional data identified during the market research, if it exists. If additional data for the nontransferable end use does not exist, this suggests that directly submetering the end use across multiple regions may be worthwhile, depending on the importance of the end use and the accuracy desired by stakeholders. If we pursue this option, we may conduct additional limited data collection directly or with partners.

Next Steps: Assessing Accuracy

The goal of this project is to produce a catalog of both aggregate and individual EULPs. For the project to be successful, the EULPs must be high fidelity and stakeholders must be confident that the EULPs are robust. To achieve this goal, a suite of metrics and techniques will be developed to evaluate the accuracy of the models across multiple dimensions.

Currently, the project team is developing a robust, quantitative process to measure the models' accuracy and uncertainty. This process includes identifying key model outputs (or performance metrics), assessing the sensitivity of selected model input parameters to iteratively guide calibration updates, and conducting uncertainty quantification around the key model outputs.[11]

The following six key model outputs are a summary of the types of outputs the project team will use to evaluate and quantify the models' accuracy.[12] When evaluating the key model outputs, the project team will also consider the outputs across different timescales, from annual to 15-minute intervals, to quantify the models' accuracy.

1. **Annual, whole-building:** Aggregate whole-building profiles for a region and building type should add up to the regional annual energy total for a building cohort. For example, annual total electricity for residential EULPs for a utility territory should match the total for that segment in the utility's load research data or EIA Form 861 reported sales if the building type is classified similarly in the model.

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[11] The project team anticipates that the approach for conducting uncertainty analysis on the ResStock and ComStock outputs will occur by propagating input uncertainty distributions through a machine learning emulator to estimate uncertainty ranges on key outputs.

[12] The project team will also consider peak performance, seasonal performance, and average deviation from totals for each of the key model outputs.

2. **Annual, end use:** Aggregate EULPs for a region and building type should match the annual total for that segment. For example, the annual total of commercial lighting for a census division should match CBECS.

3. **Annual, diversity**: The annual energy use of individual whole-building profiles and EULPs across the model should match the diversity found in the real world. For example, the distribution of modeled annual electricity use intensity for schools in a region should match the distribution seen in the metered annual electricity for schools in that region.

4. **Time-series, whole-building:** Aggregate whole-building profiles for a region and building type should match the temporal pattern found in real data, For example, the combined sector totals from ComStock should match those of the commercial sector AMI plus the metadata total across the year from a utility.

5. **Time-series, end use:** Aggregate EULPs for a region and building type should match the temporal pattern for that segment. For example, the aggregate data from residential clothes washers should match the average submetered data for that region across all time intervals.

6. **Time-series, diversity:** Individual profiles for whole-building profiles and EULPs across the model should match the diversity found in the real world across all time periods. For example, the distribution and timing of restaurant HVAC consumption in a region should match the full range of submetered data for that region across all time intervals.

As part of our assessment across these dimensions, we will perform verification, validation and uncertainty quantification, following best practices for complex physics-based models laid out by the National Research Council (National Research Council 2012). This will include quantifying the outcomes of our aggregate load profiles with uncertainty assessments. For our individual EULPs, each region, end use, and building type will receive a set of profiles to represent a range of individual building energy consumption patterns. The sets of profiles enable the uncertainty analysis for evaluating ranges of possible outcomes for individual buildings.

The TAG will continue to meet during the second and third years of the project, to provide guidance and feedback on the modeling efforts. In the project's third year, the calibrated EULPs of the U.S. building stock will be published, along with a user guide for utilities, policymakers, technology developers, and researchers. A suite of calibrated building energy models that can be used for "what-if" policy and technical analysis will also be available. For up-to-date information on the project, please see https://www.nrel.gov/buildings/end-use-load-profiles.html.

Table of Contents

List of Figures

List of Tables

1 Project Overview

End-use load profiles (EULPs), which quantify *how* and *when* energy is used, are critically important to utilities, public utility commissions, state energy offices and other stakeholders. Applications focus on understanding how efficiency, demand response, and other distributed energy resources are valued and used in R&D prioritization, utility resource and distribution system planning, and state and local energy planning and regulations. Consequently, high-quality EULPs are also critical for widespread adoption of grid-interactive efficient buildings (GEBs).[13] For example, EULPs can be used to accurately forecast energy savings in buildings or to identify energy activities that can be shifted to different times of the day.

Currently, publicly available EULPs have limited applications because of age and incomplete geographic representation. To help fill this gap, the U.S. Department of Energy (DOE) funded this three-year project—*End-Use Load Profiles for the U.S. Building Stock*—which will produce a set of temporally resolved electricity[14] EULPs for the residential and commercial building stock[15] of multiple regions of the United States. The project team, made of researchers from the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), and Argonne National Laboratory, will accomplish this through the combination of best-available physics-based stock modeling and best-available ground truth energy use data. They will leverage the project's technical advisory group (TAG), Electric Power Research Institute (EPRI), utilities, and other government and industry stakeholders to collect and evaluate end-use and whole-building load profile data from a wide range of existing sources and address critical gaps with additional data collection.

This project will use two national-scale building stock models (ResStock™ and ComStock™) to produce EULPs at both the aggregate and individual building scales. Aggregate profiles will represent the total profile for an end use in one or more customer segments in a utility territory or other region. Individual profiles will represent real building patterns, complete with the normal spikes and variability present in individual buildings. Detailed models of stochastic occupant behavior will augment the physics models by providing diversity in the timing of occupant-driven loads across the building stock. These EULPs and the underlying calibrated models will be published online, along with a user guide for utilities, policymakers, technology developers, and researchers. This foundational data set will help users make critical decisions about prioritizing research and development, utility resource and distribution system planning, and state and local energy planning and regulation.

Figure 1 provides a diagram summarizing the overall project approach.

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[13] See https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings for more information on GEBs.

[14] Although this report and project focus on electricity end -uses, quantifying load profiles for natural gas, propane, and fuel oil are also of interest and will be included in this work.

[15] Load profiles from other sectors are outside the scope of this project. As an initiative of DOE's Building Technologies Office, this report and the associated project focus on energy used in the commercial and residential buildings sectors. Energy used for manufacturing, agriculture, and street lighting, although relevant for some of our identified use cases, is outside the scope of the project. Similarly, on-site power generation (e.g., rooftop solar) and plug-in electric vehicle charging are not the focus of this report, but the Building Technologies Office is coordinating with the respective DOE offices to leverage work on characterizing load profiles for distributed solar and plug-in electric vehicle charging.

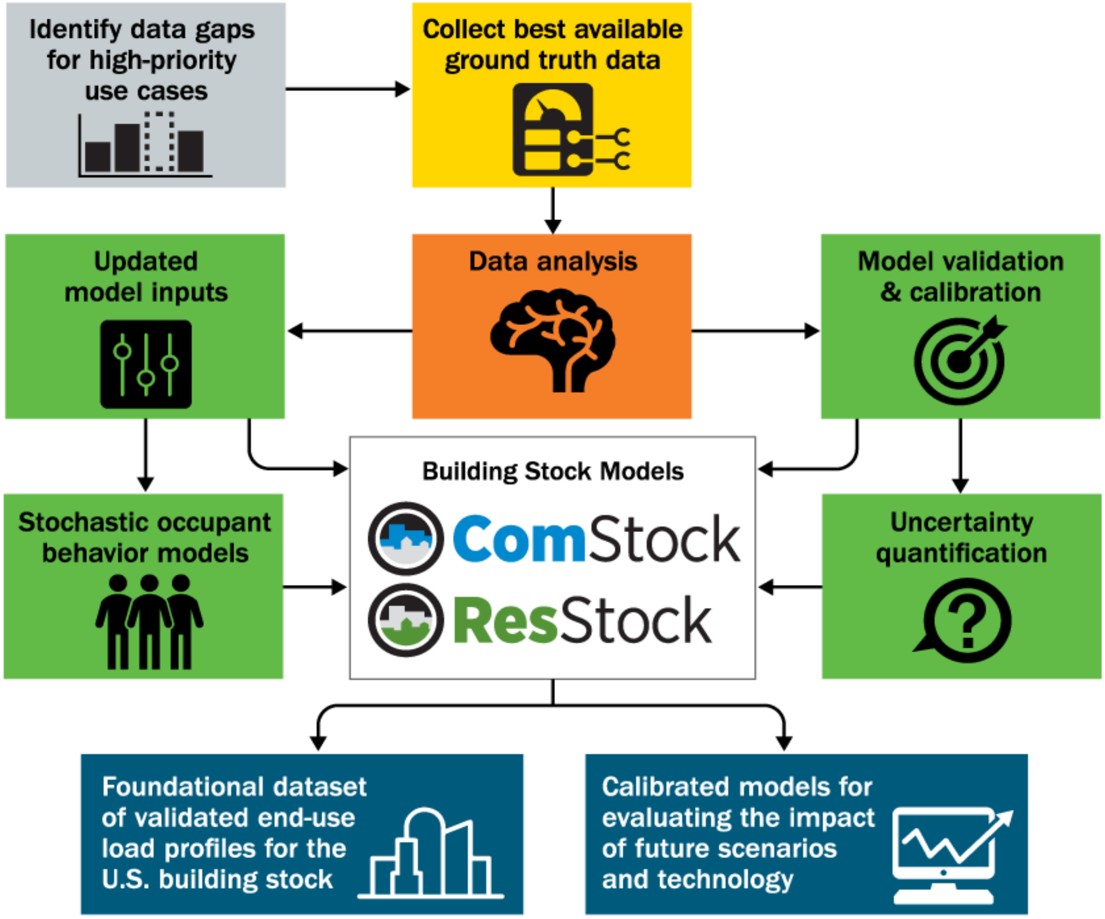

Figure 1. Project overview

What is an End-Use Load Profile?

EULPs quantify *how* and *when* energy[16] is used. The *how* refers to the way energy is used inside the building. Examples of end uses include space conditioning, water heating, refrigeration, or any other energy use in a building. Table 1 provides a working list of commercial and residential end uses for this project.

Table 1. Working List of End Uses for This Project

Commercial Building End Uses*	Residential Building End Uses*
HVAC	HVAC
Heating	Heating
Cooling	Cooling
Fans	Furnace/Air-conditioning fan
Pumps	Boiler pumps
Heat rejection	Ventilation fans
Humidification	Domestic water heating
Heat recovery	Major appliances
Service water heating	Refrigerator
Refrigeration	Clothes washer
Plug and process loads	Clothes dryer
Lighting	Dishwasher
Interior	Cooking range
Exterior	Pool/spa pumps, heaters
	Miscellaneous plug loads
	Lighting
	Interior
	Exterior

* The data set can be filtered by parameters such as building type, HVAC system type, etc.

EULPs also describe *when*—the time of day or hour of the year—an end use is consuming energy. The terms *load profile, load shape,* and *load curve* are often used interchangeably, but all refer to the timing of energy use. At the most basic level of granularity, the timing of energy use can be characterized by a coincidence factor (energy consumption that is coincident with an electric utility's peak load) or portion of the energy used during an on-peak (e.g., 2 p.m. to 6 p.m.) or off-peak (e.g., 9 p.m. to 9 a.m.) period of the day, as defined by an electric utility or grid operator. More detailed characterization of energy use involves defining the energy used in each hour of a year (e.g., 8,760 values) or subhourly using 15-minute or even subsecond intervals.

EULPs can be categorized in a variety of ways. This report uses the term *load profiles* to refer to both load profiles that are directly *measured* (e.g., using advanced metering infrastructure [AMI] or measurement and verification metering) and load profiles that are *modeled* (e.g., simulated using building energy modeling software). This project will create *modeled* EULPs that are calibrated to, and validated against, *measured* load profile data.

EULPs can be further categorized as aggregate or individual load profiles. Aggregate, or diversified, load profiles are the normalized sum of many individual building load profiles. They tend to be a smooth shape, devoid of sharp transitions and scattered peaks (i.e., a regional average) because of the diversity of occupant behavior and equipment operation. These types of profiles are important for characterizing end-use energy consumption across a region or segment of buildings (e.g., utility load shape).

At an individual building level, the variability and intermittent nature of discrete occupant- or schedule-driven events becomes apparent. Historically, individual customer loads were only important for sizing electrical service drops to individual buildings and distribution transformers serving a small number of customers.

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[16] Although this report and project focus on electricity end uses, quantifying load profiles for natural gas, propane and fuel oil are also of interest and will be included in this work.

