ENERGY STAR® for Tenants

An Online Energy Estimation Tool for Commercial Office Building Tenants

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Matthew Dahlhausen,[1] and Cindy Jacobs[2]

1 National Renewable Energy Laboratory
2 Environmental Protection Agency

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
NREL/TP-5500-74478
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List of Acronyms

AEDG	Advanced Energy Design Guide
CBECS	Commercial Buildings Energy Consumption Survey
DOE	U.S. Department of Energy
EC2	Elastic Compute Cloud (Amazon)
EPA	Environmental Protection Agency
EPD	equipment power density
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
LED	light-emitting diode
LEUI	lighting energy use intensity
LPD	lighting power density
NREL	National Renewable Energy Laboratory
PAT	Parametric Analysis Tool
PFP	parallel fan-powered
PSZ-AC	packaged single-zone air conditioner
PSZ-HP	packaged single-zone heat pump
PLR	part-load ratio
PNNL	Pacific Northwest National Laboratory
PVAV	packaged variable air volume
QA/QC	quality assurance/quality control
TMY3	typical meteorological year 3
VAV	variable air volume
WWR	window-to-wall ratio

Executive Summary

The Commercial Buildings Group at the National Renewable Energy Laboratory (NREL) is working with the Environmental Protection Agency (EPA) to develop an ENERGY STAR for Tenants program, formerly called Tenant Star. This program aims to recognize office building tenants who are committed to energy efficiency and environmental stewardship. Tenants seeking recognition must complete five steps (United States Environmental Protection Agency 2018):

1. Estimate energy use
2. Meter energy use
3. Use efficient lighting
4. Use efficient equipment
5. Share data.

NREL designed the web tool and analysis framework underlying Step 1, estimating energy use. An online survey was developed for tenants to input information about their office space and its internal loads. In the pilot phase, NREL performed a parametric analysis across a large parameter space of office buildings. The analysis results were processed to map the user inputs to output ranges of annual energy consumption. The mappings enable the web tool to provide users with instant energy usage estimates based on a limited number of inputs. The web tool generates a PDF report for the office space, which the tenant must save and include in their application to satisfy Step 1. The web tool can be found at: https://www.energystar.gov/TenantEstimationTool/.

The tenant must also complete the remaining four steps, which include installing energy meters, implementing efficient lighting and controls, using ENERGY STAR equipment, and sharing energy use data with their landlord upon request. A licensed professional is required to inspect the office space and verify that the information in the tenant's application is accurate to the best of their knowledge. The licensed professional must ensure that all meters are installed properly and are rated at +/- 2% accuracy. In addition, they must inventory all lighting and equipment present in the office space and verify that this information matches what was entered in the web tool. With all five steps completed and verified by the licensed professional, the tenant's application is submitted to the EPA for review. If the tenant space satisfies all criteria, it becomes eligible for recognition. The EPA recognized nearly 50 tenant spaces during the pilot phase of the project. These charter tenants have demonstrated their commitment to environmental stewardship and are officially recognized on the ENERGY STAR website.

The EPA and NREL have analyzed the pilot results from the charter tenants to assess areas that were successful and areas for improvement. A second phase of the tenant recognition program was launched with the aim of modifying the pilot phase for market-scale recognition. In the second phase, NREL ran a large analysis across a similar parameter space. Based on our analysis of the pilot results and feedback from the EPA and charter tenants, we refined our energy modeling methods and implemented quality assurance and quality control (QA/QC) checks to improve the accuracy of results. Additionally, we developed this Technical Support Document, which outlines the modeling procedures and assumptions made in the parametric analysis. The goal of the second phase of the tenant recognition program is to represent a larger number of tenant spaces, give more accurate energy estimation results, and attract a larger pool of applicants through improvements to the web tool and its underlying analysis.

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1 Introduction

1.1 Problem Definition

The commercial building sector consumes over 18% of the total energy in the United States (U.S. Energy Information Administration 2018). According to the 2012 Commercial Building Energy Consumption Survey (CBECS), office buildings comprise nearly 16 billion square feet of floor space and consume 253 billion kWh of energy annually (U.S. Energy Information Administration 2012). Office buildings represent nearly one-fifth of the energy consumed by commercial buildings, more than any other building type. Therefore, monitoring and reducing energy consumption in office buildings has become an increasingly important focus across the United States. Further, deployment of energy efficiency measures in office buildings is often hindered by the split-incentive dilemma, in which building owners are less inclined to make investments and upgrades to the building because they are not responsible for paying the energy bills (Australian Government, Department of the Environment and Energy 2013). As a result, tenant behavior is a key contributor to energy efficiency in office buildings.

The goal of the ENERGY STAR for Tenants program is to recognize office building tenants who demonstrate a commitment to energy efficiency and environmental stewardship. In addition to estimating energy usage through the ENERGY STAR Tenant Estimation Tool, interested tenants must also meet the remaining four energy efficiency criteria—metering energy use, lighting efficiently, using efficient equipment, and sharing data—to be eligible for recognition.

The Tenant Estimation Tool allows tenants to obtain an estimate of their heating, ventilation, and air conditioning (HVAC), lighting, plug load, and total energy consumption based on the information entered about their office space. These results, combined with metering, data sharing, and efficiency improvements, will help guide tenants toward a lower energy bill and carbon footprint. In addition, recognized tenants will demonstrate their organization's commitment to sustainability to their employees, clients, and customers. Ultimately, this program aims to inspire greater adoption of energy efficiency, metering, and data sharing to reduce energy consumption in commercial office buildings.

This Technical Support Document details the modeling assumptions the National Renewable Energy Laboratory (NREL) made to develop the Tenant Estimation Tool using the OpenStudio platform. The tool uses tenant inputs from an online survey to estimate energy consumption from a comprehensive database of building models. NREL uses Latin hypercube sampling to simulate across a vast parameter space of office building sizes, shapes, locations, orientations, internal loads, and so on. Thus, a model for any tenant office space can be mapped to the closest model in the existing database to obtain annual energy consumption values. A database of 300,000 building models (20,000 per climate zone) was generated, as will be discussed in Section 4. The energy consumption outputs include three categories—HVAC, lighting, plug load—as well as the total. Lighting and plug load consumption are presented as discrete values, while HVAC and total consumption are presented as a range. The reasoning for this will be explained in subsequent sections.

To limit the amount of information the tenant must acquire about their office building, a number of default model assumptions were made regarding the HVAC system, building envelope, schedules, and other specific model inputs. These assumptions were sourced from U.S. Department of Energy (DOE) prototype building models and the ASHRAE 90.1 standards through the OpenStudio-Standards library. This tool is limited to single-floor office spaces; therefore, some geometry and sizing simplifications were made to analyze individual tenant spaces inside a larger building. The methodology and modeling assumptions will be described in the following sections. This Technical Support Document was developed by the Commercial Buildings Research Group at NREL under the direction of the Environmental Protection Agency (EPA).

1.2 Project Scope

Since the fall of 2017, the EPA has been exploring ways to recognize energy-efficient tenant spaces using the design criteria set in Congress's Energy Efficiency Improvement Act of 2015 (EPA 2018). The ENERGY STAR for Tenants program will further encourage commercial office building tenants to monitor and reduce energy use.

The Tenant Estimation Tool provides interested tenants with an estimate of their office space's annual energy consumption based on inputs regarding the building, their individual office space, and the internal loads it contains. The size, age, and location of the building are used to determine proper assumptions for the remaining model inputs. The tool is best suited for tenants with 1,000-50,000 square feet of floor space, as will be discussed in Subsection 2.6.

The ENERGY STAR for Tenants program aims to demonstrate to individual tenants ways in which they can positively impact their energy performance. While large-scale changes in building envelope and HVAC systems may be infeasible, areas like equipment and lighting present significant opportunity to individual office spaces to improve their energy consumption as well as reduce their electricity expenses. The Tenant Estimation Tool provides tenants with a starting estimate for their energy consumption, which they could use as a baseline when implementing energy efficiency, metering, and other performance-improvement metrics.

