Building Energy Modeling Enhancements to Identify Least-Cost Pathways to Net-Zero Carbon Homes

Preprint

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National Renewable Energy Laboratory

Presented at the 2022 ACEEE Summer Study on Energy Efficiency in Buildings
Pacific Grove, California
August 21–26, 2022

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5500-83205
August 2022

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Suggested Citation
Polly, Ben, Jeff Maguire, Scott Horowitz, Eric Wilson, Rohit Chintala, David Roberts, Shanti Pless, and Yueyue Zhou. 2022. *Building Energy Modeling Enhancements to Identify Least-Cost Pathways to Net-Zero Carbon Homes: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-83205. https://www.nrel.gov/docs/fy22osti/83205.pdf.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5500-83205
August 2022

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NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office.

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Building Energy Modeling Enhancements to Identify Least-Cost Pathways to Net-Zero Carbon Homes

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ABSTRACT

Residential grid-interactive efficient buildings (GEBs) can utilize high levels of energy efficiency and demand flexibility to deliver value to occupants, the grid, and society. However, without the ability to analyze, design, and optimize residential GEBs there is a risk that homes will not realize their full potential value as efficient and dynamic resources, which could ultimately lead to higher than necessary energy costs for U.S. households and lower realization of potential energy efficiency and demand flexibility benefits such as increased convenience/automation, thermal comfort, durability, indoor air quality, resilience, and greenhouse gas reductions.

In 2018, the National Renewable Energy Laboratory's (NREL's) Residential Modeling Team developed a vision for an open-source Residential GEB Analytics Platform built within DOE's EnergyPlus™ and OpenStudio® modeling environment that would enable the design and optimization of residential GEBs, including the identification of least-cost pathways to highly energy-efficient and energy-flexible homes (e.g., net-zero carbon homes). We created a detailed workplan for the development of new and enhanced residential GEB component-level models for EnergyPlus and OpenStudio needed to progress toward the vision for the analytics platform while delivering near-term benefits to industry. This paper (1) presents the vision for the platform, summarizing the workplan for residential GEB modeling enhancements; (2) highlights significant advancements that have been achieved between 2018 and 2022, including stochastic residential occupancy modeling, hourly emissions calculations, flexible water heater modeling, detailed lithium-ion stationary battery modeling, and realistic residential HVAC modeling; and (3) outlines ongoing efforts and next steps toward the full vision for the platform.

Introduction

Traditionally, homes have had limited capability to dynamically shift, reduce, and flex their electric loads. However, with more "smart" and connected devices being installed in homes than ever before, and increasing prevalence of physical distributed energy resources, there is a growing need and opportunity for homes to respond to grid conditions and signals in a way that provides new value to homeowners, the utility system, and the country.[1]

As U.S. electric utilities increase the amount of variable renewable generation in their systems in response to growth, rapidly declining prices and aggressive decarbonization goals, the need for fast-response resources and energy storage is increasing. Grid-interactive efficient buildings (GEBs) "combine energy efficiency and demand flexibility with smart technologies and communications to inexpensively deliver greater affordability, comfort, productivity and

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[1] https://www.energy.gov/eere/buildings/articles/buildings-and-grid-101-why-does-it-matter-energy-efficiency

high performance to America's homes and commercial buildings" (Satchwell et al. 2021). Residential GEBs can act as fast-responding resources for the grid through responsive and flexible loads. For example, GEBs can be used to help mitigate peak loads during the summer or during increasingly common winter peaks as buildings electrify, thereby allowing faster and deeper penetration of renewables on the grid. Without the ability to analyze, design, and optimize residential GEBs there is a risk that homes will not realize their full potential as resources to the grid, which could ultimately lead to higher than necessary energy costs for U.S. households and slow decarbonization of the grid.

Building energy modeling (BEM) using personal computers or high-performance computing has its roots in the 1960s (Brackney et al. 2018, Judkoff et al. 2008/1983). Among other things, modern BEM is used to explore design options for new construction and retrofits to assess energy savings and cost-effectiveness. More recently, techniques that combine BEM with automated optimization have emerged, replacing the trial-and-error approach to using BEM to determine optimal design (Shi et al. 2016). For example, tools such as NREL's Building Energy Optimization software (BEopt™) can find minimum-cost residential building designs at different target energy savings levels by combining BEM and optimization. However, as seen in Figure 1, there is additional complexity when optimizing designs for GEBs.

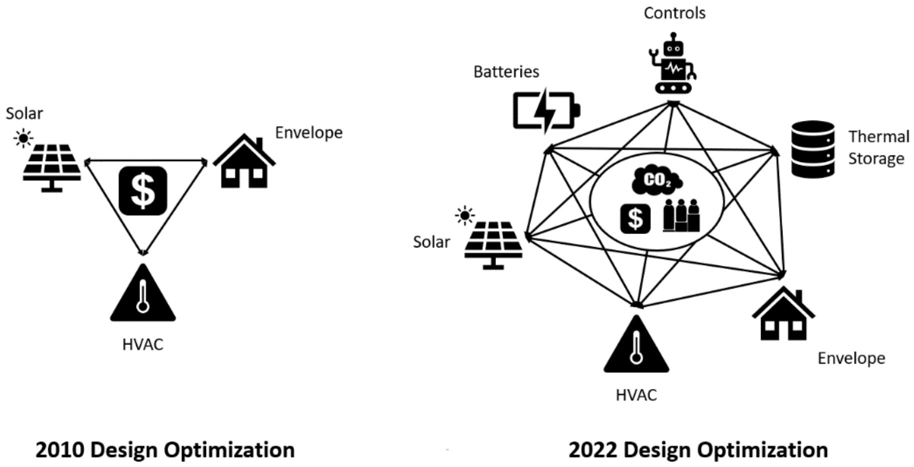

Figure 1. The addition of battery and thermal storage and associated control possibilities, along with additional design objectives such as carbon and equity, dramatically increases the complexity of the optimization problem. *All figures by NREL.*

There is a need for open-source residential GEB analytics that can be applied to individual homes where on-site photovoltaics (PV) and behind-the-meter battery storage are increasingly considered for reducing energy costs and providing resilience in the event of grid outages. Depending on utility rate structures and PV/battery interconnection agreements, GEBs can help increase the size of cost-effective PV systems and reduce the cost of battery systems needed to manage net loads and provide specific levels of backup power. Without the ability to analyze, design, and optimize residential GEBs there is a risk that industry will arrive at PV and battery solutions that ignore potentially cost-effective building efficiency and load flexibility strategies, which may have additional benefits such as reduced overall energy usage and increased convenience, thermal comfort, durability, indoor air quality, and resilience.