However, a growing number of EULP applications—for example, understanding building level demand response potential—rely on EULPs for a “typical” individual customer (or preferably, an array of many typical and atypical individual customers) for accurate decision-making.

Figure 2 is an example of aggregate and individual load profiles. The plot on the left represents an aggregate water draw profile, where the sector total has been summed and normalized. The plot on the right represents an individual profile with realistic water draws that would exist in a real home. It is clear from this example that using the aggregate profile for an individual building would mischaracterize the energy associated behavior (i.e., water heating) for that building.

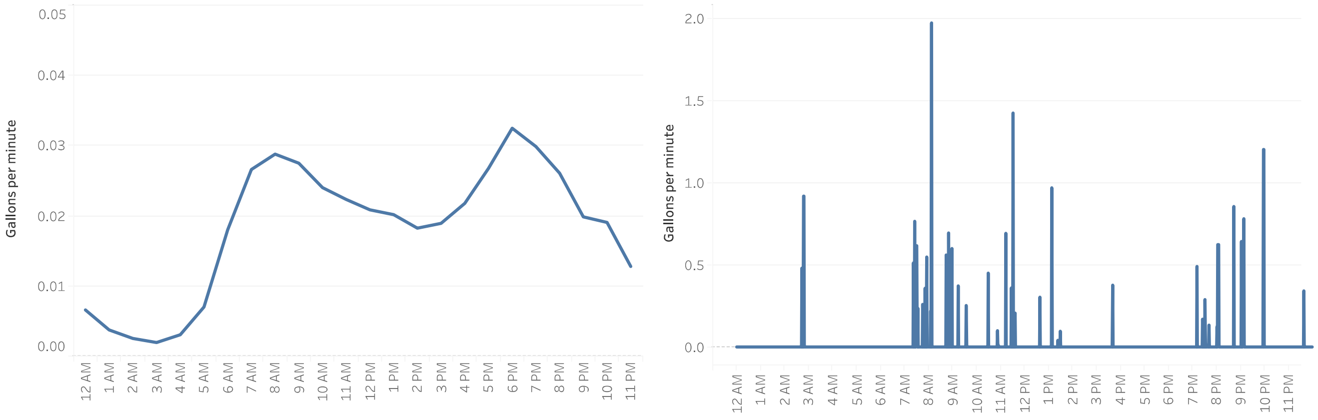

Figure 2. Example aggregate (left) and individual (right) EULP concept demonstrations using water draws

Report Purpose

This report serves as the first-year deliverable for the *End-Use Load Profiles for the U.S. Building Stock* project. The two primary milestones for the first year of the project are to identify (1) market needs for EULPs and (2) gaps in data to both build (*model input data)* and calibrate (*model calibration data*) the project’s building energy models. This report does not detail the calibration methodology or uncertainty quantification, as details of these will be included in the final project report and in supporting peer-reviewed publications.

The remainder of the report is organized into three sections. Section 2 discusses market requirements for EULPs. Section 3 discusses the data needs for the project and the state of *model input data* and *model calibration data*. Section 4 discusses project plans to address gaps in data availability.

Energy Savings Load Profiles

Understanding the difference between EULPs and savings load profiles is critical to determining how efficiency, demand response, and other distributed energy resources are valued. In short, the difference between end-use and savings load profiles is that the time pattern of savings from substitution of a more efficient technology does not always mimic the EULP.

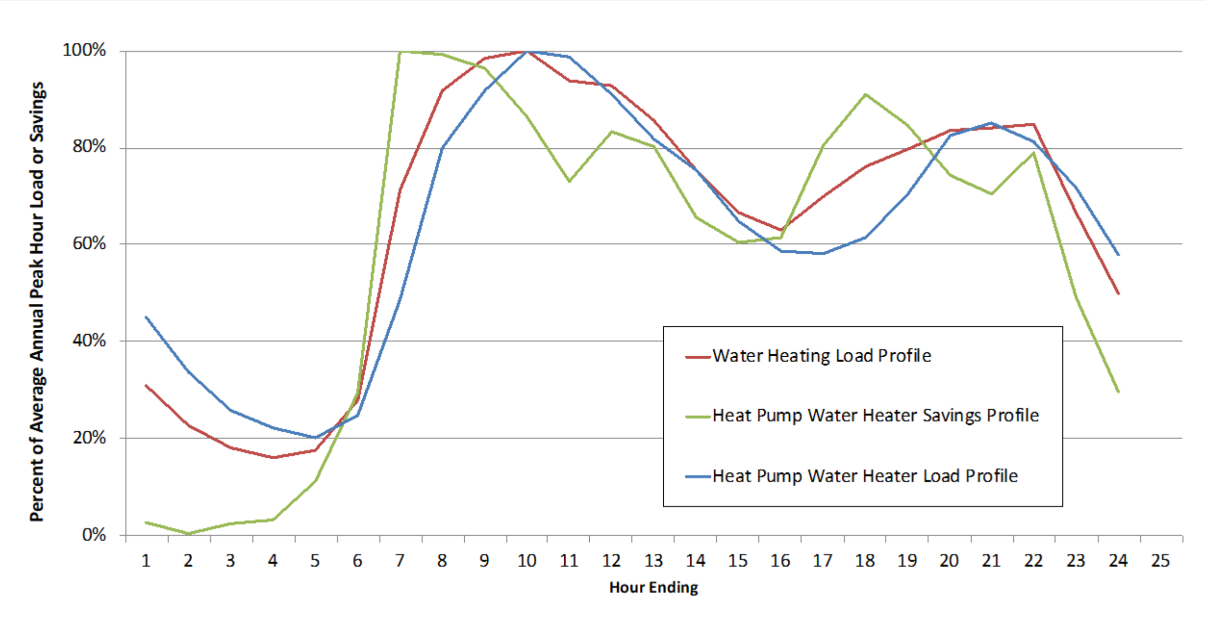

Figure 3. Load profile versus savings profile for a water heater

Figure 3 shows the potential inaccuracy introduced if an EULP, rather than an energy savings load profile, is used to estimate the value of measure savings. Figure 3 has three load profiles: an EULP for a residential water heater (red line), a heat pump water heater (blue line), and the savings profile of a heat pump water heater (green line). If a planner wants to understand the value of the energy savings, the delta between the water heating and heat pump water heating profile—the savings profile—should be used. Figure 3 shows that the heat pump water heating savings are highest from 6–7 a.m. (hour ending 7), although the heat pump water heater energy consumption is at its highest from 9–10 a.m. (hour ending 10). The avoided costs used to estimate the measure value are likely not the same from 6–7 a.m. as they are from 9–10 a.m., thus creating a different electric system value.

It is outside the scope of this project to include quantification of savings shapes. However, the project's resulting calibrated stock models could be used to estimate savings shapes in the future, either by the project team or by third parties. For information on savings shapes see Mims, Eckman, and Goldman (2017).

2 Market Needs

One of the primary motivations for this project—a first of its kind—is to increase and update national EULP coverage. All regions of the country need updated EULPs because the underlying data used to create them are dated. This need is exacerbated by changing end-use consumption patterns and the rapid introduction and adoption of new electricity consuming technologies.

2.1 Current Coverage of End-Use Load Profiles[17]

As part of our research for this project, the team conducted a comprehensive review of publicly available EULPs and created an inventory, available on LBNL's website.[18] Data sources were added to the inventory if they provided hourly or more frequent (e.g., minute, seconds) load shape data and were publicly available. The review focused on EULPs created after 2000, with the exception of the End-Use Load and Consumer Assessment Program because of the large sample size of this study.

More than 220 data sources were reviewed, but many source documents could not be located or did not contain sufficiently granular and publicly available data, or both. For example, some data sources contain consumption by time-of-use period (e.g., summer on-peak, winter off-peak), particularly among state energy efficiency technical resource manuals. A list of the data sources reviewed, but not used are included in a separate tab in the inventory, with a brief description as to why they were not included.

The current geographic coverage and coverage of some building types in EULP studies are currently quite limited (Figure 4). Most EULP studies focus on a specific end use, and the larger studies are concentrated in just a few areas of the country (i.e., Pacific Northwest and New England). Because of the high use of EULPs in multiple applications, this underscores the market need for further EULP development for other regions.

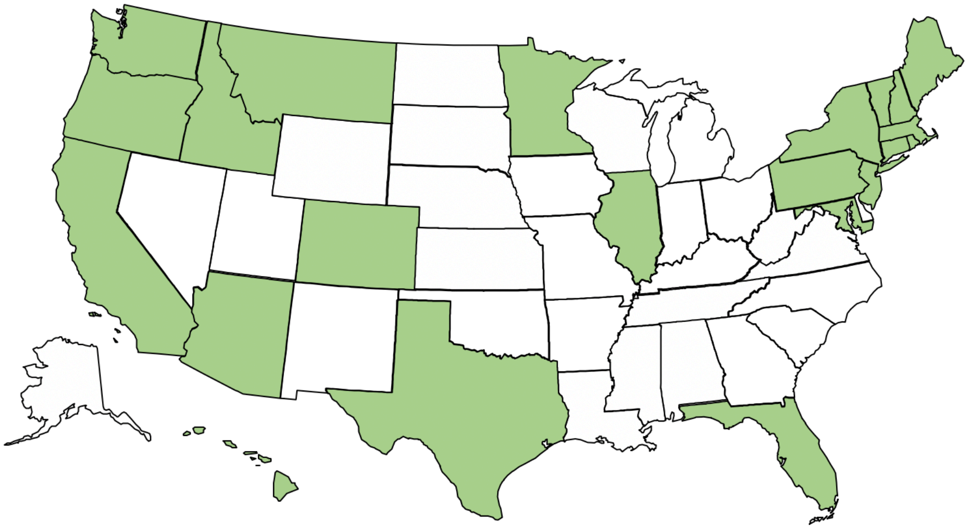

Figure 4. States with publicly available end-use load profile data[19]

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[17] Contributions to this section were made by Jun Zhang, Gabe Mantegna, Michael Sontag, and Snuller Price (Energy and Environmental Economics [E3]).

[18] The inventory is available at: https://emp.lbl.gov/publications/end-use-load-profile-inventory.

[19] The quantity of data and number of EULPs that are available in each state vary greatly. See the EULP inventory for more information. https://emp.lbl.gov/publications/end-use-load-profile-inventory.

2.2 Selection of the Technical Advisory Group

The project team drew upon the experience and expertise of a diverse TAG to help identify data gaps and use cases and guide the project. Outreach to experts to request their participation in the TAG was based on several criteria:

1. *Robust geographic representation* to assist with identifying and acquiring EULP input and calibration data, and to ensure regional (and national) support for the project approach and analysis
2. *Strong utility and public utility commission staff representation* to ensure that the primary users of our EULPs understand and are supportive of our approach
3. *Diverse organizations* that represent a variety of expertise and experience creating and using EULPs

The TAG comprises approximately 70 individuals representing more than 50 organizations, including utilities, independent system operators/regional transmission organizations (ISO/RTOs), public utility commissions, state and local government, consulting firms, software companies, academic institutions, nongovernmental organizations representing utilities and regional/national efficiency groups, and DOE.[20] Geographically, TAG members are located in 20 states, covering seven of the eight North American Electric Reliability Corporation regions, with many members conducting work regionally or nationally.

Looking Forward: Increasing the Importance of Accurate EULPs in Benefit-Cost Analysis

The usefulness of EULPs grows with variability in utility-avoided costs and customer participation in time-varying rates, including demand-based rate options.

In some cost-effectiveness estimates, a single avoided energy cost value is used in benefit-cost analysis, thus valuing energy savings or generation in all hours of the year equally. The full value of distributed energy resources that can generate, reduce or shift energy consumption is not captured with a singular avoided cost value. As distributed energy resource adoption evolves and incorporates load shifting technologies, the importance of hourly end-use data and associated avoided cost values becomes integral to capturing the resource’s full value.

Increased adoption of solar resources in several parts of the country has led to periods of lower, or even negative, avoided costs during mild, sunny days and increased ramp rates for other generation sources as the sun sets. These conditions require greater response and attention to grid management. EULPs and the underlying building energy models can help users identify opportunities to respond to these issues through use of distributed energy resources to shift or build load during low-cost periods and reduce or shift load away from high-cost peak periods.

Gathering feedback on how different types of stakeholders employ EULPs and what the data needs are for their potential uses was a focus in the project’s first year. Our main source of outreach was through our TAG meetings and individual discussions with TAG experts. Collaboratively, the project team and the TAG identified EULP use cases and the project team conducted expert interviews on the project approach with TAG members This is discussed further in Section 2.5.