1.3 Report Organization

This report is organized into four sections. Section 1 provides background, overview, and scope of the project. Section 2 introduces the modeling methodology, including definitions, analysis framework, and post-processing of results. Section 3 describes the model development process, outlining the modeling inputs and assumptions regarding program, form, fabric, and equipment. Section 4 discusses the QA/QC results and final simulation procedure.

2 Modeling Methodology

Our objective was to analyze simulated office building energy performance across a comprehensive parameter space, allowing the energy consumption of any particular tenant space to be estimated. Careful attention was paid to electric equipment and lighting, as these are the loads most controllable by tenants. The overall approach to the modeling process for the Tenant Estimation Tool is described next, including the tenant survey, ASHRAE standards, prototype building models, and the OpenStudio-Standards gem.

2.1 Definitions

The modeling workflow consists of three main steps depicted in Figure 1. First, a general office building prototype model is developed from the ASHRAE standards and templates corresponding to the location, age, and size of the tenant's building.

Then, the prototype model is customized to represent the individual tenant space, based on the survey inputs about geometry, envelope features, and internal loads. A series of HVAC sizing runs is completed to ensure the HVAC loads are estimated properly based on the size of the building and individual tenant space. A QA/QC analysis on HVAC system sizing and internal load operation is conducted to ensure that the building model operates as intended. The QA/QC protocol will be discussed further in Subsection 2.7.

The model representing the tenant's survey inputs is mapped to the existing database, using lookup keys to identify the building model with the same parameters and characteristics as the tenant space. The corresponding energy consumption values are outputted to the tenant within seconds of completing the survey. The remainder of Section 2 gives additional detail and background about the steps shown in Figure 1.

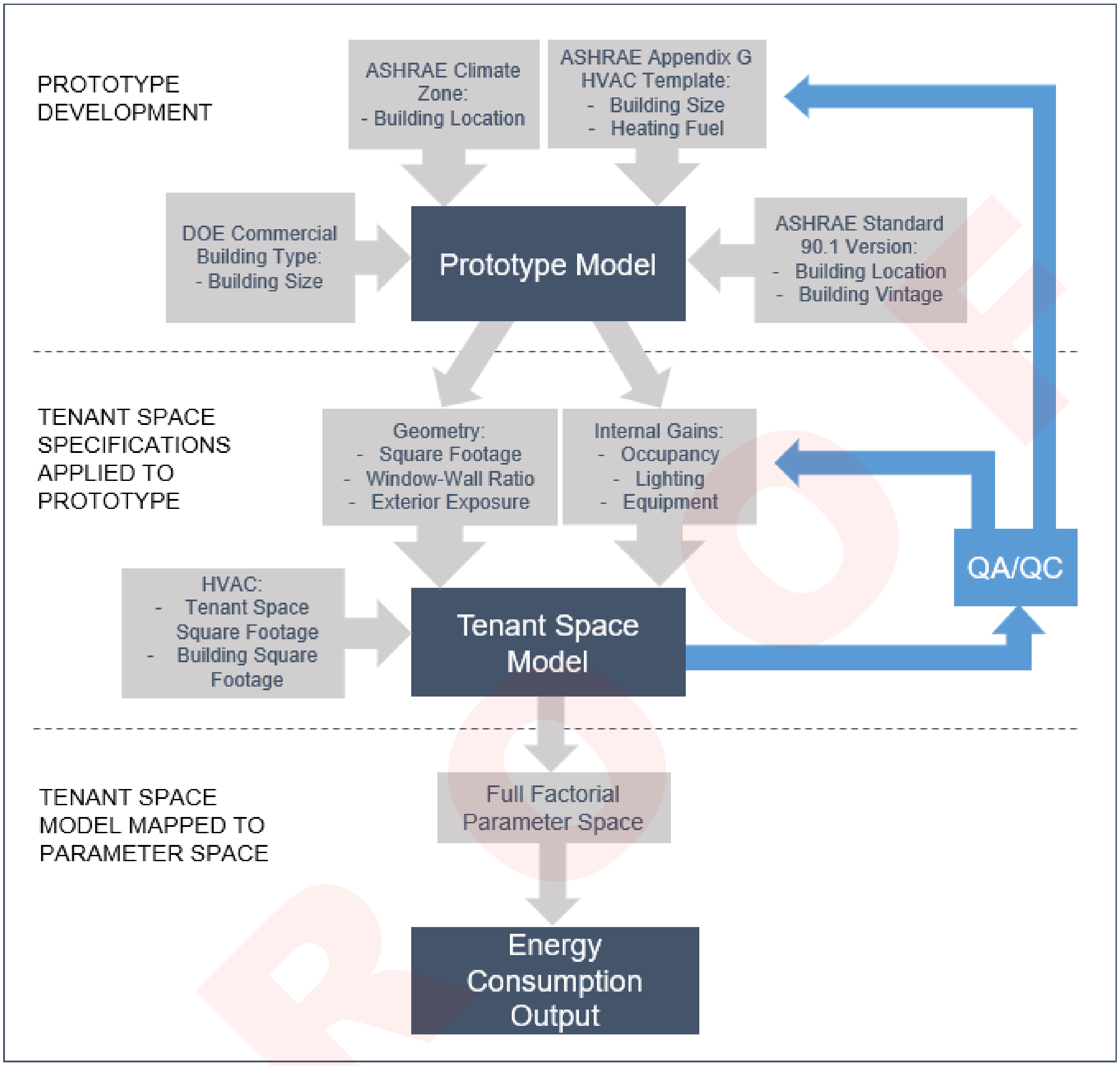


Figure 1. Modeling protocol flowchart

2.2 Definitions

To calculate building energy use, the boundary of the problem must be clearly defined. The Tenant Estimation Tool considers both site energy and source energy as key performance metrics, defined as follows:

- **Site Energy:** The energy directly consumed at the building, typically measured with utility meters.
- **Source Energy:** The sum of the energy consumed at the building and the energy required to extract, convert, and transmit that energy from the source to the building. To calculate a building's total source energy, imported and exported energy are multiplied by the appropriate site-to-source conversion multiplier.

Site energy was converted to source energy using multiplication factors of 2.80 for electricity and 1.05 for natural gas. These factors represent an average for the entire United States and are consistent with the conversion factors used in ENERGY STAR Portfolio Manager (EPA 2018).

2.3 Tenant Estimation Tool

A pilot version of the Tenant Estimation Tool was developed in 2017 and is currently available on the ENERGY STAR website: https://www.energystar.gov/TenantEstimationTool/. The survey contains five categories of inputs, summarized as follows:

- Building Information: building location, size, primary heating fuel
- Tenant Floor/Suite Information: square footage, weekly operating hours, number of workers, thermostat setback settings
- Building Envelope: where the tenant space is located within the building, which orientations have exterior exposure, window-to-wall ratio (WWR)
- Equipment Information: type and quantity of electric equipment in the tenant space
- Lighting Information: type and quantity of lighting in the tenant space

A licensed professional assisting the tenant must verify that the information entered in the tool is accurate. Section 3 will explain how the tenant's survey answers are used to derive specific model inputs.