In 2018, the NREL Residential Modeling Team developed a vision for an open-source Residential GEB Analytics Platform built within DOE's EnergyPlus and OpenStudio modeling environment that would enable the design and optimization of residential GEBs, including the identification of least-cost pathways to highly energy-efficient and energy-flexible homes (e.g., net-zero carbon homes). We created a detailed workplan for the development of new and enhanced residential GEB component-level models for EnergyPlus and OpenStudio needed to progress toward the vision for the analytics platform while delivering near-term benefits to industry. This paper (1) presents, for the first time, the vision for the platform, summarizing the workplan for residential GEB modeling enhancements, and (2) highlights significant advancements that have been achieved toward developing the platform between 2018 and 2022.

A Vision for GEB Analytics

Existing Residential Optimization Capabilities

BEopt can be used to find the least-life-cycle cost pathway to increasing levels of source energy savings in residential buildings. The user defines a baseline or reference building design and then selects individual energy efficiency measures from the built-in libraries of BEopt options to consider for cost-performance analysis.

Each measure option (e.g., HVAC system, wall construction, PV) has performance and cost data associated with it. The performance data feed into EnergyPlus input files. The cost data feed into the BEopt life cycle costs analysis, and includes costs related to the technology component, its installation, and its potential replacement during the analysis period (if wear-out events are applicable during the life cycle cost analysis period).

An example BEopt output, called the Path to Zero Net Energy, is shown in Figure 2. Each gray point on the graph represents a different building design that was simulated in EnergyPlus during the optimization. The x axis is the annual average source energy savings of the design versus the reference design (e.g., percent annual average source energy savings of the design relative to a minimum code efficiency reference design). The y axis is the annualized energy-related costs (utility bills + incremental mortgage costs associated with improved efficiency). BEopt uses a sequential search technique to quickly identify points along the optimal pathway rather than running all potential combinations of options. During each iteration, the search algorithm identifies the next incremental building design that delivers additional source energy savings for the least additional cost per unit of savings.

This example demonstrates how BEopt can be used to find optimal combinations of energy efficiency features and PV for increasing levels of source energy savings in residential construction design. BEopt can consider advanced utility rate and PV compensation structures when calculating the utility costs that feed into the life cycle cost analysis, but there are limitations in the time granularity of those rates and the realism/accuracy of BEopt/EnergyPlus electric load modeling to which those rates are applied (e.g., BEopt currently cannot consider minute-by-minute rates, nor does it generate realistic minute-by-minute electric load profiles).

Finally, it is important to understand that source energy savings for BEopt optimizations are currently calculated using national annual average site-to-source energy multipliers (e.g., 3.15 is the default for electricity). Thus, there is no consideration of time-dependent or geographic nature of the electricity generation mix, or the impacts of energy use and savings on the grid, or the expected changes to the grid in the future, or how changes to energy use are best quantified using marginal (as opposed to average) factors.

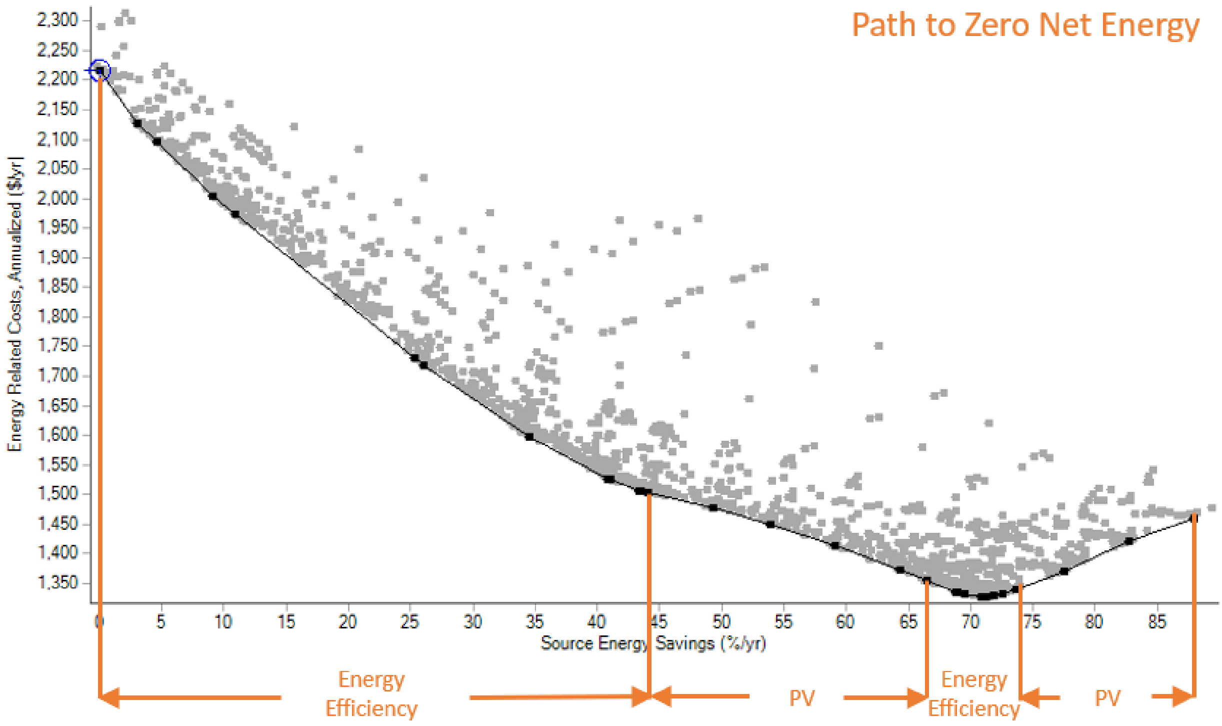

Figure 2. Example BEopt optimization output, circa 2016, for a single-family detached new construction home in Chicago.