2.3 Use Case Identification

For this report, a *use case* is defined as any type of process or analysis that utilizes EULPs. To ensure that the outputs of this project are useful to as many stakeholders as possible, extensive stakeholder engagement was included in use case identification.

First, EULP use cases were identified by reviewing a variety of sources, including regulatory filings and academic publications. From this effort, the project team identified about 60 unique use cases. A detailed list of the use cases can be found in Table B-1. in Appendix B.

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[20] Appendix A is a list of all TAG members.

This list was then presented to the TAG and collaboratively discussed and prioritized based on need and usefulness during a two-day workshop. The project team reviewed the TAG input and interpreted, grouped and presented the 10 most mentioned use cases to the TAG as a standardized list. These top 10 use cases are discussed below.

2.3.1 Energy Efficiency Planning

This use case includes three aspects of utility or program administrator energy efficiency program planning: benefit-cost analysis, potential assessments, and energy efficiency program planning.

Energy efficiency *benefit-cost analysis*, or cost-effectiveness, compares the relative benefits and costs of measures, programs, or portfolios from different perspectives.[21] Energy efficiency benefit-cost analysis is widely used—utilities and program administrators use it in program implementation, planning, and evaluation. It is used by utilities and regulators to assess the cost-effectiveness of proposed energy efficiency investments and, along with other factors, inform the level of investment in efficiency that a utility will make. If life cycle benefits exceed costs, the measure, program, or portfolio is considered cost-effective. Historically, many states relied on the *California Standard Practice Manual*, adopting and modifying the manual's different perspectives to determine energy efficiency cost-effectiveness. In recent years, experts in this field formed the National Efficiency Screening Project and developed the *National Standard Practice Manual*[22] with the intention to replace state use of the *California Standard Practice Manual.* The *National Standard Practice Manual* provides a comprehensive framework for assessing the cost-effectiveness of energy efficiency resources. The *National Standard Practice Manual* is intended to create a state-specific test that represents the regulatory perspective based on the state's applicable policy objectives.

Energy efficiency *potential assessments* consider the opportunity for efficiency in a jurisdiction, often from different perspectives. The objective of the assessment is to provide accurate and reliable information regarding the quantity of savings, the timing of savings (through EULPs or savings load profiles), availability, and the cost of acquiring or developing energy efficiency resources.[23]

There are many types of *energy efficiency program designs*, including energy audits, rebate, financing, direct install, upstream or midstream[24] incentives, retrocommissioning, technical assistance, and new construction programs.[25] There are also several objectives that energy efficiency programs may seek to achieve, such as resource acquisition, market transformation, or education and training. Given the variety of program types and objectives, energy efficiency program design must consider many components, including measure and program cost-effectiveness, energy and demand savings, the amount of the incentive payment to the customer (if applicable), whether the incentive payment will be upstream of the customer, how to market the program, and how to verify program savings.[26] Each of these efficiency program design elements can benefit from EULPs. For example, accurate EULPs inform program administrators about when end uses or measures are consuming or saving electricity, helping them to identify the necessary measures and programs to meet energy savings goals or requirements.

2.3.2 Program Impact Evaluation[27]

Impact evaluation includes a range of retrospective assessments and activities aimed at determining the effects of policies, portfolios, programs or projects. Impact evaluation can document metrics such as performance

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[21] For more information on cost-benefit analysis, see the *National Action Plan for Energy Efficiency* (2008) and Appendix C.

[22] For more information on the *National Standard Practice Manual,* see: https://nationalefficiencyscreening.org/national-standard-practice-manual/.

[23] For more information on developing potential studies, see U.S. EPA (2007). For more information on existing potential studies, DOE maintains an Energy Efficiency Potential Catalog at https://www.energy.gov/eere/slsc/energy-efficiency-potential-studies-catalog. Also refer to the Database of State Efficiency Screening Practices (DSESP) at https://nationalefficiencyscreening.org/state-database-dsesp/.

[24] Upstream programs provide an incentive to product manufacturers, and midstream programs provide an incentive to product distributors. Both reduce the cost to program participants.

[25] For more information on best practices in energy efficiency program design, see https://www.epa.gov/sites/production/files/2015-08/documents/napee_chap6.pdf.

[26] Other considerations at the portfolio level include continuity of programs over time, service for all customer classes, and customer education.

[27] For more information on energy efficiency evaluation, measurement and verification, see https://www4.eere.energy.gov/seeaction/evaluation-measurement-and-verification-resource-portal.

(e.g., energy and demand savings or avoided air emissions) and provide data necessary for determining cost-effectiveness. Impact evaluation activities have three primary objectives: (1) to measure and verify the benefits (i.e., impacts) of a program and determine whether the subject program (or portfolio of programs) has met its goals, (2) to identify ways to improve current and future programs by determining why program-induced impacts occurred, and (3) to support energy demand forecasting, resource planning, or energy capacity auctions by understanding the historical and future resource contributions of energy efficiency as compared to other energy resources.

Specifically, efficiency impact evaluations (or evaluation, measurement, and verification) utilize energy savings information from facilities where efficiency measures are installed, as well as information about the measures themselves, to determine temporal variations in savings and specific metrics of interest, such as peak and coincident[28] demand savings. Thus, robust EULPs that provide hourly profiles of kilowatt and kilowatt-hour savings are important for accurate evaluation, measurement, and verification.

Using EULPs for Wholesale Energy Markets Impact Evaluation

Both the PJM company and ISO New England's (ISO-NE's) forward capacity markets allow passive energy efficiency resources to be bid alongside generation assets. Utilities and other energy efficiency service providers offering energy efficiency resources must comply with specific evaluation requirements in both ISO-NE (M-MVDR) and PJM (Manual 18b) that require the use of measured load shapes, or at least the parts of the load shape that overlap with their designated summer and winter peak periods. Evaluators have repeatedly measured summer and winter hourly impacts of a host of energy efficiency measures in both ISO-NE and PJM and assisted utilities in delivering these passive resources.

In ISO-NE's 13th Forward Capacity Auction, ISO-NE cleared 3,051 megawatts (MW) of energy efficiency resources for delivery in 2022/2023. At a price of $3.80/kW-month, these resources (if installed) will receive $139.1 million in 2022/2023. In the latest PJM base residual auction (See 21/22 Base Residual Auction Results), 2.6 gigawatts of energy efficiency resources cleared as annual capacity performance resources, all of which must have measured summer and winter load shapes documented. At a clearing price of $140/MW per day, these load-shape-dependent energy efficiency resources were valued at approximately $130 million in the auction.

2.3.3 Demand Response Planning

Demand response—reducing or shifting electricity usage in response to time-based rates or other forms of financial incentives—can provide capacity, energy, and reliability to the grid. Demand response programs can provide valuable grid services under both economic and emergency scenarios. It is valuable for grid operators and utilities to know how much demand can be expected to curtail if a program is called upon at a certain time of day and under certain temperature conditions. Different end-use technologies will provide a different result based on their load profiles.[29] Demand response program planners and implementers use EULPs to develop estimates of curtailment capability and identify end uses that are best suited to reduce or shift consumption during different times of the day and year. For example, metering devices can be used to collect high-resolution load data for heat pumps, central air conditioners, resistive heat strips, water heaters, and pool pumps to better understand both summer and winter demand response resources.

2.3.4 Electricity Resource Planning

This use case includes long-term resource planning processes (10–40 years), such as *load forecasting* and *integrated resource planning*.

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[28] The timing of savings from each project or site where efficiency measures are installed is not necessarily aligned exactly with the electricity system peak, which is how the avoided peak demand is defined. The metric that represents the fraction of the peak demand reduction from an efficiency measure, across all installations, that occurs at the time of a utility system's peak is referred to as the measure's *coincidence factor*. In some cases, coincidence factor is defined as the ratio of peak demand to *maximum* demand, rather than *diversified* demand. This definition simply incorporates the diversity factor adjustment in the derivation of coincidence factor.

[29] The California Public Utilities Commission's demand response potential study used end-use load shapes to determine potential. For more information, see Demand Response Evaluation and Research at https://www.cpuc.ca.gov/General.aspx?id=10622.

Load forecasts are used to predict total electricity consumption (measured in kilowatt-hours [kWh]), peak load (measured in kilowatts [kW]), and the timing of peak load. Energy and peak load demand forecasts provide the foundation for resource planning, daily and seasonal operation, and risk management in the electric power sector. These forecasts are used by electricity resource planners primarily as a basis for understanding future electricity needs and developing plans to ensure there are adequate resources to meet that demand, without incurring excess costs.

Load forecasts are an input to utility *integrated resource planning*, a process used to identify a resource portfolio and management strategy that provides an adequate, efficient, economical, and reliable power supply while controlling for the risks associated with future uncertainties.[30] Integrated resource planning processes are often used to determine a least-cost preferred portfolio of energy resources to meet future demand for electricity through exploring different mixes of resources. If an integrated resource planning process requires utilities to consider energy efficiency and other demand-side resources, EULPs can be used to understand when energy consumption or savings occur. In some integrated resource planning approaches, energy efficiency measures are bundled together to create conservation supply curves based on their cost and EULP shape.

2.3.5 Transmission and Distribution Planning

Electric transmission planning is a process that identifies areas of the transmission system that are in need of upgrade or expansion to maintain or improve reliability and accommodate new generation or load. Electric distribution system planning focuses on assessing needed physical and operational changes to the local grid to provide safe, reliable, and affordable electricity. EULPs can help analysts understand the end uses that drive the need for the potential infrastructure investment.

In some areas of the country, evaluating non-wires alternatives for transmission and distribution infrastructure expansion needs is required as part of the planning process. EULPs provide analysts with hourly (or subhourly) data on the end uses that are consuming energy each hour, and can be used to develop the optimal portfolio of resources to defer a potential infrastructure investment in a non-wires alternative analysis.

2.3.6 Policy and Rate Design

EULPs can support city, utility, state, RTO/ISO, or federal policy and regulatory decision-making. Many policies including codes and standards development, utility rate design, and climate policy can benefit from EULPs.

Building energy codes are adopted by state or local governments and vary widely. Codes typically identify cost-effective requirements that reduce energy consumption. In California, the cost-effectiveness of efficiency measures is considered when the state updates its building energy code. Measures that save energy during on-peak hours are valued more than measures that do not, and determining which measures reduce peak load requires EULPs.

Electricity retail *rate design*, or the structure of electricity prices to consumers, affects how (and in some cases when) consumers use electricity. Time-based rates are electricity prices that vary with time and are intended to provide utility customers with price signals that better reflect the time-sensitive and marginal costs of producing and delivering electricity (Cappers, Hans, and Scheer 2015). Well-designed time-based rates can provide the appropriate price signals to incentivize energy efficiency measures. Additionally, as more utilities begin offering time-of-use rates and demand charges, utilities can employ EULPs to aid customers in understanding how specific end uses affect their bills. Coupled with well-designed time-based rates, utilities can use EULPs to help design their efficiency programs and awareness campaigns that will help customers manage their energy costs.

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[30] For more information on integrated resource planning, see Wilson and Biewald (2013) and Frick and Schwartz (forthcoming).

2.3.7 Emissions Analysis[31]

Many states have emissions reduction targets for air pollutant emissions (carbon, criteria, or toxic pollutants) based on federal or state requirements. When determining avoided emissions, a key consideration is the timing of energy savings because it determines which electric generation units' output is displaced.[32] For example, criteria pollutants such as ground-level ozone have diurnal and seasonal variations.[33] EULPs may allow states, cities or utilities to identify end uses and measures whose efficiency savings occur when emissions are highest and therefore can be reduced most significantly.[34]

EULPs also enable states to compare the different emission profiles correlated with different end uses, to help with development of abatement strategies, and could support a more detailed analysis of the emissions impacts of building energy consumption.

2.3.8 Electrification Planning[35]

Electric vehicle adoption and the transition of end uses such as water and space heating to electricity are trends that significantly affect electricity resource planning.[36] To understand the impact of increased demand for electricity, utility or grid system planners can use EULPs to more accurately understand how electrification could affect annual consumption and how the increase in consumption is spread across the hours of the year. EULPs can provide insights into how electrification impacts hourly load shapes. For example, if electrification increases load predominantly during peak hours, the requirements on the grid and resources necessary to meet the grid needs will be different than if electrification largely drives increased demand in off-peak hours. This is an important element for evaluating generation resource adequacy with mass electrification.