The new Tenant Estimation Tool includes changes to the pilot version of the survey and modeling process to better estimate tenant energy use and to provide more output information to guide decisions. Notable modifications include:

- Greater detail in the equipment portion of the survey to include the quantity and type of equipment that is ENERGY STAR certified. This information will improve estimates of equipment power density (EPD) by accounting for energy saving features of ENERGY STAR appliances. In addition, server wattage is now modeled as a function of occupancy, rather than calculated from a quantity of servers, because servers can vary greatly in power drawn.
- Limiting the model to single-story or partial-story tenant spaces. This assumption simplified the modeling process and eliminated discrepancies when dealing with stairways and elevators. The tenant indicates if their space is single-story or partial-story by specifying which faces have exterior exposure. If a tenant space spans across multiple floors of a building, the tenant simply must complete separate survey entries for each floor.
- Improved HVAC sizing procedure. Whole-building HVAC equipment like chillers will be sized to only serve the load for the tenant space but will have efficiency levels as if they were sized for the whole building. This aspect will be discussed in further detail in Subsection 3.4.3.
- Improved assumptions for building codes and standards. The model now infers space information and HVAC equipment efficiencies from the ASHRAE 90.1 standard version most applicable to the building's vintage and location.
- Output to include source energy. The output to the tenant will give site energy, as well as source energy, using the conversions as described in Subsection 2.2.

2.4 ASHRAE

ASHRAE codes, standards, and other commercial buildings data was commonly referenced during this project. The modeling process required research into ASHRAE commercial code adoption by state, ASHRAE 90.1 Appendix G HVAC templates, and ASHRAE climate zones.

2.4.1 Commercial Code Adoption

Every state in the United States has different policies and timelines for adopting new commercial building codes, as can be seen in Figure 2. Some states, like Maryland and Massachusetts, require all commercial buildings to meet or exceed the latest version of ASHRAE 90.1. Nine states have no statewide building standards, and building code is adopted by county, city, or municipality. It is important to know which building code was applied to each tenant's office building during construction when evaluating overall energy consumption. Buildings in states that have adopted newer codes will likely perform better due to energy efficiency improvements required by each new version of ASHRAE 90.1. The tenant must enter the location and year the building was built, which determines the applicable ASHRAE 90.1 code requirements.

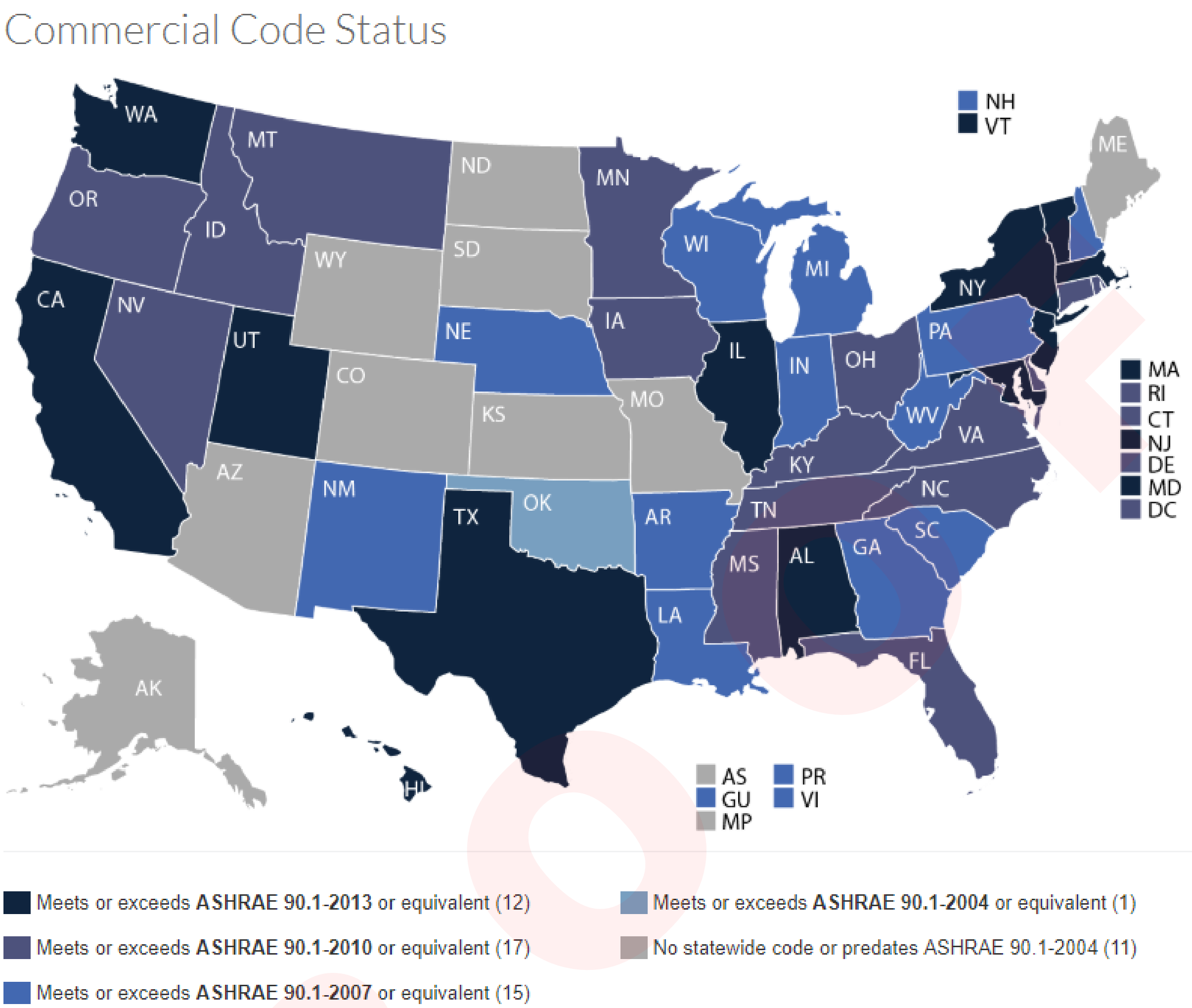


Figure 2. Commercial building code status by state as of 2018

Source: (Building Codes Assistance Project 2018)

The ASHRAE code version determines building envelope and HVAC model inputs. Model parameters pertaining to internal loads are determined from tenant survey inputs and override any defaults defined in the building standards. Based on the pilot results, most tenants' buildings in the survey were built before 2003. Thus, the DOE Ref Pre-1980 and DOE Ref 1980-2004 building standards were given the heaviest weighting in the parametric analysis. Standards 90.1-2004, 90.1-2007, 90.1-2010, and 90.1-2013 have significantly smaller weights. Appropriate weights for each of the six building standards were determined from a combination of CBECS 2012 data and the distribution of vintages in the pilot results (U.S. Energy Information Administration 2012). The results are shown in Table 1.

Table 1. Weights for Target Building Standard

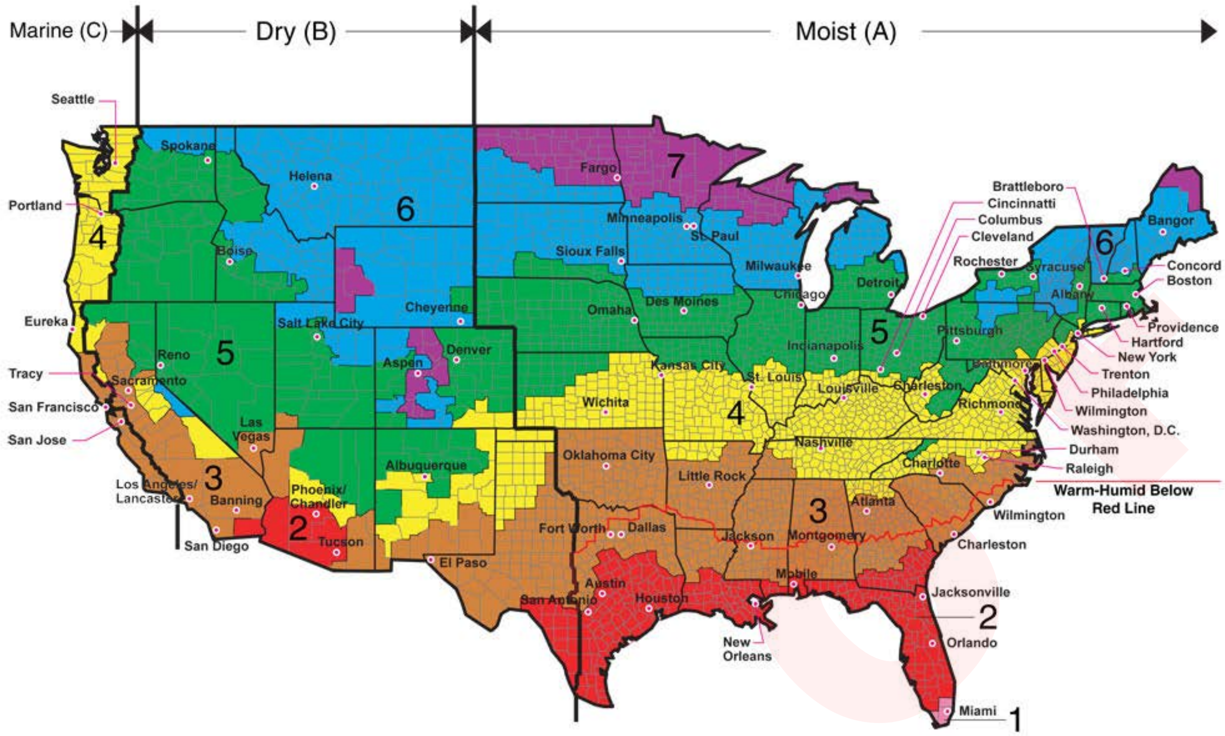
Target Standard	Weight
DOE Ref Pre-1980	45%
DOE Ref 1980-2004	30%
90.1-2004	4%
90.1-2007	4%
90.1-2010	4%
90.1-2013	13%