The current version of BEopt (version 2.8.0.0), which has not had any substantial updates since 2018, reflects the state of residential optimization capabilities when our research team originally developed the workplan. A new version of BEopt is planned to provide more GEB optimization capabilities, among other things. The following sections describe the vision we laid out in 2018 for residential GEB optimization.

Residential GEB Optimization

The intent of the residential GEB analytics platform[2] is to be a foundational capability that can help guide residential buildings integration science by:

- Identifying least-cost pathways to:
    - Increasing levels of energy savings
    - Increasing levels of demand flexibility and “grid-friendliness” (see Figure 3)
- Developing cost and performance targets for emerging residential GEB technologies, that if met, would make technologies competitive with existing flexible load strategies, battery storage, and on-site PV, from a whole-home integration perspective.

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[2] We referred to the capabilities generically as a “platform” because we envisioned enhancements could occur in various tools and workflows for different residential modeling use cases.

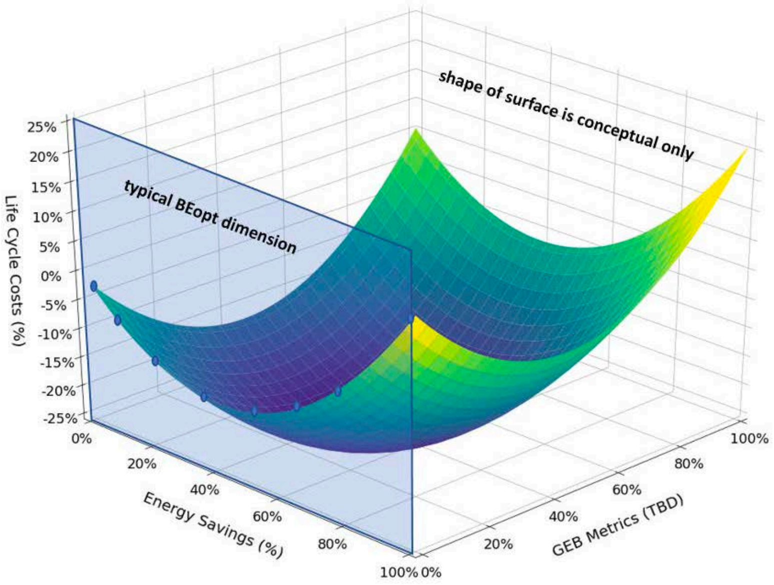

Figure 3. The Residential GEB Analytics Platform could be used to identify least -cost pathways to increasing levels of energy savings, demand flexibility, and "grid-friendliness" (specific metrics to-be-determined; shape of surface is conceptual only to illustrate that there may be cost-saving home designs that deliver improvements in both energy savings and GEB metrics relative to standard practice).

The Residential GEB Analytics Platform is being built within the current generation EnergyPlus and OpenStudio ecosystem to meet near-term residential GEB analysis needs for industry and research but done so with an eye toward the "next generation" OpenStudio and Spawn of Energy Plus ecosystem. For example, we consider the additional value of making component-level model improvements in EnergyPlus's Energy Management System (EMS) such that improvements are more easily ported into the next-generation ecosystem.

As a part of developing the residential GEB analytical platform, NREL is leveraging and further updating existing residential analysis capabilities, including BEopt, URBANopt™, and ResStock™ to address residential GEBs from individual building to community to national scales. For example, residential GEB enhancements made to the foundational OpenStudio-HPXML (OS-HPXML) workflow can be leveraged by URBANopt and ResStock, which are now integrated with OS-HPXML (see Figure 4); a planned update to BEopt to leverage OS-HPXML will likewise enable such capabilities (more on this later).

There are many potential use cases for residential GEB analysis. For this workplan we focused on core residential GEB modeling improvements to EnergyPlus and OpenStudio needed for GEB demand flexibility analysis. This analytics platform addresses residential GEB design and upgrades requiring demand flexibility analysis down to minute timescales. This is a use case where there are existing markets, utility demand-side management programs, utility rate structures, etc., for homeowners to capitalize on GEB opportunities. The workplan could be updated in the future to address additional use cases, including scenarios that require coupling[3] of EnergyPlus and OpenStudio to other analysis platforms such as utility distribution feeder models, bulk power system models, and more.

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[3] This could range from loose coupling to co-simulation.

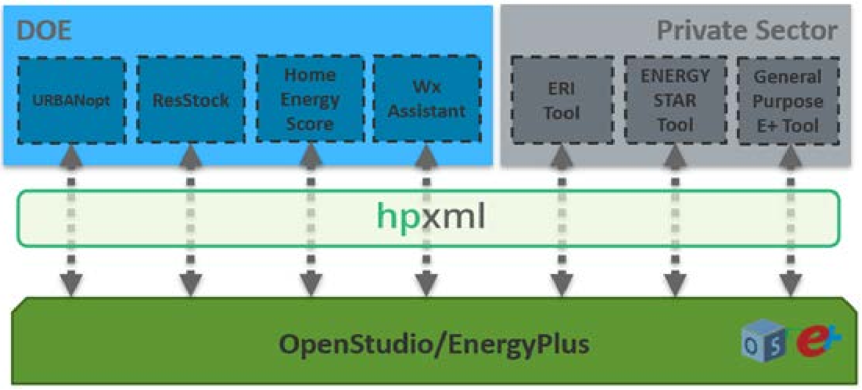

Figure 4. Diagram of OpenStudio-HPXML architecture with potential end user GEB tools.

In terms of scope, it should be noted that this analytical platform is more focused on design tradeoffs between energy efficiency, demand flexibility, PV, and battery storage than optimizing the operation/dispatching of flexible loads and battery storage given a particular building design. It is expected that improvements in GEB metrics can be achieved through passive design strategies and component-level active control strategies. That said, the workplan outlines some potential enhancements for whole-home coordination and control that could help quantify the additional benefits of coordinated dispatching and control in homes. Key future research may include nested optimization approaches, where dispatching and control strategies are optimized for individual building designs within a larger design optimization.