2.3.9 Improved Building Energy Modeling

EULPs can be used to improve default energy modeling assumptions at the building level for new building design as well as identify major regional differences for multibuilding modeling. Currently, building energy models often have default schedules for occupancy and equipment usage that are not necessarily reflective of either real-world practice or regional differences. Calibrating EULPs region-by-region and the supporting building energy models end use-by-end use will help to improve these assumptions, to enable more realistic modeling of energy consumption and improved building design.

2.3.10 Photovoltaics Planning

As adoption of photovoltaics and other variable renewable energy resources increases, it is necessary to understand how the need for electricity resources shifts throughout the day and year. EULPs can help planners understand the impact of photovoltaics on the distribution grid and on the demand for electricity. For example, EULPs offer utility or grid system planners more insights on how the adoption of distributed energy resources affects end-use consumption and how the increase or decrease in consumption is spread across the hours of the year. EULPs can also provide insights into how to cost-effectively integrate photovoltaics and distributed energy resources on electricity systems. In addition, a better understanding by utilities and the solar industry of energy demand, through EULPs, can lead to more appropriate sizing of distributed and utility-scale photovoltaics and battery storage systems.

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[31] The TAG identified that EULPs are particularly important for analyzing emissions reductions. Although this is a subset of policy and rate design, we separated it as its own use case.

[32] The location of the energy efficiency measure will also determine which electric generation unit is displaced.

[33] For more information, see the EPA's website Ground-level Ozone Basics at https://www.epa.gov/ground-level-ozone-pollution/ground-level-ozone-basics.

[34] Air pollution data are available on an hourly basis for all large fossil fuel generators (greater than 25 MW), through the EPA. The agency also offers the Avoided Emissions and generation Tool (AVERT) to evaluate how efficiency and renewable energy reduces air pollutant emissions. AVERT offers several options to users so that the tool can be used with high- or low-resolution data. For example, modeling options enable the user to evenly reduce generation across all hours of the year, designate the percentage reduction in fossil fuel generation, or manually input hourly annual reductions from efficiency.

[35] The TAG identified that EULPs are particularly important for analyzing impacts of electrification. Although this is a subset of policy and rate design, we separated it as its own use case.

[36] For more information on the impact of electrification on the electricity system, see Deason et al. (2018) and Steinberg et al. (2017).

2.4 Data Requirements for Use Cases

Using information gathered from the TAG, the project team identified the time, geographic, and electricity system data requirements for the use cases to determine the parameters for the EULP model inputs and calibration data.

- **Time resolution:** What is the minimum time resolution needed to serve the majority of stakeholders for this use case?
- **Geographic resolution:** What is the ideal geographic area needed to serve the majority of stakeholders?
- **Electrical characteristics:** Does the use case need real power[37] (the portion of electricity that supplies energy to the load) or reactive power[38] (the portion of electricity that establishes and sustains the electric and magnetic fields of alternating-current equipment)?

The goal of identifying the data requirements was to focus the project efforts on achieving the necessary fidelity to serve the majority of stakeholders for the most important use cases (as identified by the TAG). The bold use cases in Table 2 highlight where the data currently being used are typically insufficient, and where this project will make material improvements to the data for the use case. These are ranked in priority order, based on feedback from the TAG.

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[37] For more information, see: https://www.nerc.com/files/glossary_of_terms.pdf.

[38] For more information, see: https://www.nerc.com/files/glossary_of_terms.pdf.

Table 2. Use Case Data Requirements

Use Case	Time Resolution	Geographic Resolution	Electrical Characteristics
Electricity Resource Planning	Hourly, peak day, monthly peak	Service territory	Real power
Energy Efficiency Planning	Hourly, peak day, seasonal peak and off peak	Service territory	Real power
Policy and Rate Design	15 min, hourly	City, climate zone, or state	Depends on application
Transmission and Distribution System Planning	15 min or smaller, hourly	Distribution feeder, or substation	Real and reactive power
Program Impact Evaluation	Hourly	Service territory	Real power
Demand-Response Planning	15 min, hourly, peak day	Service territory	Real power
Improved Building Energy Modeling	15 min, hourly	Region	Real power
Electrification Planning	Hourly, peak day, seasonal peak and off peak	Service territory or smaller	Real power
Emissions Analysis	Hourly	Service territory or larger	Real power
Photovoltaics Planning	1 min	Weather station	Real power

Key takeaways on the EULP data requirements include the following:

- **Time resolution:** The status quo for most use cases is hourly profiles. Based on the project team's expertise, the ideal time resolution for many of the use cases is more granular. Thus, we will focus on 15-minute resolution for EULP modeling because several use cases require it and the other use cases will benefit from higher-fidelity time resolution.
- **Geographic resolution:** Stakeholders have many use cases that require EULPs at the utility service territory, with some needing profiles at the feeder level. Many TAG members mentioned that they would like to be able to mix and match from a bank of profiles based on their customer characteristics to create a custom profile that is representative of a territory or specific distribution feeders. Use cases such as distribution system planning, especially, will require more information on the diversity of use shapes and occupant behavior because a smaller geographical area will be more sensitive to individual building load profiles. For this project, it is beyond the scope to develop custom profiles for each utility service territory or feeder in the United States, but if an adequate diversity of profiles is provided for each region, service territory or feeder profiles could be synthetically created. These approaches will be discussed in the accompanying user guide.
- **Electrical characteristics:** Most of the identified use cases only need real power. Some distribution system applications or policy applications would benefit from having information on reactive power for each end use. For this project, we consider reactive power out of scope because of the limited use cases. Guidance on postprocessing reactive power load shapes will be discussed in the user guide.

2.5 Market Acceptance of Proposed Approach

As a final step in determining market needs, expert feedback was solicited through multiple channels on our proposed modeling approach, data inputs, model output resolution, and usefulness and acceptance of the end-use load profiles. Key subject matter experts include previous developers of EULPs as well as potential users of our results. Most, but not all, are members of our TAG. Key subject matter experts are supportive of the modeling approach and proposed data collection process, and are supportive of using the end-use load profiles (and models). In addition, there is general agreement that the fidelity of the models is appropriate, and the level of accuracy we are proposing is useful and relevant for their applications.[39]

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[39] See the End-Use Load Profiles for the U.S. Building Stock project website at https://www.nrel.gov/buildings/end-use-load-profiles.html and Technical Advisory Group meeting materials for project updates.

3 Data Needs for Load Modeling

ResStock and ComStock use EnergyPlus, a physics-based building energy modeling software, to calculate energy consumption of each end use in a building on a subhourly basis (Wilson et al. 2017). Physics-based building energy modeling uses the characteristics of the building (e.g., insulation levels; interior lighting power; heating, ventilating, and air-conditioning (HVAC) equipment performance characteristics) operational schedules, and weather data as inputs to physics equations (e.g., heat transfer, fluid flow) to produce time-series results of the energy use of a building's systems and appliances.

ResStock and ComStock use a stock modeling approach that considers the diversity of all of these energy modeling inputs across the stock. This is in contrast to a more common and simplistic modeling approach, which considers just a few individual prototype buildings and scales the resulting load profiles to reflect the building stock. Although the modeling approach is not the focus of this report, it is important to note that in the ResStock and ComStock approach, hundreds of thousands of building energy models will be used to represent the building stock (~1 model for every 200 buildings). These models will have thousands of permutations to represent the diversity of characteristics in the real building stock as much as possible.
ResStock and ComStock are currently calibrated to annual energy consumption values from the Energy Information Administration's Residential Energy Consumption Survey (RECS) and the Commercial Buildings Energy Consumption Survey (CBECS), respectively, at both a national and regional level. One of the primary objectives of this project is to improve the spatial and temporal resolution of ResStock and ComStock. As the models are calibrated, the project team will determine what additional data sources are be necessary to update model inputs and to provide end-use load profiles at 15-minute increments for utility territories. Figure ES-2 overviews the workflow for updating ResStock and ComStock inputs and highlights that time-series data sets can provide both input and calibration information for the models by leveraging different features of the data sets.

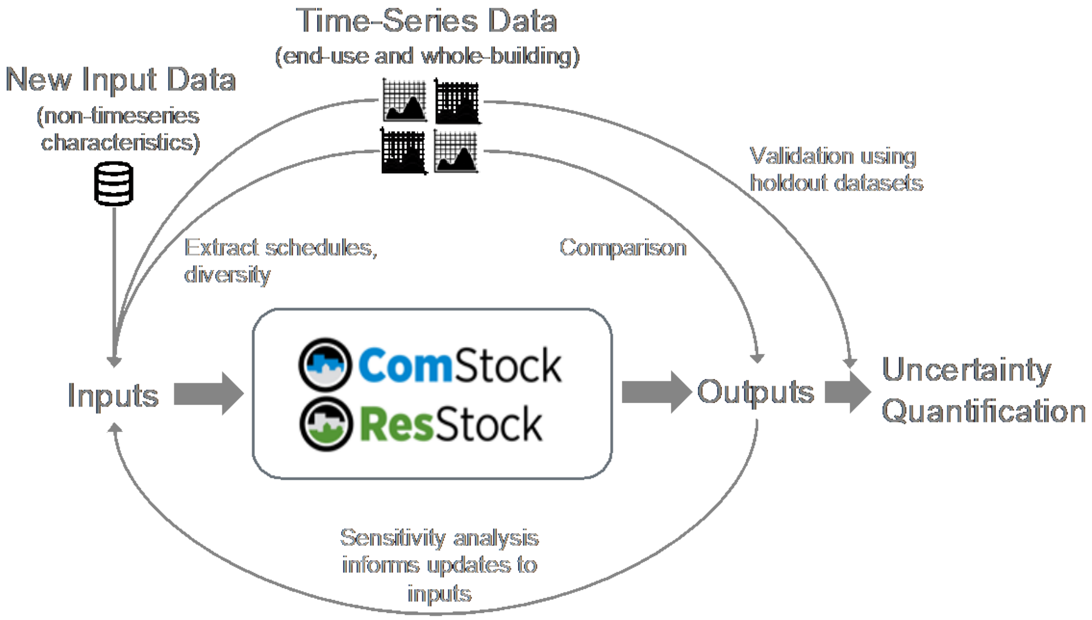

Figure 5. End-use load profiles modeling workflow

3.1 Model Input Data

ResStock and ComStock, with 370 and 287 inputs, respectively, leverage decades of research on residential and commercial building energy modeling, such as the Building America House Simulation Protocols (Wilson et al. 2014) and DOE Commercial Reference Building models (Deru et al. 2011). Both models were originally developed as tools for assessing the potential for end-use intensity reduction across the U.S. building stock. As such, the models are calibrated to the *annual* timescale. It is yet to be evaluated how well the models perform in each region for higher-resolution timescales. However, because both models are based on EnergyPlus, they already produce time-series output, which can be calibrated to produce EULPs. As we calibrate our models, region-by-region, to develop individual and aggregate EULPs, the project team will conduct ongoing sensitivity analyses to identify the parameters most significant to ResStock and ComStock time-series outputs. These sensitivity analyses will directly inform the calibration procedure and determine which inputs should be improved.

To jump-start the process, the project team identified a subset of 78 model inputs as most relevant to the time-series outputs needed for EULP use cases. For each of the input parameters to ResStock and ComStock, the project team reviewed the existing input and documented its current source. The models have three major input categories:

1. *Schedule-related inputs* (e.g., business hours, lighting on/off schedules) directly affect the timing of energy use; these are directly related to human behavior or scheduled operations. This category of inputs also involves understanding the variability and saturation of different behavior types across the building stock.
2. *Characteristic inputs* (e.g., floor area, lighting power density, HVAC system cooling type) indirectly affect the magnitude and timing of energy use. These are the physical description of the building, its equipment, and the saturation of these components across the stock.
3. *Environmental inputs* (e.g., humidity, temperature) directly affect the timing and magnitude of energy use; these are external to the building.

Next, each input was categorized as high-, medium-, or low-priority based on the expected contribution of each end use to the total and peak load as well as the judgement of the project team on the significance of the input and the representativeness of it for the entire U.S. building stock. This judgement was informed by years of previous work on these models. Not all identified inputs will be significant to model results, so we plan to use regional sensitivity analyses to determine how to allocate effort on updating model inputs.

For each of these inputs, the project team identified potential data sources that could improve upon current inputs. There is full coverage for high-priority inputs (the ones most likely to be updated) and good to fair coverage for medium- and low-priority inputs. The goal is to have a full appendix of potential data sources that can be quickly pulled and used as needed for the project. If the sensitivity analyses identify important inputs not on this list, the project team will conduct a literature review on these inputs and leverage TAG resources if necessary to identify data sources.