2.4.2 ASHRAE 90.1 Appendix G

In addition to code adoption, Appendix G of the ASHRAE 90.1 standards was referenced for selection of HVAC systems for the office building models (ASHRAE 2013). Appendix G provides a guideline for choosing HVAC systems and components based on the building square footage, number of floors, and heating fuel. Three categories exist for building size (small, medium, large) and two for heating fuel (electric, fossil fuel), resulting in a total of six potential HVAC systems. These predetermined HVAC systems were used for this project because many tenants may not know the details of the building's HVAC system, and these additional inputs would greatly add to the complexity of the survey. Multiple HVAC sizing runs are conducted during the simulations to ensure the HVAC energy consumption results are as accurate as possible despite the HVAC system assumptions made. More details about the HVAC templates used are described in Subsection 3.4.3.

2.4.3 Climate Zones

ASHRAE and the International Energy Consumption Code (IECC) define 8 climate zones and 15 climate subzones in the United States. The zones are categorized by heating degrees days and cooling degree days, ranging from hottest (Zone 1) to coldest (Zone 8). Subzones indicate different humidity conditions. Humid subzones are designated by the letter A, dry subzones by B, and marine subzones by C. The climatic conditions that buildings are exposed to have a significant impact on their heating and cooling needs and overall energy performance. Figure 3 shows a map of U.S. climate zones.



All of Alaska in Zone 7 except for the following Boroughs in Zone 8: Bethel, Dellingham, Fairbanks, N. Star, Nome North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk

Zone 1 includes: Hawaii, Guam, Puerto Rico, and the Virgin Islands

Figure 3. Climate zone map

Source: (Deru et al. 2011)

For each of the 15 climate subzones, the IECC names representative cities that best reflect the climatic conditions for that subzone. (IECC 2015) The weather files used are typical meteorological year 3 (TMY3) files and represent the typical hourly weather data for each location derived from the 1991-2005 period of record (DOE Building Technologies Office). The 15 climate zones, representative cities, and corresponding weather files used in this project are shown in Table 2.

Table 2. Climate Zones and Representative Cities.

Climate Zone and Type	Representative City	Weather File
1A Very Hot-Humid	Miami, Florida	USA_FL_Miami.Intl.AP.722020_TMY3.epw
2A Very Hot-Dry	Houston, Texas	USA_TX_Houston-Bush.Intercontinental.AP.722430_TMY3.epw
2B Hot-Humid	Phoenix, Arizona	USA_AZ_Phoenix-Sky.Harbor.Intl.AP.722780_TMY3.epw
3A Hot-Dry	Memphis, Tennessee	USA_TN_Memphis.Intl.AP.723340_TMY3.epw
3B Warm-Dry	El Paso, Texas	USA_TX_El.Paso.Intl.AP.722700_TMY3.epw
3C Warm-Marine	San Francisco, California	USA_CA_San.Francisco.Intl.AP.724940_TMY3.epw
4A Mixed-Humid	Baltimore, Maryland	USA_MD_Baltimore-Washington.Intl.AP.724060_TMY3.epw
4B Mixed-Dry	Albuquerque, New Mexico	USA_NM_Albuquerque.Intl.AP.723650_TMY3.epw
4C Mixed-Marine	Salem, Oregon	USA_OR_Salem-McNary.Field.726940_TMY3.epw
5A Cool-Humid	Chicago, Illinois	USA_IL_Chicago-OHare.Intl.AP.725300_TMY3.epw
5B Cool-Dry	Boise, Idaho	USA_ID_Boise.Air.Terminal.726810_TMY3.epw
6A Cool-Humid	Burlington, Vermont	USA_VT_Burlington.Intl.AP.726170_TMY3.epw
6B Cool-Dry	Helena, Montana	USA_MT_Helena.Rgnl.AP.727720_TMY3.epw
7 Very Cold	Duluth, Minnesota	USA_MN_Duluth.Intl.AP.727450_TMY3.epw
8 Sub-Arctic	Fairbanks, Alaska	USA_AK_Fairbanks.Intl.AP.702610_TMY3.epw

2.5 Pacific Northwest National Laboratory Prototype Building Models

Aside from information from the tenant survey, several other parameters were defined to complete the model. The DOE prototype building models developed by the Pacific Northwest National Laboratory (PNNL) are used as the main resource for building model assumptions (DOE 2018). Because this study is focused on individual office spaces within a larger building, tenants are limited in the amount of information they can obtain about the entire building. The tenant survey, as it is part of the EPA's ENERGY STAR initiative, focuses heavily on internal loads such as electric equipment and lighting, rather than construction, geometry, space types, and so on. Thus, three DOE office prototype building models are used to fill in the blanks in these areas. Each prototype model has several different versions corresponding to levels of ASHRAE 90.1 codes. The most relevant ASHRAE code for the tenant's building, as discussed in Subsection 2.4, is used to select the corresponding version of the prototype building.

The tenant survey asks for the total square footage and number of floors in the building, from which one of the three office prototype models is selected as the reference for model assumptions. Buildings with 25,000 ft^2 or less correspond to Small Office, 25,000-150,000 ft^2 to Medium Office, and 150,000 ft^2 or more to Large Office. Each prototype model contains specifications for building form, architecture, HVAC, internal load schedules, and more. The model inputs not covered by tenant survey responses or Appendix G HVAC templates are assumed from the prototype models. These assumptions primarily include building construction, materials, zoning, and space types. Inputs determined from the tenant survey will overwrite any default assumptions from the prototype models.

2.6 Building Energy Modeling Methodology

2.6.1 OpenStudio/EnergyPlus

All building models were developed through the OpenStudio software platform, which was developed by NREL and other DOE National Laboratories (DOE Office of Energy Efficiency and Renewable Energy). OpenStudio is a collection of software tools to support whole building energy modeling, and it includes a graphical application for creating and editing models, running simulations, and viewing results. OpenStudio uses EnergyPlus, DOE's detailed building energy simulation tool, to compute energy use based on the interactions between climate, building form and fabric, internal gains, HVAC systems, and renewable energy systems (DOE Building Technologies Office). The modeling work for the Tenant Estimation Tool was done using OpenStudio's Parametric Analysis Tool (PAT), which is discussed next.