Value to Industry

The residential GEB analytics platform is intended to provide several direct benefits to industry, including: (1) new component-level residential GEB models in EnergyPlus and OpenStudio that can be leveraged by industry software tools, home rating systems, product manufacturers, utilities, and others to properly design and value technologies based on their time of energy use and savings; (2) new whole-building analysis and optimization techniques for residential GEBs that can be adopted by industry to move beyond the annual energy use and savings paradigm; and (3) enhanced modeling input assumptions that provide sufficient fidelity and realism for the modeling of occupancy, appliances, lighting, equipment, and other residential end uses to analyze residential GEBs.

Workplan for Residential GEB Modeling Capabilities

This section summarizes the workplan for residential GEB modeling capabilities and enhancements. Activities are divided into those that focus on the overall residential optimization framework, stochastic modeling and model fidelity/realism, and component-level modeling.

Residential GEB Optimization Framework

Add GEB Metrics Calculations. The first category of residential GEB modeling improvements identified in the workplan is adding residential GEB metrics into the optimization framework.

There are a variety of potential metrics, and ultimately metrics will be selected based on the specific use cases and industry consensus/adoption.

In the workplan we outlined how GEB optimization metrics could involve applying different hourly or sub-hourly weighting factors to energy use and savings to better represent the dynamic energy mix and the impacts of energy consumption and generation on the grid. For example, source energy savings could be calculated using hourly, local electric site-to-source multipliers rather than an annual average multiplier. This would require applying hourly site-to-source multipliers to the hourly output from each OpenStudio/EnergyPlus simulation. At the time, other NREL researchers were in the initial stages of developing hourly site-to-source multipliers and carbon emissions factors, as well as other time sensitive values. These values were to be derived based on the outputs of the NREL Standard Scenarios of future bulk power system electricity grid profiles (Cole et al. 2017). With these types of improvements, we noted that it would be possible to explore how optimal solutions vary considering dynamic electricity generation mix and the impacts of energy consumption and generation relative to the grid.

The workplan also recognized that a variety of other GEB metrics could be relevant for certain use cases and objectives. For example, one metric of interest for certain use cases where aligning loads with on-site renewable generation is important (e.g., designing for backup-power operation/resilience) could be load cover factor (Shah et al. 2020, Torcellini et al. 2020), which is the percentage of the load that is met by on-site renewable energy. This metric is just one example, and others that focus more on the characteristics of the net load could also be explored.

Enhance Modeling Standards to Support Residential GEB Analysis. Approximately 15 years ago, the House Simulation Protocols document was developed out of a need for ensuring accurate, consistent analysis techniques to measure Building America's progress toward its program goals. The document provides guidance to program partners and managers so they can compare energy savings for new construction and retrofit projects. Over the years, the document has seen numerous updates and improvements as the buildings industry and technologies have changed, with its most recent publication in 2014 (Wilson 2014). Portions of the House Simulation Protocols have informed or been incorporated into external, third-party standards and simulation protocols.

Recently, the home energy rating industry has undergone rapid growth and now accounts for a significant percentage of residential building energy analyses performed each year in the United States. The ANSI/RESNET®/ICC 301-2019 "Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index" dictates the assumptions and calculations required for energy simulations used to calculate the Energy Rating Index. This "301 Standard" has evolved into a consensus standard used by many new construction programs – RESNET home energy ratings, utility programs, code compliance (IECC and ASHRAE 90.2), and above-code programs (ENERGY STAR® and Zero Energy Ready Homes).

To better align the Building America program with industry while maintaining accurate modeling capabilities for GEB technologies, NREL originally proposed transforming the House Simulation Protocols into a living, online document that would point to the 301 Standard for core operational assumptions, while including supplemental information or addenda to the 301 Standard where additional modeling guidance is needed. While the 301 Standard primarily includes guidance and assumptions for purposes of calculating annual energy consumption, it is in the process of being updated, in support of RESNET's new CO_2 Index metric, to account for when energy is used and to allow credit for GEB technologies that shift energy use to times with lower grid emissions. Therefore, NREL decided to directly contribute to the development of the 301 Standard through transfer of Building America knowledge to industry in lieu of continued maintenance of the House Simulation Protocols.

Stochastic Modeling of Occupant-Driven Energy Use and Improvements to Model Fidelity/Realism

Existing Capabilities (as of 2018). The EnergyPlus and OpenStudio residential building energy modeling platform was originally developed to primarily estimate the annual energy consumption impacts of different building efficiency technologies (e.g., kWh or thermal savings per year). Therefore, a variety of assumptions were made that limit the realism of hourly and sub-hourly load profile estimates. For example, smoothed or average profiles were generally used that are well suited to representing average occupant behavior across many buildings, but do not capture the full variability of individual occupant behavior and electricity-consuming devices within individual buildings. Also, electrical and mechanical equipment models do not capture the full details of equipment cycling.

This average load paradigm can be contrasted with a stochastic load paradigm that attempts to represent appliance operation for individual households at an appropriate time resolution using stochastic appliance events and cycling. Figure 5 illustrates the difference between the average load (blue lines) and stochastic load (red lines) paradigms. For Figure 5 the stochastic loads are from measured data; as discussed in the remainder of this section, there is the potential to enhance modeling approaches to produce stochastic load profiles.