The next sections briefly discuss some of the high-priority inputs. A full list of all high-, medium-, and low-priority inputs with alternate data sources is listed in Appendix D.

3.1.1 High-Priority Inputs for ResStock

For ResStock, several major types of inputs were identified as high-priority, and likely to be updated for this project. The project team's identified future inputs are listed in Appendix D.

Schedule-related inputs. For time-sensitive model outputs (e.g., timing of peak demand), accurately characterizing when occupants are home, how they use appliances, and the diversity of these behaviors is critical for this project. As such, the project team identified parameters such as occupant presence, number of occupants, appliance schedules, vacancy rates, and set point schedules as high-priority inputs. Anticipating the need for increased nuance in this category, the project team is developing separate occupancy models that will integrate with ResStock and ComStock to inform the range of schedules used (Appendix F). A description of these models will be forthcoming in future project publications.

Characteristic inputs. Several characteristic inputs are flagged as high-priority for this project, and they are primarily focused on characteristic saturations across the residential stock. Appropriately accounting for the range of external and internal thermal mass (construction materials, furniture, and other contents of homes) across the stock is not something ResStock currently does well, and it will likely be of importance in regions with large amounts of masonry construction. The external mass inputs can be updated with available input data on construction materials, but the internal mass amounts will need to be calibrated against thermal time constants observed in calibration data, such as the smart thermostat data set that we have obtained. Similar, RECS data are limited or missing some emerging technologies such as heat pump water heaters, so additional updates will likely need to be made, particularly in regions with faster uptake of these technologies. Metrics on ventilation, such as distributions of range vent and bath vent flow rates are similarly not surveyed by RECS, and ResStock currently uses the same flow rate for all homes. Various regional surveys and manufacturer sales sheets may be used to improve these inputs if needed.

Environmental inputs. Representative weather is essential for this project. As such, the project team will construct our own actual meteorological year (AMY) datafiles from weather station data to ensure consistency with time-series calibration data. For the residential sector, it is well known that weather-dependent loads drive energy consumption, so all of the environmental inputs will be updated regardless of sensitivity results.

3.1.2 High-Priority Inputs for ComStock

Schedule-related inputs. Similar to residential applications, improving schedule-related inputs for commercial buildings is essential to model time-sensitive quantities of interest. This includes operation schedule (e.g., business hours), equipment usage schedules, and occupant presence and count. Additional work is being done to develop better commercial schedules for ComStock, utilizing additional data sources such as a Google Maps database of popular times and operating hours (Appendix F). The project team will also use its experience deriving hours of operation from AMI data.

Characteristic inputs. In ComStock and the commercial building sector more generally, many proprieties of the building and equipment are driven by building codes. The project team identified both building code compliance (deviations above and below code) and building component replacement rates as high-priority inputs. Industry and DOE studies on these topics exist and may be incorporated if needed. Additionally, increasing information on building properties such as aspect ratio, shading from surrounding buildings, orientation, and window location were identified as significant. Many new data sets exist for updating these, such as Light Detection and Ranging (LiDAR) and OpenStreetMap. Equipment identified as high-priority include the power density of data centers and IT closets; there have been several studies recently that could improve this input if needed.

Environmental inputs. Commercial building loads are typically less sensitive than residential buildings to weather. However, some end uses and building types are more sensitive. ComStock will use the same AMY files as ResStock for consistency across the project.

3.2 Model Calibration Data

To determine how accurate the models are and to help identify areas where model inputs need refinement, model calibration data (metered ground truth data) are needed. For example, a building energy model lighting load profile output could be compared to hourly whole-building lighting energy consumption to determine the accuracy of the model. The comparison could be used to improve the building energy model input assumptions about lighting power density or lighting schedule inputs. Calibration data will not necessarily be available for all regions, or only certain types of data might be available. The project team will utilize uncertainty analysis (e.g., sensitivity assessment and uncertainty propagation) to estimate the model performance and drive additional data collection where necessary.

Different types of metered and sampled data will be used to calibrate ResStock and ComStock. Table 3 provides a summary of the types of model calibration data available. Each of the types of calibration data in

Table 3 can be used in different ways to verify the characterization of both the aggregate and individual profiles within a segment. For example, comparisons of model outputs to calibration data informs which inputs need to be updated.

Table 3. Summary of Calibration Data[40]

Type of Calibration Data	Summary of Availability
Utility Sales: Annual sales/consumption data by sector by utility	Universally available from U.S. EIA
Load research data: Utility customer class aggregate load shapes	Acquired for ~20 utility companies and the Electric Reliability Council of Texas
AMI and Metadata: Building characteristic metadata joined with AMI data	Acquiring for a subset of the AMI data sets
AMI: Whole-building AMI data	Acquiring in multiple census divisions via nondisclosure agreements with utility companies, and from some one-off academic studies
Submetered: End-use metering data, including smart thermostat data	Multiple data sets available for residential; few data sets available for commercial buildings

Utility Sales. Annual utility load data are universally available through EIA Form 861, which includes the total annual sales by (i.e., residential or commercial) as well as the highest hourly peak demand for the year. This can be used as a more specific regional check on total consumption than the current RECS/CBECS census division approach because weather years can be matched, and the sales provide greater geographic specificity.

Load Research Data. In addition to publicly available EULPs, some utilities also conduct their own load research as part of the evaluation and planning process for demand-side management programs to inform energy efficiency or demand response potential studies, to perform technology assessments, and for other purposes.

For this project, load research data will be used for matching the aggregated total for utility regions and for matching temporal variations. ResStock and ComStock outputs should match the sector totals for a given utility at all time periods throughout the modeled year.[41]

Advanced Metering Infrastructure. Increasing numbers of utilities are installing AMI that collects whole-building data, typically at 15-minute intervals. Similar whole-building information is sometimes collected for research projects or by the private sector. When available for a large area (e.g., utility service territory) AMI/whole-building data can be used to determine the regional total that should be matched and the diversity of building energy use patterns that exists within each sector. AMI data will be crucial for instilling appropriate diversity in the models.

Submetered Data. Submetered data typically come from specific studies focused on data collection and research. This includes the existing EULP studies (e.g., the 1987–1989 End-Use Load and Consumer Assessment Program), which are summarized in the EULP inventory.[42] Submetered data will be used for verifying the aggregate and individual EULPs within each end use, and as a second check of the end-use calibration from AMI data. Some submetered data sets, such as Pecan Street, are biased in that they do not represent the entire population; whereas, others, such as the Northeast Energy Efficiency Alliance (NEEA)

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[40] See Appendix D for complete list of calibration data.

[41] ResStock and ComStock can match the year of data received by utilizing weather files for the corresponding year.

[42] See the End-Use Load Profile Inventory at https://emp.lbl.gov/publications/end-use-load-profile-inventory.

Home Energy Metering Study and Commercial Energy Metering Study are nominally bias free (NEEA 2019a). Identifying and correcting for bias in these data sets will be an important step prior to using the data as inputs or to calibrate ResStock and ComStock.

3.2.1 Data Sources Identified, Pursued, and Obtained

To improve the coverage of calibration data for the project, all the types of data listed in Table 3 were pursued. The project team identified publicly available data and also solicited the TAG and other partners for data sources. Data sets were categorized by sector, building type, end use, U.S. Census Division, International Energy Conservation Code climate zone, and time resolution. After categorization, a review of coverage was conducted to understand which categories had limited or poor-quality data. Some transferability exists for certain types of data; for example, when both end-use and AMI data are available in one region, but only AMI is available in another, it is possible to make inferences about end uses in the second region by using weather corrections.

Appendix E lists the calibration data sources either received by the project team or likely to be received in the near term. Data outreach and acquisition is ongoing.

3.2.2 Gaps in Calibration Data

Based on the initial data collection, the largest identified gap was submetered data for commercial buildings. Within ComStock, we consider 17 building types (e.g., schools, retail, midrise apartments), and there are limited submetered data sets that differentiate between building types. As discussed in Section 4, there is likely some level of transferability between building types, but the project team will need to assess the strength of that relationship. For residential buildings, several major submetered data sets are available for input and data calibration.

AMI data for the residential and commercial sectors will be crucial to characterizing the diversity and patterns of building energy use in different regions. Having these AMI data tagged with metadata (at a minimum building type, and preferably floor area and vintage as well) will be especially important in evaluating transferability between building types. We anticipate the amount of AMI data available will increase, given our work with EPRI and the TAG on data outreach.

4 Addressing Calibration Data Gaps

After identifying the calibration data gaps, the project team developed approaches to acquire missing data, transfer data from other stock segments, infer information from nontraditional data sources, and assess the quality and accuracy of the EULPs. A parallel process could be used if additional input data needs are discovered beyond the high-priority inputs in the sensitivity analyses.

4.1 Targeted Data Outreach

The major identified calibration data gap from the first phase of the project is publicly available submetered data for commercial end uses and building types. The project team is exploring data purchase options through outreach to organizations that may have data for sale, determining the quality of data, and understating restrictions on data use if purchased. A complete list of options and the corresponding data needs will be complete by November 2019 to determine if additional steps are needed.[43]

4.2 Evaluating Transferability

Some data gaps might be well addressed by transferring data from other building types, end uses, years, or regions. We posit that our approach of using building stock models calibrated at multiple levels of temporal and spatial resolution is one such key technique enabling this transferability. For example, we hypothesize that our models capture the physics-based heat transfer relationship between heating, cooling, temperature, and energy consumption. With information on the building composition, heating and cooling equipment types, and temperature, for example, it is likely that the coldest climate zones can be well represented using our stock models even in the absence of large amounts of calibration data. We can test transferability by evaluating the stock models' output against AMI data sets in areas where we have not calibrated the models.

This is the first EULP research project of this scale, so there are still open research questions on which end uses are transferable between locations and building types. The project team anticipates that understanding transferability of data will also yield insights on unanalyzed topics such as the relationship between building stock, equipment, and operation by geography. Results on transferability will be made public via peer-reviewed publications and project reports.

In cases where we assume transferability but find through analysis that a segment is not transferable, we will consider purchasing additional data identified during the market research, if it exists. If additional data for the nontransferable end use does not exist, this suggests that directly submetering the end use across multiple regions may be worthwhile, depending on the importance of the end use and the accuracy desired by stakeholders. If we pursue this option, we may conduct additional limited data collection directly or with partners. Each step of this transferability and data acquisition process will be discussed with our TAG.

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[43] See the End-Use Load Profiles for the U.S. Building Stock project website at https://www.nrel.gov/buildings/end-use-load-profiles.html and Technical Advisory Group meeting materials for project updates.

5 Next Steps: Assessing Accuracy

This project's goal is to produce a catalog of both aggregate and individual EULPs. For the project to be successful, the EULPs must be high fidelity and stakeholders must be confident that the EULPs are robust. To achieve this goal, a suite of metrics and techniques will be developed to evaluate the accuracy of the models across multiple dimensions.

Currently, the project team is developing a robust, quantitative process to measure model accuracy and uncertainty. This process includes identifying key model outputs (or performance metrics), assessing the sensitivity of selected model input parameters to iteratively guide calibration updates, and conducting uncertainty quantification around the key model outputs.[44]

The following six key model outputs are a summary of output types the project team will use to evaluate and quantify the models' accuracy.[45] When evaluating the key model outputs, the project team will also consider the outputs across different timescales, from annual to 15-minute intervals to quantify the models' accuracy.

1. **Annual, whole-building:** Aggregate whole-building profiles for a region and building type should add up to the regional annual energy total for a building cohort. For example, annual total electricity for residential EULPs for a utility territory should match the total for that segment in the utility's load research data or EIA Form 861 reported sales.

2. **Annual, end use:** Aggregate EULPs for a region and building type should match the annual total for that segment. For example, the annual total of commercial lighting for a census division should match CBECS.

3. **Annual, diversity:** Annual energy use of individual whole buildings and EULPs across the model should match the diversity found in the real world. For example, the distribution of modeled annual electricity use intensity for schools in a region should match the distribution seen in metered annual electricity for schools in that region.

4. **Time-series, whole-building:** Aggregate whole-building profiles for a region and building type should match the temporal patterns found in real data. For example, the combined sector totals from ComStock should match those of the commercial sector AMI plus metadata total across the year from a utility.