2.6.1.1 PAT

PAT is an OpenStudio application that accelerates the modeling and simulation process by running many models (each with a unique combination of inputs) simultaneously. This PAT project utilizes Latin hypercube sampling to generate a multidimensional parameter space of building models for the Tenant Estimation Tool. The parameter space will encompass any combination of tenant inputs to account for those parameters varying based on tenant survey answers. When a tenant fills out the survey, the tool uses the inputs as lookup keys into the existing database and outputs the energy consumption results corresponding to the most similar model in the database.

2.6.1.2 OpenStudio-Standards

OpenStudio-Standards is an OpenStudio library that contains standards data and methods that are applied to generate standards-compliant energy models. The OpenStudio platform contains a database of measures, which are sets of programmatic instructions that make changes to an energy model (DOE Office of Energy Efficiency and Renewable Energy). The *Create Bar From Building Type Ratios* measure generates model geometry, then the *Create Typical Building from*

Model measure uses the OpenStudio-Standards library to apply ASHRAE standards to generate the prototypical building model. The *Change Building Location* measure then assigns the climate zone, weather file, ground temperatures, and water main temperatures based on the building location. The tenant survey responses are then used to customize and overwrite certain aspects of this prototype model.

2.6.2 Modeling Overview

This subsection gives an overview of the input ranges and weights that make up the parameter space of building models. We determined these ranges and values using research, engineering judgement, and results from the pilot phase of the Tenant Estimation Tool. Table 3 shows the parameter ranges represented in our analysis and their justifications. The parameters in Table 3 are continuous parameters, meaning that PAT can sample across their entire range. Table 4 shows how certain model inputs were weighted to obtain a parameter space that best represents the distribution of building sizes, locations, and vintages in the United States. The weighting values in Table 4 are discrete parameters, meaning that PAT is limited to using specific values. Each option is weighted individually, and the sum of weights for each parameter must be 100%.

Table 3. Parametric Analysis Ranges

Input	Range in PAT	Justification
Tenant Floor Area	1,000-50,000 ft^2	Increased range from 1,000-30,000 ft^2 based on pilot results
Building Rotation	0-180 degrees from N	Same as pilot version. Not a survey input; both extremes will be encompassed in HVAC and total energy consumption results (presented as a range)
Aspect ratio	0.5-2	
WWR	0.2-0.9	Increased range from 0.3-0.9 based on pilot results
Weekly Hours of Operation	30-70 hours	Decreased range from 20-70 based on pilot results (no tenant spaces reported less than 40 hours/week)
LPD	1-12.5 kBtu/ ft^2	Same as pilot version
EPD	0.05-2 W/ ft^2	Changed range from 0.25-4 based on pilot results, new equipment calculation methods, and engineering judgement
People per Floor Area	0.0005-0.02 people/ft^2	Increased range from 0.001-0.02 based on pilot results
Space Infiltration Flow	0.06-0.22 cfm/ft^2	Same as pilot version. Not a survey input; both extremes will be encompassed in HVAC and total energy consumption results (presented as a range)
Total Building Floor Area	30,000-500,000 ft^2	New PAT input for full-building HVAC sizing measure; range based on pilot results and engineering judgement (there is a theoretical max for chiller efficiencies once a certain building size is reached)

Table 4. Parametric Analysis Weights

Input	Weights in PAT	Justification
Target standard	Pre-1980 = 0.45	Weights are based on distribution of vintages in pilot results and CBECS 2012 data for office buildings.
	1980-2004 = 0.30	
	90.1-2004 = 0.04	
	90.1-2007 = 0.04	
	90.1-2010 = 0.04	
	90.1-2013 = 0.13	
Party walls N/S/E/W	0 = 0.75	Weights based on pilot results, in which >75% of each face did not have a party wall (aka no exterior exposure).
	1 = 0.25	
HVAC System Type	PSZ-AC with gas coil heat (small building, fossil fuel heating) = 0.08	Pilot version weighted each of the six HVAC systems equally. Based on pilot results, 73% of charter tenants were in large office buildings. The remaining 27% had more medium than small buildings. In general, there was an equal split between fossil fuel and electric heating.
	PSZ-HP (small building, electric heating) = 0.08	
	PVAV with reheat (medium building, fossil fuel heating) = 0.12	
	PVAV with parallel fan-powered (PFP) boxes (medium building, electric heating) = 0.12	
	VAV with reheat (large building, fossil fuel heating) = 0.3	
	VAV with PFP boxes (large building, electric heating) = 0.3	

2.7 QA/QC Protocol

An important aspect of simulation-based analysis is establishing a protocol to manage quality assurance and quality control. We focused our QA/QC analysis on HVAC system sizing and operation, as well as on internal loads such as lighting and equipment.

2.7.1 System Sizing

HVAC sizing determines whether a given system can meet thermal loads. If a system is undersized, it will not maintain space temperature setpoints; if it is oversized, it may use more energy than an equivalent, properly sized system. In EnergyPlus, systems can be sized automatically based on the results of the design-day-based sizing routines. This project does pose some additional challenges for sizing, as models must capture the behavior of a system sized for multiple stories, but only serving a single floor. To address this issue, the modeling process incorporates two separate HVAC sizing runs, one for the tenant space and one for the entire building. The HVAC components are sized according to the tenant space to avoid oversizing and overestimating the tenant's energy consumption. The sizing run for the entire building is used solely to determine efficiencies for HVAC components, as these values can vary greatly with the size of a building. The process for sizing HVAC systems and components will be discussed further in Subsection 3.4.3. A QA/QC protocol was used to ensure the resulting building models operate as intended, monitoring the following system metrics:

- Hours when a zone is occupied and zone air temperature is outside the thermostat setpoint, otherwise known as unmet hours. Unmet hours indicate thermal discomfort and unmet heating or cooling loads, possibly because of undersized system components. For cases with significant unmet hours, it is beneficial to examine equipment run time fraction values to determine if components were running at full capacity for extended periods (an indication of undersizing) and adjust sizing factors accordingly. A threshold of <600 unmet hours (300 heating, 300 cooling) was used to define acceptable performance.
- HVAC component part-load ratios (PLRs). A part-load ratio is the instantaneous equipment load divided by the design sizing load for a given time step. A component that never exceeds a PLR of 0.6 during periods of peak load indicates oversizing. We tracked part-load ratios for major HVAC equipment to ensure that our sizing techniques resulted in reasonable PLRs and were consistent with industry practice.
- Validation. Pressure drops across fans were checked, economizer activation/deactivation according to outdoor temperature was validated, and HVAC energy usage versus temperature was evaluated to ensure the relationship matched expectations.

2.7.2 Internal Loads

Internal loads, such as equipment, lighting, and occupancy, are an important factor in this project. While partial responsibility lies with the tenants to enter the correct information about their office's internal loads and operating hours, the remaining inputs about schedules and operation rely on accurate assumptions and measures in the modeling process. A QA/QC protocol was followed to ensure the internal loads and schedules were reasonable and operating as intended. The following metrics were monitored:

- Internal loads following correct schedules. We confirmed that equipment, lighting, and occupancy followed the schedules generated by the *Create Parametric Schedules* measure. All schedules represent typical operating conditions for an office building with X number of operating hours per week, where the number of hours, X, is entered by the tenant.
- Internal loads responding correctly to weekends. We tracked internal load fractions and schedules throughout the year to ensure weekends and weekdays are operating as expected.

3 Model Development and Assumptions

This section walks through the modeling process by explaining the model inputs and how they were determined (from prototype models versus tenant survey).

3.1 Building Operation

This subsection overviews the building and how it is used. These decisions are important to a building's energy consumption, as they influence internal gains, ventilation requirements, operating schedules, and more.