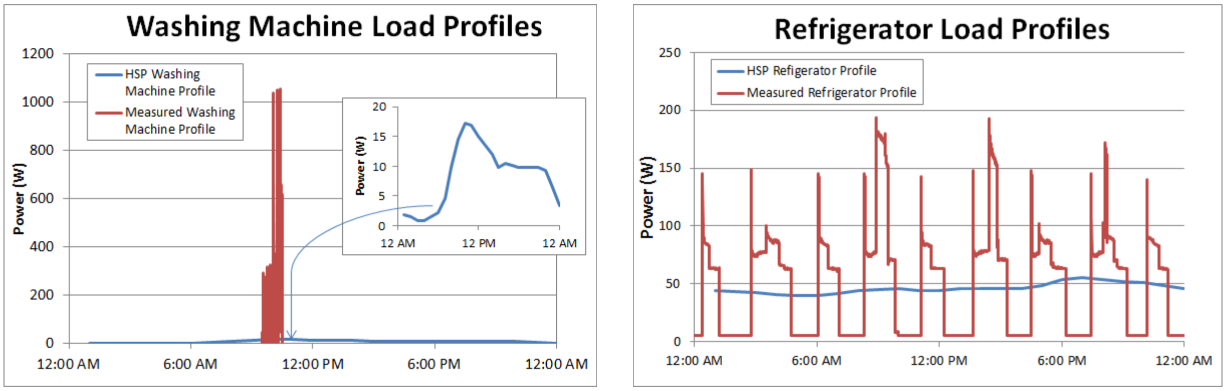

Figure 5. Modeled load profiles using average occupancy assumptions are shown in blue, compared to measured 1-second load data, shown in red. A single washing machine cycle is shown on the left and a refrigerator's daily use profile is shown on the right. In both examples, the total daily energy use is identical between the modeled and measured profiles.

The average load paradigm works well for some use cases. For example, it is sufficient for individual building analysis when electricity is purchased at a constant volumetric rate ($/kWh) and on-site PV generation can be sold to the utility at this constant retail rate. It is also sufficient for developing aggregate electric load profiles that represent thousands of homes, to inform the time-sensitive value of energy efficiency from the utility's perspective or to feed into bulk power system models of electric grids.

However, new residential rate structures (time-of-use, demand charges, real-time pricing) and PV "sell rates" that differ from "buy rates" make it inappropriate to use average occupancy and smooth non-cycling HVAC load modeling. Stochastic modeling of loads is also necessary to rigorously quantify load flexibility and demand response potential (Mims Frick et al. 2019). As of 2018, NREL residential modeling used pre-generated stochastic event schedules for hot water draws, clothes washer power draw, and dishwasher power draw, as well as bathroom, kitchen, and clothes dryer exhaust ventilation. This is because event schedules can be important for modeling the effect of clustered draw events on heat pump water heaters and for modeling the interaction between exhaust ventilation events and natural air infiltration. However, we concluded that there was great potential and need to apply stochastic load modeling more comprehensively in the EnergyPlus/OpenStudio residential modeling platform across many other residential end-use categories.

Recommended Enhancements. In our original workplan, we recommended the following enhancements: (1) enable a residential stochastic load modeling paradigm that captures statistical variability and realism in occupancy behavior, and (2) develop new or improved algorithms to model the operation of electrical power-consuming equipment with more fidelity. Compared to the component-level modeling improvements described in a following section, this is a broad category of modeling enhancements that could impact nearly all aspects of how we model homes. As such, NREL planned a phased approach for these enhancements that included: (1) pre-analysis to quantify potential impact of using versus not using stochastic load modeling and high-fidelity equipment modeling in residential GEB use cases, (2) full literature review and selection of modeling approaches, (3) identification and acquisition of empirical datasets needed to develop and validate models, (4) development and validation of residential stochastic occupant-driven load model and high fidelity equipment modeling, and (5) linkages and/or direct incorporation of models into EnergyPlus/OpenStudio.

Component-Level Modeling

As of 2018, the library of residential OpenStudio measures was almost exclusively focused on energy efficiency measures. While conventional energy efficiency measures affect the shape of load profiles, that is not their primary purpose. The workplan recommended developing additional residential demand flexibility measures for OpenStudio to provide a more comprehensive set of strategies for reducing energy use and improving demand flexibility and "grid friendliness." It was noted that the largest opportunities for load flexibility and load control exist within thermostatically controlled loads (e.g., air conditioning, electrically driven heating, water heating) and schedulable loads (e.g., electric vehicle charging, clothes dryers, and dishwashers), whereas certain end uses are not well-suited for load flexibility (e.g., lighting) (Jin et al. 2017). The following is an outline of potential component-level enhancements that were identified in the workplan for different technology categories. We have not included detailed descriptions here due to space constraints, but are planning to publish documentation/peer-reviewed papers as we make specific enhancements:

- Heating, ventilating, and air conditioning (HVAC)
  - Realistic HVAC equipment operation

    - HVAC technology modeling improvements
        - Connected and “smart” thermostat controls
        - Single-stage air-conditioner direct load control
        - Two-stage and variable-speed air conditioner load control
    - HVAC-coupled thermal storage
        - Modeling specific thermal storage technologies
        - Modeling controls for thermal storage
- Domestic water heating
    - Variable residential water heater set points and controls
    - Stratified tank model for residential electric resistance water heater
    - Allow heat pump water heaters to operate in heat pump-only mode
    - Improvements to the Domestic Hot Water Event Schedule Generator
- Appliances
    - Demand response schedule algorithms for different appliances
    - Realistic demand response participation probability rates
    - OpenStudio measures to deploy demand response
    - Power draw event shapes and clusters for use in stochastic load modeling
- Enclosure
    - Thermal mass and thermal energy storage
    - Dynamic opaque envelope components
    - Dynamic glazing and façades
- Sub-hourly weather and on-site solar photovoltaics
    - Algorithms for down-scaling solar radiation data to sub-hourly time steps
    - Multiple-orientation solar array optimization
- Behind-the-meter electric batteries and electric vehicle charging
    - Enhanced lithium-ion battery model in EnergyPlus
    - Enhanced battery controls in EnergyPlus and coupling with external controllers
    - Electric vehicle charging/controls in EnergyPlus; residential profiles and measures in OpenStudio
- Whole-home coordination and control
    - Energy management system sensors and actuators to facilitate more effective design of supervisory controls
    - Improving support for model-predictive control through co-simulation
    - Hardware-in-the-loop testing of supervisory controller hardware linked to EnergyPlus.

Workplan Progress Update

This section (1) highlights significant advancements that have been achieved between 2018 and 2022, including stochastic residential occupancy modeling, flexible water heater modeling, detailed lithium-ion stationary battery modeling, and realistic residential HVAC modeling, and (2) outlines ongoing efforts and next steps toward the full vision for the platform. A key progress summary is provided in each section using italics.