5. **Time-series, end use:** Aggregate EULPs for a region and building type should match the temporal pattern for that segment. For example, aggregate residential clothes washers should match average submetered data for that region across all time intervals.

6. **Time-series, diversity:** Individual profiles for whole buildings and EULPs across the model should match the diversity found in the real world across all time periods. For example, the distribution and timing of restaurant HVAC configurations and consumption in a region should match the full range submetered data for that region across all time intervals.

As part of our assessment across these dimensions, we will perform verification, validation, and uncertainty quantification, following best practices for complex physics-based models laid out by the National Research Council (National Research Council 2012). This will include quantifying the outcomes of our aggregate load profiles with uncertainty assessments. For our individual EULPs, each region, end use, and building type will

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[44] The project team anticipates that the approach for conducting uncertainty analysis on the ResStock and ComStock outputs will occur by propagating input uncertainty distributions through a machine learning emulator to estimate uncertainty ranges on key outputs.

[45] The project team will also consider peak performance, seasonal performance, and average deviation from totals for each of the key model outputs. A full set of the key output metrics will be available in the final project report.

receive a set of profiles to represent a range of individual building energy consumption patterns. The sets of profiles will enable uncertainty analysis for evaluating ranges of possible outcomes for individual buildings.

In addition to assessing accuracy in the upcoming year, the TAG will continue to meet during the second and third year of the project to provide guidance and feedback on the modeling efforts. In the third year of the project, the calibrated EULPs of the U.S. building stock will be published along with a user guide for utilities, policymakers, technology developers, and researchers. A suite of calibrated building energy models that can be used for “what-if” policy and technical analysis will also be available. For up-to-date information on the project, please see the End-Use Load Profiles for the U.S. Building Stock website at https://www.nrel.gov/buildings/end-use-load-profiles.html.

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Appendix A. End-Use Load Profile Technical Advisory Group

Table A-1. Technical Advisory Group Members

Name		Organization
Ayad	Al-Shaikh	CalTF
Jen	Amann	ACEEE
Jamie	Barber	GA PSC
Cyrus	Bedwhar	SEEA
Mark	Bielecki	Navigant
Kevin	Bilyeu	DTE Energy
Stephen	Bird	Clarkson University
Michael	Bishop	Solar Investments Inc
Brad	Borum	IURC
Ali	Bozorgi	ICF
Kristen	Brown	ComEd
Chris	Burgess	MEEA
David	Clement	NEEA
Matt	Cox	Greenlink Group
Ron	Domitrovic	EPRI
Carolyn	Elam	City of Boulder
Jamie	Fine	Environmental Defense Fund
Ellen	Franconi	PNNL
Adam	Gerza	Energy Toolbase
Mimi	Goldberg	DNV GL
Krish	Gomatom	EPRI
Chris	Holmes	EPRI
Bryan	Jung	E-Source
Steven	Keates	ADM
Phillip	Kelsven	BPA
Sami	Khawaja	Cadmus
Ben	King	DOE
Kurtis	Kolnowski	AEG
Peter	Langbein	PJM
Jim	Leverette	Southern Company
Jessica	Lin	Oracle Utilities (Opower)
Angela	Long	PacifiCorp
Ross	Macwhinney	City of New York
Pasi	Miettinen	Sagewell
Erik	Miller	IPL
Katherine	Mitchell	Xcel
Claire	Miziolek	NEEP
Sarah	Mullkoff	MI PSC
Mike	Myser	Energy Platforms
Paulomi (Lucy)	Nandy	MEEA
Chris	Neme	Energy Futures Group

Name		**Organization**
Clay	Nesler	JCI
Monica	Neukomm	DOE
Abhijeet	Pande	TRC Solutions
Dave	Parsons	HI PUC
Dan	Patry	Oracle
Bob	Pauley	IURC
David	Podorson	Xcel
Susan	Powers	Clarkson University
Curt	Puckett	DNV GL
Bob	Ramirez	DNV GL
Mike	Reed	NYSERDA
Griffin	Reilly	ConEd
Rachel	Scheu	Elevate Energy
Scott	Schuetter	Slipstream
Prasenjit	Shil	Ameren
Rodney	Sobin	NASEO
Justin	Spencer	Navigant
Robert	Stephenson	VEIC
Kenji	Takahashi	Synapse
Elizabeth	Titus	NEEP
JJ	Vandette	VEIC
Valerie	von Schramm	CPS Energy
Dave	Walker	MI PSC
Robert	Weber	BPA
Bob	Willen	Ameren
Craig	Williamson	DNV GL
Dan	York	ACEEE
Henry	Yoshimura	ISO-NE
Ben	Zhang	Duke Energy

Appendix B. Detailed List of Use Cases

Table B-1 lists all the use cases the project team brainstormed. As discussed in Section 2, the time, geographic, and electricity system data requirements to determine the parameters for the EULP model inputs and calibration data are focused on the utility planning, operations, and public policy use cases.

Table B-1. All Use Cases

Category	Goal of Use Case	Use Case
Utility planning	Bill customers equitably	Renewable integration studies for distribution planning
Utility planning	Bill customers equitably	Understand bill impacts on buildings that install electric vehicle chargers
Utility planning	Bill customers equitably	Rate design for time-varying and real-time pricing structures
Utility planning	Bill customers equitably	Rate design impacts on low-income customers
Utility planning	Ensure system reliability	Resilience studies to understand magnitude of critical versus noncritical loads
Utility planning	Ensure system reliability	Understand load profiles during extreme weather events
Utility planning	Ensure system reliability	Understand black start load magnitudes
Utility planning	Ensure system reliability	Demand response planning—understand what loads are shiftable and when
Utility planning	Ensure system reliability	Analysis of peer-to-peer energy trading impacts
Utility planning	Lower the cost of distribution infrastructure	Analysis of non-wires alternatives to avoid or defer distribution line and substation upgrades
Utility planning	Lower the cost of distribution infrastructure	Distribution planning—accommodate future distributed energy resource buildout
Utility planning	Lower the cost of distribution infrastructure	Transformer sizing
Utility planning	Lower the cost of generation capacity	Energy efficiency program planning
Utility planning	Lower the cost of generation capacity	Integrated resource planning
Utility planning	Lower the cost of generation capacity	Long-term load forecasting
Utility planning	Lower the cost of generation capacity	Long-term contract and futures purchasing decisions
Utility planning	Lower the cost of generation capacity	Demand-response potential of building stock or particular end uses
Utility planning	Lower the cost of generation capacity	Understanding when heat pumps will run versus when backup electric resistance will run
Utility planning	Lower the cost of generation capacity	Impact of smart, occupancy-based thermostats on grid
Utility planning	Lower the cost of transmission infrastructure	Analysis of non-wires alternatives to avoid or defer transmission system upgrades
Utility operations	Decrease resource procurement costs	Short-term (such as day-ahead) load forecasting

Category	Goal of Use Case	Use Case
Utility operations	Decrease resource procurement costs	Forecast aggregate usage and schedule supply
Utility operations	Ensure system reliability	Analysis of controls to manage power factor
Utility operations	Ensure system reliability	Load shifting/smoothing (for reduced peak, reduced ramping, etc.)
Utility operations	Ensure system reliability	Spinning reserves
Utility operations	Ensure system reliability	Supplemental reserves
Utility operations	Ensure system reliability	Nonspinning reserves
Utility operations	Ensure system reliability	Localized voltage support
Utility operations	Ensure system reliability	Frequency regulation
Utility operations	Ensure system reliability	Effect on power factor of different load shedding (e.g., AC versus electric water heater)
Utility operations	Lower the cost of generation capacity	Conservation voltage reduction analysis
R&D	Develop new products or services	Battery control scheme development
R&D	Develop new products or services	Developing HVAC for sensible versus latent internal heat generation
R&D	Develop new products or services	Creating a data value proposition for connectedness
R&D	Develop new products or services	Energy-related software as a service development
R&D	Develop new products or services	Improving products with utility needs as a target
R&D	Develop new products or services	Cold climate heat pumps grid impacts
R&D	Develop new products or services	Consumer electronics smart controls/standby impacts
R&D	Develop new products or services	Home energy management control to “flatten” load at house/feeder levels
R&D	Develop new products or services	Determining best control volume for balancing load and generation (e.g., building, feeder, city, utility)
R&D	Develop new products or services	Developing control systems for buildings
R&D	Develop new products or services	Inputs for urban-scale building energy models
R&D	Research	Correlation of different end uses for household type identification and use prediction
R&D	Research	Comparison of competing algorithms using neutral/public data sets
R&D	Research	Determining occupancy patterns
R&D	Sell existing products or services	Valuation of thermal energy storage
R&D	Sell existing products or services	Residential battery sizing, inverter sizing
R&D	Sell existing products or services	Uncertainty on cost to integrate renewables

Category	Goal of Use Case	Use Case
Public policy analysis	Lower cost or environmental impact of energy consumption	Energy codes and standards development
Public policy analysis	Lower cost or environmental impact of energy consumption	Renewable portfolio standard development
Public policy analysis	Lower cost or environmental impact of energy consumption	Regional air quality analysis
Public policy analysis	Lower cost or environmental impact of energy consumption	Analysis of greenhouse gas or renewable energy goals
R&D	Research	Urban climate modeling research
Community and business financial decisions	Decrease impact from utility outages	Microgrid design
Community and business financial decisions	Lower cost or environmental impact of energy consumption	Procurement decisions by companies or community choice aggregators
Community and business financial decisions	Lower cost or environmental impact of energy consumption	Solar and energy storage proposal analysis
Community and business financial decisions	Lower cost or environmental impact of energy consumption	District and campus planning research
Community and business financial decisions	Sell existing products or services	Warranty program development and management
Community and business financial decisions	Sell existing products or services	Analysis of combined cooling heat and power or district systems potential
Community and business financial decisions	Sell existing products or services	Automated solar loan product generation
Community and business financial decisions	Sell existing products or services	Grid service aggregators

The priority numbers (i.e., “votes” by the TAG) of use cases in each category are shown in Table B-2.

Table B-2. Use Case Counts by Category and Goal

Category and Goal	Count
Utility planning	20
Lower the cost of generation capacity	7
Ensure system reliability	5
Bill customers equitably	4
Lower the cost of distribution infrastructure	3
Lower the cost of transmission infrastructure	1
Utility operations	11
Ensure system reliability	8
Decrease resource procurement costs	2
Lower the cost of generation capacity	1
R&D	18
Develop new products or services	11
Research	4
Sell existing products or services	3
Public policy analysis	4
Lower cost or environmental impact of energy consumption	4
Community and business financial decisions	8
Sell existing products or services	4
Lower cost or environmental impact of energy consumption	3
Decrease impact from utility outages	1
Total	61

Appendix C. Benefit-Cost Analysis Tests

Table C-1. California and National Standard Practice Manual Test Costs and Benefits[46]

Source	Benefit-Cost Test	Benefits	Costs
California Standard Practice Manual	Participant Cost Test	*Benefits and costs from the perspective of the customer installing the measure*	
		• Incentive payments • Bill savings • Applicable tax credits or incentives	• Incremental equipment costs • Incremental installation costs
	Program Administrator Cost Test (also called the Utility Cost Test)	*Perspective of utility, government agency or third-party implementing program*	
		• Energy-related costs avoided by the utility • Capacity-related costs avoided by the utility, including generation, transmission and distribution	• Program overhead costs • Utility/program administrator incentive costs • Utility/program administrator installation costs
	Ratepayer Impact Test	*Impact of efficiency measure on nonparticipating ratepayers overall*	
		• Energy-related costs avoided by the utility • Capacity-related costs avoided by the utility, including generation, transmission, and distribution	• Program overhead costs • Utility/program administrator incentive costs • Utility/program administrator installation costs • Lost revenues to utility because of reduced energy bills
	Societal Test	*Benefits and costs to all in the utility service territory, state, or nation as a whole*	
		• Energy-related costs avoided by the utility • Capacity-related costs avoided by the utility, including generation, transmission, and distribution • Additional resource savings • Nonmonetized benefits (e.g., health)	• Program overhead costs • Program installation costs • Incremental measure costs (whether paid by utility or customer)
	Total Resource Test	*Benefits and costs from the perspective of all utility customers (participants and nonparticipants) in the utility service territory*	
		• Energy-related costs avoided by the utility • Capacity-related costs avoided by the utility, including generation, transmission and distribution • Additional resource savings • Monetized environmental and nonenergy benefits • Applicable tax credits	• Program overhead costs • Program installation costs • Incremental measure costs (whether paid by utility or customer)
National Standard Practice Manual	Resource Value Test	*Benefits and costs from the perspective of the regulator or decision-maker*	
		This test is designed to represent a regulatory perspective that reflects the objective of providing customers with safe, reliable, low-cost energy services while meeting a jurisdiction's other applicable policy goals and objectives. The Resource Value Test may be the same as one of the other cost tests, or may be unique based on the jurisdiction's applicable policy goals.	