3.1.1 Space Types

This program focuses solely on office tenants; the Small/Medium/Large Office prototype models are used for model assumptions. Like the DOE prototype models, our tenant space models assume a whole-building blended space type. The tenant survey asks for equipment, lighting, and occupancy information for the entire space, rather than for individual rooms. Multiple space types need not be created, as the equipment, lighting, and occupancy inputs are the same for all spaces. Each space contains a large core zone and perimeter zones. This captures the localized thermal effects near exterior walls and the benefits of daylighting, natural ventilation, and exterior wall thermal mass design, if applicable.

3.1.2 Internal Load Densities

Internal loads include the heat generated by occupants, lights, and appliances (plug and process loads). This subsection only details occupancy densities. Electric lighting and plug and process loads are discussed separately in Subsection 3.4. An occupancy density, in people per floor area, is calculated for the tenant space by dividing the number of workers on the main shift by the tenant floor area. The number of working hours per week entered by the tenant drives all schedules for internal loads, as discussed in Subsection 3.1.3.

3.1.3 Schedules

Schedules for lighting, equipment, occupancy, infiltration, thermostats, and HVAC operation are all generated through the *Create Parametric Schedules* OpenStudio measure. This measure creates typical schedules based on the number of working hours per week or the daily start and end hours of operation in the building. For this project, tenants enter the number of working hours per week. This is the only value used to generate schedules. For an input of 20-60 hours, the *Create Parametric Schedules* measure assumes a five-day work week from Monday to Friday, with hours evenly divided each day. Saturday is added when the input reaches 60-72 hours, and Sunday is added for 72-84 hours per week. From the number of working hours, a set of "typical" schedules is generated by altering the prototype model schedules to reflect the specified number of hours per week.

The HVAC operation schedule and thermostat setpoint schedules automatically assume that HVAC systems are set back on nights and weekends. This assumption will result in lower annual HVAC energy consumption than if we assumed HVAC systems are operational 24/7; however, the pilot round showed that over 90% of tenants claimed their office space has thermostat setbacks on nights and weekends. Therefore, making this assumption in our models is reasonable.

For this project, the parameter space only supported inputs of 30-70 working hours per week. The previous version of the tool supported a range of 20-70 hours; however, the pilot results had no tenant spaces with less than 40 hours of operation per week. If the tenant's input is less than 30 hours or greater than 70 hours, 30 or 70 is used as the input, respectively. The *Create Parametric Schedules* measure generates a set of typical schedules for a building with the specified number of weekly operating hours. Most schedules, except for temperature setpoints, are presented in a range from 0-1, representing the fraction of the peak value for hourly intervals.

3.2 Building Form

A building's form describes the geometry of the building and its elements, and this has important energy implications stemming from how the building interacts with the sun and ambient conditions. Most survey inputs refer to the individual office space, not the entire building. The only building-scale information required by the tenant is the total square footage and number of floors, from which the building is placed into one of three categories. Buildings with fewer than 3 floors or less than 25,000 ft^2 of floor space correspond to the Small Office prototype building model. Buildings with 4-5 floors and less than 25,000 ft^2 or more than 5 floors and 25,000-150,000 ft^2 correspond to the Medium Office model. Buildings with greater than 5 floors or more than 150,000 ft^2 use the Large Office building model assumptions.

Survey inputs about the individual tenant space include tenant usable floor area and percent of wall that is made of glass, or WWR. Additionally, the tenant must identify which faces of their space have exterior exposure, and whether their office is located on the ground or top floor of the building. This information affects the heating and cooling loads and sun exposure for the tenant space. The aspect ratio (ratio of N/S façade to E/W façade) and orientation of a building also affect the amount of sunlight and solar radiation that can reach the tenant space; however, aspect ratio and orientation can be difficult for a tenant to calculate or obtain. Instead, the parameter space we simulate includes an aspect ratio range of 0.5-2, and a building rotation range of 0-180 degrees from the north axis. The HVAC and total energy consumption for the tenant space are then outputted to the user as a range, rather than as discrete values. The output range encompasses the two extremes that result from different building shapes and orientations. For example, a building with greater south-facing surface area, and thus greater sun exposure, may fall on the lower end of the energy consumption range due to increased natural lighting and decreased HVAC loads.

The parametric analysis simulates ranges of input values, such that a model exists for almost any combination of tenant inputs. The parameter space supports tenant floor areas of 1,000-50,000 square feet, aspect ratios of 0.5-2, building orientations of 0-180 degrees, and WWRs of 0.2-0.9. For any inputs outside this range, the extreme that is closest to the tenant's input is used. The ranges supported by our analysis should represent a large majority of sizes, shapes, and envelope characteristics of office spaces. All other geometry inputs not covered by the survey are assumed from the prototype building models, including floor-to-floor height, floor-to-ceiling height, glazing sill height, shading, and azimuth. A table of the geometry model parameters and their values or range of values is shown in Table 5.

Table 5. Form Model Inputs

Model Parameters	Inputs Values Within Parameter Space	Assumptions from Prototype Buildings		
		Small Office	Medium Office	Large Office
Floor area	1,000-50,000 ft^2	From tenant survey		
Building shape		Rectangular		
Aspect ratio (N/S to E/W)	0.5-2			
Number of floors	1			
Window fraction	0.2-0.9	From tenant survey		
Shading geometry		None		
Azimuth		Nondirectional		
Thermal zoning		• Perimeter zone depth = 16.4 ft • 4 perimeter zones, 1 core zone, 1 attic zone • Perimeter 70%, Core 30%	• Perimeter zone depth = 15 ft • 4 perimeter zones, 1 core zone • Perimeter 40%, Core 60%	• Perimeter zone depth = 15 ft • 4 perimeter zones, 1 core zone, 1 IT closet zone • Perimeter 29%, Core 70%, IT Closet 1%
Floor-to-floor height		10	13	13
Floor-to-ceiling height		10	9	9
Glazing sill height		3	3.35	3

Source: (DOE 2018)

3.3 Building Envelope

This subsection describes the materials, insulation levels, glazing systems, and thermal mass of a building. The materials and properties for exterior walls, roof, windows, interior partitions, foundation, and so on, for all models were determined from the Small/Medium/Large Office prototype buildings. While different versions of each prototype models correspond to the levels of ASHRAE standards, the materials do not vary greatly from version to version. But several enclosure inputs are dependent on climate zone, such as U- and R-factors. The dimensions of each feature depend on the floor area and aspect ratio of the tenant space. The main construction inputs are shown in Table 6.

Table 6. Fabric Model Inputs

Feature	Model Parameters	Small Office	Medium Office	Large Office
Exterior walls	Construction	• Wood frame walls (2x4 16 in on-center) • 1 in stucco + 5/8 in gypsum board + wall insulation + 5/8 in gypsum board	• Steel frame walls (2x4 16 in on-center) • 0.4 in stucco + 5/8 in gypsum board + wall insulation + 5/8 in gypsum board	• Mass (pre-case concrete panel) • 8 in heavy-weight concrete + wall insulation + 0.5 in gypsum board
	Tilts and orientations	Vertical		
Roof	Construction	Attic roof with wood joist: roof insulation + 5/8 in gypsum board	Built up roof: roof membrane + roof insulation + metal decking	Built up roof: roof membrane + roof insulation + metal decking
	Tilts and orientations	Hipped roof: 10.76 ft attic ridge height, 2 ft overhang-soffit	Horizontal	Horizontal
Windows	Construction	Based on window fraction, location, glazing sill height, floor area, aspect ratio		
	Glass type and frame	Hypothetical window with weighted U-factor and solar heat gain coefficient		
	Visible transmittance	Same as above requirements		
	Operable area	0%		
Skylights	N/A	N/A		
Foundation	Foundation type	Slab-on-grade floors (ungraded)	Slab-on-grade floors (ungraded)	Basement (conditioned)
	Construction	8 in concrete slab poured directly on to earth	8 in concrete slab poured directly on to earth	8 in concrete wall; 6 in concrete slab, 140-lb heavy-weight aggregate
	Thermal properties for basement walls	N/A	N/A	No insulation
Interior partitions	Construction	2x4 uninsulated stud wall		
Internal mass		6 in standard wood (16.6 lb/ft^2)		
Air barrier system	Infiltration	• Peak: 0.216 cfm/ft^2 at natural pressure of above grade exterior wall surface area, adjusted by wind (when fans turn off)		

Feature	Model Parameters	Small Office	Medium Office	Large Office
		• Off peak: 25% of peak infiltration rate (when fans turn on) • Small/Medium Office: additional infiltration through building entrance (162/1428 cfm during peak, 21/188 cfm during off peak, respectively) (Cho, Liu, & Gowri, 2010).		