Progress Update: Residential GEB Optimization Framework

Key progress summary: To incorporate GEB metrics into a residential GEB optimization framework, NREL added the ability to calculate emissions scenarios, based on hourly emissions factors, to the OpenStudio-HPXML workflow, which underpins many residential DOE and industry software tools. Multiple emissions scenarios (e.g., average vs. marginal emissions factors, emissions factors based on alternative future projections, CO_2 vs. CO_2e) can be calculated within a single EnergyPlus simulation. For example, NREL's Cambium (Gagnon et al. 2021) data sets, which provide hourly carbon emissions factors for different regions of the country and incorporate a suite of future projections, can be used directly as the data source for these emissions calculations. Long-run marginal emissions factors from Cambium, for example, have been recently adopted by RESNET as the basis of their new CO_2 Rating Index metric, an alternative to the energy-based index. Cambium's emissions factors provide NREL's best prediction of how the grid will respond, both hourly and geographically, in upcoming years due to energy savings or shifts in energy use.

BEopt, which has long been used to identify cost-optimal building designs along the path to zero net energy, provides a logical user interface to the GEB optimization framework when focused on optimization of individual homes. A new version of BEopt is planned for 2023 that, by connecting to OpenStudio-HPXML, allows end users to optimize building designs that both minimize cost and minimize carbon emissions (instead of source energy). Combined with the addition of new GEB modeling capabilities, this optimization approach ensures that GEB technologies like battery storage or connected HVAC/domestic hot water equipment can be properly valued by society based on *when* energy is used, not necessarily *how much* energy is used.

Progress Update: Stochastic Modeling of Occupant-Driven Energy Use and Improvements to Model Fidelity/Realism

As part of DOE's End-Use Load Profiles (EULP) project, NREL, Lawrence Berkeley National Laboratory (LBNL), and Argonne National Laboratory researchers consulted with a technical advisory group of more than 70 individuals from 50 organizations and determined that a slim majority of identified load profile use cases (35 out of 61) would require or benefit from load profiles that exhibit stochastic occupant-driven loads (Mims Frick et al. 2019).

As described in the recommended enhancements listed above, NREL proceeded with a full literature review to inform modeling approaches, as documented in Chen et al. (2022). As part of the EULP project, NREL identified and acquired empirical data sets needed to develop and validate the new capabilities, including the American Time Use Survey and multiple end-use submetered data sets, as documented in Wilson et al. (2022). We then proceeded by evaluating multiple approaches and ultimately selecting a hybrid approach combining time-inhomogeneous Markov chains and probability-sampling of event durations and magnitudes. *Key progress summary: The approach was validated and implemented as an OpenStudio measure that is now used in ResStock and URBANopt (Chen et al. 2022).* A set of 550,000 pre-generated stochastically generated schedules was published for use with published OpenStudio models as part of the EULP dataset (NREL 2021). Additional enhancements identified as a need in this area include:

1. Integrating the stochastic occupant behavior modeling with thermostat schedule behavior
2. Evaluating and improving the accuracy of household day-to-day variability in the stochastic schedule generator
3. Evaluating and improving the accuracy of appliance power draws during usage events
4. Correlating occupant behavior patterns with household demographic characteristics to facilitate better understanding of the equity and environmental justice impacts
5. Adding electric vehicle charging to occupant behavior modeling
6. Modeling realistic HVAC cycling behavior (discussed in HVAC section below)
7. Integrating minute-resolution profiles for appliance cycling patterns (e.g., heating element in a dryer or dishwasher that turns on and off throughout the usage event; currently all usage events are modeled with a constant power draw)

Progress Update: Component-Level Modeling

Domestic Water Heating. Water heaters are an ideal device for GEB because they have inherent storage capacity, which means that short-term changes in water heater energy consumption generally go unnoticed by the occupants. *Key progress summary: Several new capabilities have been added into our workflows to better represent the GEB capabilities of residential water heaters.*

- A stratified tank model option has been added for all water heaters, which for electric resistance water heaters allows the model to better capture the timing of when the elements turn on, provide more accurate outlet temperature predictions, and capture the dead volume below the lower element.
- To account for times where hot water might run out due to load shifting, a comfort metric has been added to capture how much unmet load there is, allowing users to understand the potential comfort impacts of load shifting.
- Finally, the capability to schedule the water heater setpoint (and for heat pump water heaters, the operating mode and whether the backup electric resistance element can turn on) has been added for all water heaters. This allows users to simulate load shifting, with an increase in setpoint corresponding to a load add request and a reduction load shed. An example of the model in use to shift loads is shown in Figure 6.

Behind-the-Meter Electric Batteries. *Key progress summary: An enhanced model for residential behind-the-meter electric batteries was implemented in EnergyPlus and integrated into OS-HPXML to support the analysis of residential GEBs.*

- The enhanced model can be used to accurately quantify the synergies and trade-offs between employing batteries and implementing other building demand flexibility strategies (Chintala et al. 2020). The battery electrical and capacity degradation models from the System Advisor Model (DiOrio et al. 2015) were added to EnergyPlus. The models capture the two aspects of the lithium-ion nickel manganese cobalt battery that are critical for accurately predicting its behavior: (1) the electrical properties such as voltage, state of charge, depth of discharge, etc. and (2) the rate at which the maximum available capacity degrades with time and operational cycles.
- One of the key aspects of the enhanced battery model not available in the previous versions of EnergyPlus is the ability to capture the impacts of temperature on capacity

degradation. The battery temperature not only affects the rate of capacity degradation over time, but also the instantaneous maximum available capacity.

- Overall, these enhanced capabilities help ensure that within the residential GEB modeling framework, building system demand flexibility technologies are accurately evaluated alongside demand flexibility from stationary batteries.