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[46] Adapted from *National Action Plan for Energy Efficiency* (2008) and Woolf et al. (2017).

Appendix D. Identified Input Data Sources

The status of the model input data for high-, medium-, and low-priority inputs is described in this appendix through corresponding tables. The last column of each table lists the identified data sources.

Table D-1. High-Priority Input Data for Commercial Buildings

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Building Component Replacement Rate	Building Stock	Characteristic	HVAC and Refrigeration (HVAC&R)	• Service Life and Maintenance Cost Database (ASHRAE RP1237-TRP) • Life Cycle Costing for Facilities (Dell'Isola and Kirk 2003) • Life Cycle Costing for Design Professionals (Kirk and Dell'Isola 1995) • Wisconsin Focus on Energy 2018 Technical Reference Manual (Cadmus 2018) • 2015 ASHRAE Handbook HVAC Applications (ASHRAE 2015)
Energy Code Compliance Levels	Building Stock	Characteristic	HVAC&R	• Status of State Energy Code Adoption (DOE Energy Efficiency and Renewable Energy 2018) • Building Code Status Maps (BCAP 2019) • Energy Code Field Studies (DOE Energy Efficiency and Renewable Energy 2018) • State and Local Policy Database: Commercial Code (ACEEE 2017)
Weather Data	External Loads	Environmental	HVAC&R	• AMY: purchased and/or constructed from National Weather Service and National Solar Radiation Database • Bianchi and Smith (2019)
Computing: Core Data Center Equipment Power Density	Internal Loads	Characteristic	Computing	• Commercial Buildings Energy Consumption Survey, CBECS (U.S. EIA 2012) • ENERGY STAR®: Data Center Equipment (U.S. EPA 2018a) • Xu and Greenberg (2007) • Koomey (2011)
Computing: IT Closet Equipment Power Density	Internal Loads	Characteristic	Computing	
Internal Mass: Physical Property	Internal Loads	Characteristic	HVAC&R	• Effects of Furniture and Contents on Peak Cooling Load (Raftery et al. 2014) • Minimum Design Loads for Buildings and Other Structures (ASCE 2013) • Floor Live Loads for Office Buildings (Andam 1986) • Techniques for the survey and evaluation of live floor loads and fire loads in modern office buildings (Bryson and Gross 1968) • Survey Results for Fire Loads and Live Loads in Office Buildings (Culver 1976)

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Occupancy: Schedule	Internal Loads	Schedule	Indirectly affects multiple end uses	• ASHRAE Standard 90.1 (ANSI/ASHRAE/IES 2016) • Office Plug Load Field Monitoring (Ecos 2011a) • Research Findings on Consumer and Office Electronics (Ecos 2011b) • Google maps operating hours
Office Equipment: Schedule	Internal Loads	Schedule	Office equipment	
Other Equipment: Power density	Internal Loads	Characteristic	Interior equipment	• CBECS 2012 (U.S. EIA 2012)
Other Equipment: Schedule	Internal Loads	Schedule	Interior equipment	
Aspect Ratio	Geometry	Characteristic	HVAC&R	• Microsoft Building Footprint Database (Microsoft 2019) • National Land Cover Database (Multi-Resolution Land Characteristics Consortium 2011) • OpenStreetMap (OpenStreetMap Foundation 2019)
Orientation	Geometry	Characteristic	HVAC&R	
Fenestration Orientation	Geometry	Characteristic	HVAC&R	• CBECS 2012 (U.S. EIA 2012)
Shading	Geometry	Characteristic	HVAC&R	• Light Detection and Ranging (LIDAR) measurements • Open City Model (BuildingZero.Org 2019)
Decentralized: Packaged Unitary System: Constant Air Volume: Economizer: Control	HVAC&R	Characteristic	HVAC&R	• CBECS 2012 (U.S. EIA 2012) • ASHRAE Standard 90.1 (ANSI/ASHRAE/IES 2016)
Decentralized: Packaged Unitary System: Variable Air Volume: Economizer: Control	HVAC&R	Characteristic	HVAC&R	
Operation Schedule	HVAC&R	Characteristic	HVAC&R	• ASHRAE Standard 90.1 (ANSI/ASHRAE/IES 2016) • California Commercial End-Use Survey (California Energy Commission 2006) • CBECS 2012 (U.S. EIA 2012)

Table D-2. Medium-Priority Input Data for Commercial Buildings

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Illuminated Façade Area	Geometry	Characteristic	Exterior lighting	• Lighting standards/reports (FEMP 2010; Myer 2011) • Manufacturer report (ZUMTOBEL 2019)
Cooking: Kitchen Equipment Power Density	Internal Loads	Characteristic	Cooking	California Commercial End-Use Survey (California Energy Commission 2006)
Cooking: Kitchen Equipment Schedule	Internal Loads	Schedule	Cooking	
Walk-in Freezer: Capacity	HVAC&R	Characteristic	Refrigeration	Commercial Refrigeration Loadshape Project (Cadmus 2015)
Walk-in Freezer: Efficiency	HVAC&R	Characteristic	Refrigeration	
Walk-in Freezer: Part Load Performance	HVAC&R	Characteristic	Refrigeration	
Self-contained Display: Capacity	HVAC&R	Characteristic	Refrigeration	
Self-contained Display: Efficiency	HVAC&R	Characteristic	Refrigeration	
Self-contained Display: Part Load Performance	HVAC&R	Characteristic	Refrigeration	

Table D-3. Low-Priority Input Data for Commercial Buildings

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Fault	HVAC&R	Characteristic	HVAC&R	OpenStudio Fault Models Inputs (NREL 2017)
Control Type (cycle-tank/ modulate-tankless)	Service Water Heating	Characteristic	Service water heating	• Advanced Energy Design Guide (ASHRAE 2011) • ENERGY STAR: Commercial Water Heaters (U.S. EPA 2018b) • Appliance and Equipment Standards (DOE Energy Efficiency and Renewable Energy 2019)
Heater Minimum Capacity (for modulating control type)	Service Water Heating	Characteristic	Service water heating	Turndown ratio: • Bosch Green Star, residential (Bosch 2015): 23%–31% • Emerson Swan (Emerson 2019): turndown ratio 20%
Part Load Factor Curve	Service Water Heating	Characteristic	Service water heating	• Dynamic efficiency (Raypak 2019)
Off Cycle Loss Fraction to Thermal Zone	Service Water Heating	Characteristic	Service water heating	• Standby losses (Raypak 2019)
On Cycle Loss Fraction to Thermal Zone	Service Water Heating	Characteristic	Service water heating	
Location of Water Heater	Service Water Heating	Characteristic	Service water heating	• Advanced Energy Design Guide (ASHRAE 2011)

Table D-4. High-Priority Input Data for Residential Buildings

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Occupant Archetype Diversity/ Overall Usage	Internal load	Schedule	Indirectly affects multiple end uses	• AMI Data • American Time Use Survey (U.S. Department of Labor 2019) see Appendix F • Load Profile Generator (Pflugradt 2019) • Arnold et al. (2017)
Occupant Schedule	Internal load	Schedule	Indirectly affects multiple end uses	• American Time Use Survey (U.S. Department of Labor 2019) • AMI Data • Florida Solar Energy Center (FSEC) • Pecan Street (2019) • Residential Building Stock Assessment Metering (RBSAM) (NEEA 2014)
Occupant Number	Internal load	Schedule	Indirectly affects multiple end uses	• U.S. Census Bureau (2017) • RBSA (NEEA 2019b, 2019c)
Vacancy Rates (longer term)	Building Stock	Characteristic	Heating and cooling	• Housing vacancy survey (U.S. Census Bureau 2019a) • Housing vacancies and homeownership (U.S. Census Bureau 2019b)
Weather Data	Weather	Environmental	HVAC&R	• AMY: purchased and/or constructed from National Weather Service and National Solar Radiation Database • Bianchi and Smith (2019)
Well Pump Schedules	Miscellaneous electric loads (MELs)/ miscellaneous gas loads (MGLs)	Schedule	MELs/MGLs	• RBSAM (NEEA 2014): 12 well pumps • Pecan Street (2019): 19 well pumps • Parker et al. (2016) (FSEC): 4 well pumps. • (Aquacraft, Inc. 2008)
Pool Pump Schedules	MELs/MGLs	Characteristic	MELs/MGLs	• Building America House Simulation Protocols (Wilson et al. 2014) • Pecan Street (2019): 28 pool pumps • FSEC: 22 pools • Pool pump program (ADM Associates 2002) • Pool pump demand response (Design & Engineering Services 2008)
Pool Heater Schedule	MELs/MGLs	Characteristic	MELs/MGLs	• Pecan Street: 7 pools • Parker et al. (2016): 22 houses with pools • Building America House Simulation Protocols (Wilson et al. 2014) • California Residential Appliance Saturation Survey (RASS) has some usage distribution information for California.

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Plug Load Schedule Diversity	MELs/MGLs	Schedule	MELs/MGLs	• RBSAM (NEEA 2014) (104 residences) • Pecan Street (approximately 226 residences with some plug loads monitored) • FSEC (56 residences) • Krantz-Kent (2018) • Madrigal (2018). • Nielson (2018) • American Time Use Survey (U.S. Department of Labor 2019) (indirect) • MA Baseline Load Study
Plug Load Energy Usage	MELs/MGLs	Schedule	MELs/MGLs	• RECS (U.S. EIA 2015) • Pecan Street • FSEC • RBSAM • RASS
Hot Tub Spa Schedule	MELs/MGLs	Schedule	MELs/MGLs	• Pecan Street (2019) has 42 hot tub spa data • FSEC has 4 hot tub spa data • RBSAM (NEEA 2014) has 7 hot tub spa data • RASS has usage distribution information for California
Lighting Schedule Diversity	MELs/MGLs	Schedule	MELs/MGLs	• RBSAM (NEEA 2014) • FSEC • Pecan Street • American Time Use Survey (U.S. Department of Labor 2019) (indirect) • MA Baseline Load Study (aggregate) • RASS
Dishwasher Schedule	Internal Loads	Schedule	Dishwasher	• Pecan Street (2019) has 305 dishwashers' data • RBSAM (NEEA 2014): 58 • FSEC • RASS has frequency of use (California)
Clothes Washer Schedule	Internal Loads	Schedule	Clothes Washer	• Pecan Street: 239 • RBSAM (NEEA 2014): 94 • FSEC • 1990 California Study • RASS
Clothes Dryer Schedule	Internal Loads	Schedule	Clothes Dryer	• Pecan Street (2019): 355 electric dryers, and electric info for 103 gas dryers • RBSAM (NEEA 2014): 96 electric, electric info for 3 gas dryers • RASS: frequency of use (California)

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Range Vent Flow Rate	HVAC	Characteristic	MELs/MGLs	• Singer, Delp, and Apte (2010)
Range Vent Schedule Diversity	HVAC	Schedule	MELs/MGLs	• Pecan Street (2019): 47 homes with range vent energy consumption
Natural Ventilation Schedule and Diversity (weekly, yearly)	HVAC	Schedule	Cooling	• Piazza et al. (2007)
Air Source Heat Pump Minimum Temperature	HVAC	Characteristic	Heating and Cooling	• R. K. Johnson (2013) • NEEP report (2019) • Maguire et al. (2014)
Heating Set Point (including seasonality)	HVAC	Schedule	Heating	• Ecobee data (2019) (over 44,000 homes) • ENERGY STAR smart thermostat data (U.S. EPA 2018c) • RECS (U.S. EIA 2015) • RASS for California distribution (2009).
Dehumidifier	HVAC	Schedule	Heating and Cooling	• Mattison and Korn (2012) • NMR Group and Nexant (2014) • RASS
Room AC Schedule, Seasonality, Partial Cond.	HVAC	Characteristic	Cooling	• Pecan Street (2019): 5 window air conditioners • FSEC: 4 window air conditioners (2 are in garages) • RBSAM (NEEA 2014): 2 window air conditioners • AMI Data
Cooling Set Point (including seasonality)	HVAC	Schedule	Cooling	• Ecobee data (2019) • ENERGY STAR smart thermostat data (U.S. EPA 2018c) • RECS (U.S. EIA 2015) for both set points and air conditioner control type • RASS for California distribution
Bath Vent Flow Rate	HVAC	Characteristic	MELs/MGLs	• Wallender (2018) • Holladay (2014)
Bath Vent Schedule	HVAC	Schedule	MELs/MGLs	• Pecan Street (2019)
Water Heater Schedule	Hot Water	Schedule	Water heating	• Vitter and Webber (2018) • Xue et al. (2017) • Pecan Street (2019) for electric water heaters (124 water heaters)
Massing (wall/structure and internal)	Geometry	Characteristic	Heating and Cooling	• Ecobee (2019) • Raftery et al. (2014)