Source: (DOE 2018)

3.4 Building Equipment

The lighting and equipment inputs are determined from the tenant survey, while HVAC equipment and operational assumptions are derived from the standards.

3.4.1 Electric Lighting

The lighting energy use intensity (LEUI) is the main lighting input parameter and is determined from the Lighting Information page of the tenant survey. The survey asks for fixture type, light source, wattage, and quantity for each type of light. The drop-down options for light source include compact fluorescent lamp, fluorescent, incandescent, and light-emitting diode (LED). The user can include as many entries as necessary to cover all types of lights in their office space. In addition, the tenant is asked whether each type of light has motion sensors, daylighting sensors, tuning, or specialty/task lighting. A tool developed by PNNL estimates the LEUI and lighting power density (LPD) for the tenant space from the list of lights entered. The LEUI represents the lighting energy used per square foot per year, in kWh/ft^2 or kBtu/ft^2. The LPD represents the lighting load in a space and is defined in W/ft^2. The LEUI and LPD values are functions of the total fixture wattage, square footage, and annual operating hours.

PNNL's lighting tool accounts for lighting power reductions due to the presence of sensors and controls as specified by the tenant. Reductions for each control feature are represented as a percent decrease in the LEUI and LPD. The lighting schedule for the tenant space is determined by the *Create Parametric Schedules* measure, in which the only independent variable is the number of weekly operating hours. This measure uses a single lighting profile shape, which does not change due to daylighting or other lighting controls. Instead, any reductions due to controls are applied directly to the LEUI and LPD as a percent reduction, rather than altering the lighting schedule.

The lighting tool estimates an LEUI and LPD for the tenant space from the lighting information provided. It also gives the user a target LEUI value, which represents an aggressive but achievable lighting goal for an office of that size. Lighting controls, which can typically save 20%-30%, combined with high efficiency lighting (such as LEDs), would allow the tenant to meet their target LEUI (EPA 2017). By comparing the target LEUI with their actual LEUI, the tenant has insight on whether their office is lit efficiently, and what level of improvements can be made. Lighting system replacements are common as part of commercial tenant improvement projects.

3.4.2 Plug and Process Loads

The equipment power density for the office space is determined from the tenant survey. The tenant must fill out the quantity of each type of equipment in their office space, particularly computers, laptops, multimedia projectors, large screen displays, desktop printers, full-sized copy machines/printers/scanners, refrigerators, microwave ovens, coffee makers, and vending machines. In addition, the survey asks if the office space contains a server and whether it is ENERGY STAR certified. In the previous version of the tool, the quantity of servers was required, and a default server wattage was used; however, this approach left room for error, given the vast range of server power draw. In this round, the server wattage will be estimated as a function of the number of occupants. Based on the 50% Savings Advanced Energy Design Guide (AEDG) for large offices, server power can be estimated as 65 W per occupant for conventional servers and 48 W per occupant for low-energy or ENERGY STAR servers (Leach, Lobato, A.Hirsch, Pless, and Torcellini 2010). This improvement will result in more accurate server equipment power, rather than assuming the same server wattage for offices of all sizes and functions. The equipment schedule is generated by the *Create Parametric Schedules* measure and is based on the number of weekly operating hours.

The new Tenant Estimation Tool asks tenants to specify which equipment is ENERGY STAR certified. ENERGY STAR equipment uses 10%-50% less energy than standard equipment. ENERGY STAR equipment is more efficient in performing regular tasks and automatically enters low-power mode when not in use (McCombs 2015). The previous survey assumed that all equipment was ENERGY STAR, meaning equipment energy consumption results may have been inaccurate. The new survey asks for the quantity of each type of equipment, as well as the quantity that is ENERGY STAR certified. If the tenant does not know or cannot obtain the exact quantity of ENERGY STAR equipment, they may select an "I don't know" option, from which the tool will assume a default percentage of ENERGY STAR equipment for that category. The assumed peak power values for conventional and ENERGY STAR equipment are shown in Table 7. These peak load values for conventional versus ENERGY STAR equipment were taken from the office building AEDG (Leach, Lobato, A.Hirsch, Pless, and Torcellini 2010).

Table 7. Equipment Peak Loads (Conventional vs. ENERGY STAR)

Equipment Type	Peak Power (W)	
	Conventional	ENERGY STAR
Desktop Computer	65	54
Laptop Computer	19	17
Multimedia Projector*	500	
Large-Screen Display	152	104
Desktop Printer	215	180
Full-Sized Copier/Scanner/Printer	1,100	500
Refrigerator	76	65
Microwave*	1,500	
Commercial Coffee Maker	1,600	1,280
Residential Coffee Maker*	840	
Vending Machine	770	500
Server (in Small Server Closet)	65/occupant	48/occupant

Equipment Type	Peak Power (W)	
	Conventional	ENERGY STAR
*No ENERGY STAR product currently exists.		

As shown in Equation 1, the EPD in W/ft^2 for the tenant space can be calculated by multiplying the power per appliance by the quantity for each type of equipment (conventional and ENERGY STAR), summing, then dividing by the tenant square footage. The annual equipment energy consumption in kBtu can then be calculated from the EPD, floor area, and hours per week. The annual site energy consumption is calculated and outputted by EnergyPlus but can be accurately estimated by Equation 2 below. The annual source energy consumption in kBtu/ft^2, as shown in Equation 3, is the electric equipment consumption metric outputted by the tool. It is calculated by multiplying the site energy (kBtu) by the site-to-source conversion factor of 2.8 and dividing by the tenant square footage.

Equation 1. Equipment Power Density (EPD)

$$equipment\ power\ density\ \left(\frac{W}{ft^2}\right) = \frac{\sum(peak\ power_{conv}\ (W) * \ quantity_{conv}) + \sum(peak\ power_{ENERGY\ STAR}\ (W) * \ quantity_{ENERGY\ STAR})}{tenant\ floor\ area\ (ft^2)}$$

Equation 2. Annual Site Equipment Energy Consumption

$$annual\ site\ equipment\ energy\ consumption\ (kBtu) = EPD\ \left(\frac{W}{ft^2}\right) * tenant\ floor\ area\ (ft^2) * (2.59 + 0.0285 * hours\ per\ week + (if\ hours\ per\ week > 60\ then\ 0.1, else\ 0))$$

Equation 3. Annual Source Equipment Energy Consumption

$$annual\ source\ equipment\ energy\ consumption\ \left(\frac{kBtu}{ft^2}\right) = \frac{2.8 * annual\ site\ equipment\ energy\ consumption\ (kBtu)}{tenant\ floor\ area\ (ft^2)}$$

3.4.3 HVAC Systems and Components

Because information about a building's HVAC system is complex and often inaccessible to tenants, they are not required to enter any detailed HVAC information in the online survey. Instead, one of three predetermined HVAC systems is assigned based on the size of the building, following guidelines from ASHRAE 90.1 Appendix G. This approach simplifies the building modeling and reduces the amount of work the tenant must do to complete the survey. Analyzing the HVAC energy consumption attributable to a single office space that is part of a larger building system poses additional challenges, though. Because there are uncertainties with the HVAC system, the web tool outputs a range for annual HVAC energy usage.