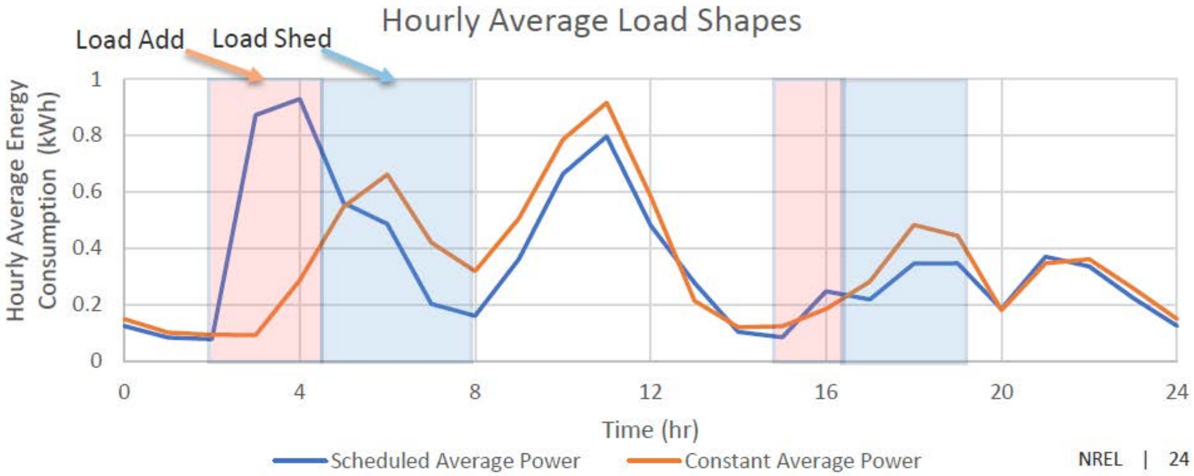

Figure 6. Example of load shifting for residential water heaters. The ability to schedule the setpoint was used to shift loads of a heat pump water heater away from peak pricing periods.

HVAC. The most widely used EnergyPlus approach to modeling thermostat and HVAC systems is to apply thermostats without a deadband, where the HVAC system is modulating to perfectly maintain the building at setpoint. Most real HVAC systems in residential buildings operate on a deadband with more explicit on/off cycles that are not captured by this approach. *Key progress summary: Improvements are currently being made to the way HVAC equipment and thermostats are modeled, including:*

1. Leveraging the deadband thermostat in EnergyPlus to capture HVAC on-off cycles.
2. Adding capabilities to model startup impacts with the deadband thermostat, where the coil is not able to reach full capacity until it has been running continuously for several minutes. This more explicitly captures cycling compared to the typical EnergyPlus approach of adding a coefficient of degradation to the coil model.
3. Adding a custom control logic that leverages a unitary system coil speed level actuator recently added by LBNL to allow more realistic time-based staging of a two-speed coils. The coil first turns on at speed one and monitors the space temperature for several minutes before determining if it needs to ramp up to speed two to meet the loads.
4. Adding more realistic back-up coil staging and control strategies. Multi-stage electric backup coils are common, but EnergyPlus currently has limited capability and flexibility to model their staging and control logic. Enhancements are proposed to allow multi-stage electric coils to be modeled as backup coils with specific control/staging logic.
5. Allowing users to specify a maximum part load ratio during certain hours for variable speed systems to model their response to CTA2045 load shed commands.

Example of Combined Impact of Progress

Figure 7 shows electric load profiles (1-minute time step) predicted for an example summer day using residential OpenStudio/EnergyPlus workflows for a home in Denver, CO with central air conditioning and electric resistance tank storage water heating. The left side of the figure shows a profile predicted using residential modeling capabilities when the workplan was originally developed in 2018, which included smoothed occupancy profiles and equipment/ appliance modeling (while the hot water use is a smooth profile, the water heater still has a realistic element capacity and includes a deadband, leading to spikes in electricity use). The right side of the figure shows a profile predicted for the same home on the same day using several enhanced modeling capabilities developed under the workplan, including stochastic profiles for occupancy, lighting, appliances, and hot water and realistic cycling for air conditioning. Figure 7 demonstrates the degree of realism and granularity that has been added to residential load profile predictions for individual homes, which can be especially important when analyzing individual GEBs and considering metrics related to peak power consumption and fast-responding demand flexibility. For example, the estimated peak electricity consumption per minute (kWh/min) is approximately 1/3 greater for this example day using the enhanced GEB modeling versus the smoothed modeling, largely due to a midday time period when the model predicts the air conditioner is running coincident with certain appliances and water heating consumption spikes. Note that predictions at 1-minute time steps can be aggregated into longer time steps (e.g., 15 minute) depending on the level of granularity that is appropriate for a GEB metric.

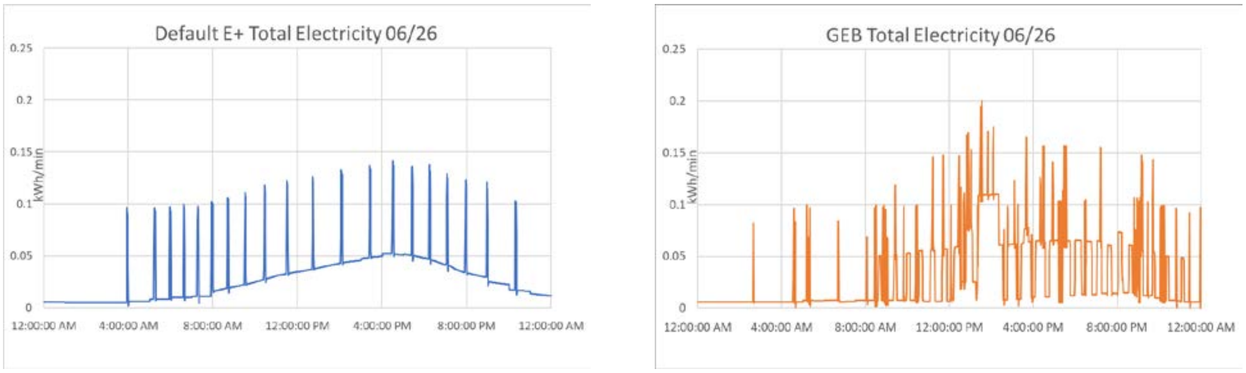

Figure 7. Example daily 1-minute electric load profile predictions for a home in Denver, CO using residential modeling capabilities when workplan was originally developed in 2018 (left, smoothed occupancy profiles) versus using several enhanced capabilities as of 2022 (right, stochastic occupancy profiles for water heating, lighting, appliances, and hot water; realistic cycling for air conditioning).