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Water Heater Type (esp. heat pump water heater)	Hot Water	Characteristic	Water Heating	• Webb (2018) • ENERGY STAR shipment report (U.S. EPA 2014) • Butzbaugh et al. (2017) • RBSA (NEEA 2019b, 2019c) • Pecan Street (2019) • RASS

Table D-5. Medium-Priority Input Data for Residential Buildings

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Vacation Schedule Diversity	Building Stock	Schedule	Indirectly affects multiple end uses	• McCarthy (2018) • Project: Time Off (2018) • Pecan Street
Heat Pump Heat Source (air, ground, etc.)	HVAC	Characteristic	Heating and Cooling	• National Ground Source Heat Pump Association • RBSA (NEEA 2019b, 2019c)
Boiler AFUE	HVAC	Characteristic	Heating	• RBSA (NEEA 2019b, 2019c)
Window Composition	Envelope	Characteristic	Heating and Cooling	• RECS (U.S. EIA 2015) • Bickel et al. (2013) • Ducker Worldwide sales data • RBSA (NEEA 2019b, 2019c)
AC SEER Diversity	HVAC	Characteristic	Cooling	• Rulemaking technical support documents • RBSA (NEEA 2019b, 2019c) • Austin audit data (City of Austin, Texas 2019)
Cooling Diversity (e.g. evaporative cooler, whole house fan)	HVAC	Characteristic	Cooling	• RECS 2015 and RECS 2009 (U.S. EIA 2015) • RECS 2015 (U.S. EIA 2015)
Water Heater Set Point Temperature	Hot Water	Characteristic	Water Heating	• NREL hot water draw data set
Water Heater Location	Hot Water	Characteristic	Water Heating	• RECS (U.S. EIA 2015) • RBSA (NEEA 2019b, 2019c) • ADM Associates (2016)
Water Heater Energy Factor	Hot Water	Characteristic	Water Heating	• Rulemaking technical support documents (U.S. DOE 2019)
Window Heat/Cool Shade Multiplier	Envelope	Characteristic	Heating and Cooling	• Bickel et al. (2013)
WWR each side (PNW only)	Geometry	Characteristic	Heating and Cooling	• RBSA (NEEA 2019b, 2019c)
Mechanical Vent Distribution	Envelope	Characteristic	Heating and Cooling	• Building America Field Data Repository (Merket 2014) • RBSA (NEEA 2019b, 2019c)

Table D-6. Low-Priority Input Data for Residential Buildings

Input	Category	Input Type	End Uses Affected	Data Source(s) Identified
Foundation Type	Envelope	Characteristic	Heating and Cooling	• RECS 2009, RECS 2015 (U.S. EIA 2015) • RBSA (NEEA 2019b, 2019c)
ACH50 Infiltration for Multifamily	Envelope	Characteristic	Heating and Cooling	• Building America Field Data Repository (Merket 2014), RBSA (NEEA 2019b, 2019c) • LBNL Residential Diagnostics Database (http://resdb.lbl.gov)
Refrigerator Efficiency Sensitivity to Indoor Temperature	Internal Loads	Characteristic	Refrigerator	• RBSAM (NEEA 2014)
Holiday Lighting	Internal Loads	Characteristic	Interior Lights	• Williford (2010) • Johnson (2004) • Nelson and Berrisford (2010) • Parker (2017) • Navigant (2008) • U.S. EPA ENERGY STAR decorative string lights • Navigant (2017) • Efficiency Maine (2007) • Pecan Street (2019)
Housing Density/Shading	Building Stock	Characteristic	Heating and Cooling	• National Land Cover Database (Multi-Resolution Land Characteristics Consortium 2011) • LIDAR data

Appendix E. Calibration Data

Table E-1. Calibration Data Source Summary to Date[47]

	Sector	Location	Sample Size	Frequency	Length of Data	Year(s) Collected
Submetered						
Home Energy Metering Study	Res	Pacific Northwest	400	1 minute	3–5 years	Live
Commercial Energy Metering Study	Com	Pacific Northwest	100	1 minute	3–5 years	Live
Clarkson University	Res	New York	12 apartments	1 minute	1 year+	Live
End-Use Load and Consumer Assessment Program	Com, Res	Pacific Northwest	79 Com, 344 Res	Hourly	3 year	1987–1989
Florida Solar Energy Center (FSEC) Phased Deep Retrofit Project	Res	Florida	56	1 minute	3 years	2012–2016
Pecan Street	Res	Texas	1k	1 minute	2 year+	Live
Powerblade	Res	Colorado	20	1 second	1 year+	Fall 2019
Powerblade	Res	Colorado	8	1 minute	1 year+	Live
Residential Building Stock Assessment Metering (RBSAM)	Res	Pacific Northwest	101	5 minutes	1 year +	Live
Residential Energy Disaggregation Data set (REDD)	Res	Massachusetts	6	1–3 seconds	Weeks	2011
Southern Company	Res	Southeast	62	1 minute	< 1 year to date	Live
Other End-Use Time-series						
ecobee	Res	Various (non-energy data)	95k	5 minute	1 year+	2015–2018
Utility AMI						
Commonwealth Edison	Com, Res	Illinois	3.8 million	30 minutes	1 year	Live

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[47] For AMI and whole-building time-series data, blank cells indicate data negotiations that are in progress, so full details of the data sets are not yet known. For load research data, the sample size column is generally irrelevant, as the profiles are representative for an entire sector of a utility territory. Additionally, many of the load research data rows are blank because we have recently acquired large amounts of load research data and are still assessing the time extent and time resolution of the data. In general, most load research data will be at least at hourly resolution over a full year.

	Sector	Location	Sample Size	Frequency	Length of Data	Year(s) Collected
CPS Energy		San Antonio, Texas	Negotiations in progress			
Electric Power Board of Chattanooga	Com, Res	Chattanooga, Tennessee	With metadata	15 minutes	1 year+	2015 or 2018
Fort Collins Utilities	Com, Res	Fort Collins, Colorado	66k Res 8k Com With metadata	15 minutes	1 year+	Live
Indianapolis Power & Light	Com, Res	Indiana		15 minutes		Live
Other Whole-Building Time-series Data						
Adams Schools	Com	Colorado	20	1 minute	1 year +	Live
Aurora Schools	Com	Colorado	50	1 minute	1 year +	Live
Boulder Valley Schools	Com	Colorado	Negotiations in progress			
Building Data Genome	Com, Res	Various	1360	Hourly	1 year+	2010–2017
Energy Toolbase	Com	Various	50–100	15 minutes	1 year	Varies
EnerNOC	Com	Various	100	5 minutes		
JeffCo Schools	Com	Colorado	150	1 minute	1 year+	Live
MA Load Shape	Com	Massachusetts	87	Hourly (Aggregate)	3 year	2014–2016
New York State Energy Research and Development Authority (NYSERDA) Real Time Energy Management Program	Com	New York	Negotiations in progress			
OpenEI	Com	Various	11	15 minutes	1 year	2010
Sagewell	Com, Res	New England	20k Res, 1.5k Com	15 minutes	2 year	
UC Berkeley	Com	California	118	Hourly	1 year	Live
Vermont Energy Investment Corporation (VEIC)	Com, Res	Vermont		15 minutes		
Load Research Data						
ADM/ California Energy Commission	Com, Res	California	NA	15 minutes	1 year	
Ameren	Com, Res	Missouri	64	Hourly	2 year	2016–2018
Austin Energy	Com, Res	Texas	Entire Territory by Building Type	Daily (Aggregate)	1.5 year	2018–2019

	Sector	Location	Sample Size	Frequency	Length of Data	Year(s) Collected
Baltimore Gas & Electric	Res	Maryland				
Bangor Hydro-Electric	Res	Maine	Modeled			
Boston Edison	Res	Massachusetts				
Central Hudson Electric	Res	New York	Modeled			
Central Maine Power	Res	Maine	Modeled			
CIPS CILCO and IP (Ameren)	Res	Illinois				
Columbus Southern Power Company	Res	Ohio				
Commonwealth Edison	Res	Illinois				
Consolidated Edison	Res	New York	Modeled			
Dayton Power and Light	Res	Ohio				
Delmarva Power and Light	Res	Delaware, Maryland				
Duke Cinergy	Res	Ohio, Illinois, Kentucky				
Duquesne Lighting Company	Res	Pennsylvania				
Electric Reliability Council of Texas	Com, Res	Texas	NA	15 minutes	1 year	
Illinois Technical Reference Manual	Com	Illinois	1k	Hourly	1 year	2010–2017
MA Load Shape	Com, Res	Massachusetts	NA			
Nantucket Electric Company	Res	Massachusetts				
New Hampshire Electric Cooperative	Res	New Hampshire				
Niagara Mohawk (National Grid)	Com, Res	New York				
Ohio Power Company	Res	Ohio				
Orange and Rockland Utilities	Res	New Jersey, New York				
Pacific Gas and Electric	Res	California				
PacifiCorp	Com, Res	Western US (California, Idaho, Oregon, Utah,	Modeled End Use by Building Type	Hourly	1 year	2017

	Sector	Location	Sample Size	Frequency	Length of Data	Year(s) Collected
		Washington, Wyoming)				
Potomac Energy Power Company (Pepco)	Res	Maryland, District of Columbia				
Public Service Electric and Gas	Res	New Jersey, New York				
Public Service of New Hampshire	Res	New Hampshire	Modeled			
Rochester Gas and Electric	Res	New York	Modeled			
Rockland Electric Company	Res	New Jersey				
San Diego Gas and Electric	Res	California				
UGI Corporation	Res	Pennsylvania				
United Illuminating	Res	Connecticut				
Unitil / UES New Hampshire	Res	New Hampshire, Massachusetts				
Vermont Energy Investment Corporation (VEIC)	Com, Res	Vermont				
Western Massachusetts Electric Company	Res	Massachusetts	Modeled			
Utility Sales						
EIA Form 861	Res, Com	Every utility in the United States	N/A	Annual	28 years	1990–2018
Xcel	Com	Colorado, New Mexico, Texas, Minnesota, Wisconsin, North Dakota, South Dakota, Michigan	~500,000	Monthly	1 year	2018

Appendix F. Development of Occupancy Models

A major identified input data gap for both commercial and residential buildings is occupant schedules and behaviors (i.e., *schedule inputs)*. Significant work is underway to generate supporting models for both ComStock and ResStock, to augment existing approaches.

Commercial Occupancy

Occupant presence and movement, as well as their interactions with building systems, have significant influence on energy use in buildings and occupant comfort and well-being. The DOE reference building models use simplified homogeneous schedules of occupants, lighting, and plug loads, which do not capture the diversity and stochastics of occupant activities and behavior in buildings, leading to potential underestimate or overestimate of real energy use in buildings by a factor of up to three. For commercial buildings, we have created an “occupancy simulator” to generate occupant schedules in buildings and occupant models of lighting and plug loads to enhance the occupant data in the DOE reference building models, which will be used to simulate the occupant-driven end-use loads. We will combine a range of data sources across building types to improve existing schedules in ComStock. Technical details of modeling occupants will be described in a separate publication.

Residential Occupancy

For residential occupancy, we are developing a stochastic occupancy model. This model will use a Markov Chain to predict 15-minute interval occupancy of a home based on the American Time Use Survey. We cluster American Time Use Survey responses by demographic characteristics (e.g., age, gender, employment) and identify major trends. The occupancy activities from the American Time Use Survey are then used to associate appliance schedules and behavioral inputs to ResStock. The National Household Travel Survey will also inform some of the regional differences in the model. The stochastic occupancy model will be used to generate a suite of *schedule inputs* that can be varied region-to-region based upon differing demographic characteristics. This work will also have wide-ranging applications for any building energy modeling that requires additional temporal detail in outputs.

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