Conclusions

The ability to model residential GEBs is important for homes to achieve their full potential value as efficient and dynamic resources to the grid. The workplan we developed in 2018 for a residential GEB optimization platform outlined a vision for identifying least cost pathways to energy-efficient and energy-flexible homes (e.g., net-zero carbon homes). We outlined needed enhancements to the optimization framework (e.g., GEB metrics), stochastic/high-fidelity modeling of occupancy and equipment, and component-level modeling. Between 2018 and 2022 we took several majors steps toward achieving the full vision of the platform, including the addition of emissions calculations based on hourly grid factors, the development and implementation of a stochastic modeling approach for occupant-driven loads, and component-level enhancements for water heaters and stationary electric batteries. Ongoing work includes enhancements to residential HVAC GEB modeling, enhanced lithium-ion battery controls, and preparing/designing combined residential GEB workflows for potential integration into tools like BEopt, URBANopt, and ResStock. Component-level enhancements are being made available through releases to OS-HPXML and EnergyPlus.

Acknowledgements

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

The authors would like to thank Joan Glickman, Eric Werling, Dale Hoffmeyer, and Amir Roth of DOE for their continued support. The original workplan was developed by the NREL Residential Modeling Team. The overall effort was led by Ben Polly. Contributing members of the team included: Craig Christensen, Dane Christensen, Chioke Harris, Scott Horowitz, Xin Jin, Jeff Maguire, Dave Roberts, Eric Wilson, Jon Winkler, and Jason Woods. Additional contributions and/or reviews were provided by Lieko Earle, Shanti Pless, Tau Kung, Steve Frank, Nick DiOrio, Matteo Muratori, Eric Bonnema, and Noel Merket.

References

Brackney, Larry, Andrew Parker, Daniel Macumber, and Kyle Benne. 2018. *Building energy modeling with OpenStudio*. New York: Springer International Publishing.

Chen, Jianli, Rajendra Adhikari, Eric Wilson, Joseph Robertson, Anthony Fontanini, Ben Polly, Opeoluwa Olawale. 2022. S*tochastic simulation of residential building occupant-driven energy use in a bottom-up model of the U.S. housing stock.* Under peer review.

Chintala, R., Polly, B., Jin, X., Christensen, D., & Merket, N. 2020. *Residential Battery Modeling for Control-Oriented Techno-Economic Studies* (No. NREL/CP-5500-76065). National Renewable Energy Laboratory, Golden, CO (United States).

DiOrio, N., A. Dobos, S. Janzou, A. Nelson, and B. Lundstrom. 2015. *Technoeconomic modeling of battery energy storage in SAM.* NREL/TP-6A20-64641. National Renewable Energy Laboratory, Golden, CO (United States).

Gagnon, Pieter, Will Frazier, Wesley Cole, and Elaine Hale. 2021. *Cambium Documentation: Version 2021.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81611. https://www.nrel.gov/docs/fy22osti/81611.pdf.

Judkoff, R., Wortman, D., O'Doherty, B., Burch, J. 2008/1983. *A Methodology for Validating Building Energy Analysis Simulations.* National Renewable Energy Laboratory, Golden, CO. Technical Report: NREL/TP- 550-42059. https://www.nrel.gov/docs/fy08osti/42059.pdf

Mims Frick, Natalie, Wilson, Eric J, Reyna, Janet, Parker, Andrew S, Present, Elaina K, Kim, Janghyun, Hong, Tianzhen, Li, Han, and Eckman, Tom. 2019. *End-Use Load Profiles for the U.S. Building Stock: Market Needs, Use Cases, and Data Gaps.* United States. https://doi.org/10.2172/1576489. https://www.energy.gov/sites/prod/files/2019/11/f68/bto-20191115_EULP_Yr1_report_0.pdf.

National Renewable Energy Laboratory (NREL). 2021. *End-Use Load Profiles for the U.S. Building Stock [data set]*. Retrieved from https://data.openei.org/submissions/4520.

Satchwell, A., Piette, M. A., Khandekar, A., Granderson, J., Frick, N. M., Hledik, R., ... & Nemtzow, D. 2021. *A national roadmap for grid-interactive efficient buildings*. Lawrence Berkeley National Laboratory, Berkeley, CA (United States).

Shah, Monisha, Dylan Cutler, Jeff Maguire, Zac Peterson, Xiangkun Li, Josiah Pohl, and Janet Reyna. 2020. *Metrics and Analytical Frameworks for Valuing Energy Efficiency and Distributed Energy Resources in the Built Environment*: Preprint. Golden, CO: National Renewable Energy Laboratory NREL/CP-6A20-77888. Presented at the 2020 ACEEE Summer Study on Energy Efficiency in Buildings August 17-21, 2020. https://www.nrel.gov/docs/fy21osti/77888.pdf.

Shi, Xing, Zhichao Tian, Wenqiang Chen, Binghui Si, Xing Jin. 2016. "A review on building energy efficient design optimization from the perspective of architects." *Renewable and Sustainable Energy Reviews*, Volume 65, Pages 872-884, ISSN 1364-0321.

Torcellini, Paul A., Sammy Houssainy, Shanti D. Pless, William Livingood, and Ben Polly. 2020. *The Future of Zero Energy Buildings: Produce, Respond, Regenerate*: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-77415. Presented at the 2020 ACEEE Summer Study on Energy Efficiency in Buildings August 17-21, 2020. https://www.nrel.gov/docs/fy20osti/77415.pdf.

Wilson, E., C. Engebrecht Metzger, S. Horowitz, and R. Hendron. 2014. *2014 Building America House Simulation Protocols.* National Renewable Energy Laboratory, Golden, CO. Technical Report: NREL/TP-5500-60988. https://www.nrel.gov/docs/fy14osti/60988.pdf.

Wilson, Eric et al. 2022. *End-Use Load Profiles for the U.S. Building Stock: Methodology and Results of Model Calibration, Validation, and Uncertainty Quantification*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500 80889. https://doi.org/10.2172/1854582.