Three types of HVAC systems were modeled in the parametric analysis. The system type depends on the number of floors and total floor area of the building. It is assumed that all buildings are both heated and cooled. The tenant must report if their building is heated electrically or by fossil fuels. For electric heating, slight variations of the three main HVAC systems are used, resulting in six potential HVAC options.

Table 8 shows the HVAC system types and specifications for each of the three categories of building sizes. Both fossil fuel and electric heating are included.

Table 8. HVAC Systems Corresponding to Different Building Sizes

Heating Source		Less than 3 floors or less than 25,000 ft^2	4 or 5 floors and less than 25,000 ft^2 or 5 floors or less and 25,000-150,000 ft^2	More than 5 floors or more than 150,000 ft^2
Fossil Fuel, Fossil/Electric Hybrid, and Purchased Heat	Number/Code	3–PSZ-AC	5–PVAV w/ Reheat	7–VAV w/ Reheat
	System Type	Packaged rooftop air conditioner	Packaged rooftop variable air volume with reheat	Variable air volume with reheat
	Fan Control	Constant volume	VAV	VAV
	Cooling Type	Direct expansion	Direct expansion	Chilled water
	Heating Type	Fossil fuel furnace	Hot water fossil fuel boiler	Hot water fossil fuel boiler
Electric	Number/Code	4–PSZ-HP	6–PVAV w/ PFP Boxes	8–VAV w/ PFP Boxes
	System Type	Packaged rooftop heat pump	Packaged rooftop variable air volume with reheat	Variable air volume with reheat
	Fan Control	Constant volume	VAV	VAV
	Cooling Type	Direct expansion	Direct expansion	Chilled water
	Heating Type	Electric heat pump	Electric resistance	Electric resistance

Source: (ASHRAE 2013)

3.4.3.1 System Control

Because the tenant survey does not include any information about HVAC, the model specifications were kept as the defaults for each of the three HVAC templates. This includes thermostat settings, supply air temperatures, chilled and hot water supply temperatures (large office only), economizers, ventilation, and more. Control settings for the three HVAC systems are summarized in Table 9.

Table 9. HVAC System Control Inputs

Model Parameter	Small Office	Medium Office	Large Office
Thermostat Setpoint	75°F Cooling/70°F Heating	75°F Cooling/70°F Heating	75°F Cooling/70°F Heating
Thermostat Setback	85°F Cooling/60°F Heating	80°F Cooling/60°F Heating	85°F Cooling/60°F Heating
Supply Air Temperature	Maximum 104°F/ Minimum 55°F	Maximum 104°F/ Minimum 55°F	Maximum 110°F/ Minimum 52°F
Chilled Water Supply Temperatures	N/A	N/A	44°F
Hot Water Supply Temperatures	N/A	N/A	180°F
Economizers	Requirements in codes or standards		
Ventilation	ASHRAE 62.1		
Demand Control Ventilation	Requirements in codes or standards		
Energy Recovery	Requirements in codes or standards		

Source: (DOE 2018)

3.4.3.2 System Sizing

The design day method was used to determine equipment heating (boilers, central hot water coils, and reheat coils in VAV terminal boxes) and cooling (chillers, central cold water coils) capacities, as well as air system flow rates. This autosizing method was selected because the heating and cooling capacities of the system vary based on the location of the building. Design days come from ASHRAE Standard 169-2006 (ASHRAE 2006). The internal loads (occupancy, lights, plug and process loads, and so on) are set to zero throughout the heating design day, and to their peak values throughout the cooling design day.

Because this project focuses on single-floor tenant spaces within a larger building, two separate autosizing runs are conducted. The tenant survey includes inputs about both the entire building and the individual tenant space. First, an autosizing run is completed using the square footage of the entire building. The key takeaways from this run are the efficiencies for any building-scale HVAC components, primarily chillers. Chillers have large variations in efficiency based on the size of the building they serve. Larger buildings have greater efficiency requirements because their energy performance has a larger impact on the environment. Thus, sizing HVAC components solely based on the size of the tenant space would result in less accurate energy consumption results.

The chiller efficiency value from the full-building sizing run is then applied to a second autosizing run, this time using the square footage of the tenant space. The HVAC system thereby captures the efficiency of a chiller sized for the entire building, while only being sized to serve a single space. To account for these changes, NREL developed a new OpenStudio measure and added it to the PAT simulation. The new measure conducts a sizing run for the entire building, extracts the chiller efficiency value, and replaces the efficiency in the tenant space sizing run.

This measure is only relevant for buildings that fall in the Large Office category, as the small and medium office HVAC systems do not include chillers. For small and medium offices, the PAT analysis skips the full-building sizing run measure.

The only limitation of this new approach is that the tenant space may not run at exactly the same part-load ratio as the entire building; however, we believe this improvement will lead to a more accurate HVAC annual energy consumption estimate as compared to the pilot version.

3.4.3.3 Outdoor Air

Ventilation rates by floor area are laid out in the prototype building models and follow ASHRAE Standards 90.1 and 62.1. For buildings with ASHRAE 90.1-2007 or later, a ventilation rate of 0.085 cfm/ft^2 is assumed for the entire office space. For ASHRAE 90.1-2004 or earlier, this value is 0.100 cfm/ft^2 (ASHRAE 2013). The prototype models assume the same ventilation rate for all zones.

Infiltration rates are set in the *Set Space Infiltration By Exterior Surface Area* measure. This measure models a range of infiltration rates of 0.06-0.22 cfm/ft^2. The survey does not ask tenants to enter an infiltration rate for their building or tenant space. Instead, a reasonable range is modeled in the parameter space, and this is encompassed in the HVAC energy consumption range outputted to the tenant.

3.4.3.4 Economizers

The ASHRAE 90.1 standards determine whether buildings require economizers. Each version of ASHRAE 90.1 outlines the requirements based on climate zone and cooling capacity. Generally, warmer and more humid climate zones do not require economizers. According to ASHRAE 90.1-2013, climate zones 1a, 1b, 2a, 3a, and 4a do not require economizers. In 2b, 5a, 6a, 7, and 8, economizers are required when the building's cooling capacity exceeds 135,000 Btu/hr. In 3b, 3c, 4b, 4c, 5b, 5c, and 6b, the minimum cooling capacity requiring economizers is 65,000 Btu/hr (ASHRAE 2013). These requirements vary slightly from one version of ASHRAE 90.1 to the next. The target standard chosen for the tenant space determines the requirements for adding economizers to the model.

3.4.3.5 Minimum Efficiency

The code-minimum efficiency for heating and cooling equipment depends on system type and size. The minimum efficiencies for HVAC equipment are used in the building models, including any part-load efficiencies if specified, to define the baseline building equipment performance. ASHRAE 90.1 requires that natural gas-fired water boilers larger than 2.5 million Btu/h (732.7 kW) to have a minimum efficiency of 80% of the combustion efficiency (ASHRAE 2013).

3.4.3.6 VAV Fan Power Assumptions

For HVAC systems with a variable air volume unit, the following VAV fan power assumptions are made (Table 10).

Table 10. HVAC Fan Inputs

Model Parameter	Small Office	Medium Office	Large Office
Fan Type	Constant Volume	Variable Volume	Variable Volume
Fan Efficiency	69.99%	60.45%	60.45%
Pressure Rise (in H_2O)	2.01		
Maximum Flow Rate	Autosized		
Motor Efficiency	90%	93%	93%
Motor in Airstream Fraction	1		

Source: (DOE 2018)

4 Validation and Results

4.1 QA/QC Protocol

As discussed in Section 2, a series of quality assurance and quality control checks were implemented during this round of analysis. These QA/QC checks ensure that the modeling procedures used result in properly sized systems and normal building operation.

4.1.1 System Sizing

Three QA/QC sizing checks were followed to determine if the HVAC systems selected can meet the thermal loads of a vast range of office spaces. Several assumptions regarding system sizing were made and are summarized/justified below:

- For all models, a vacant building (zero internal load) assumption was used to size the HVAC systems, as is standard practice by engineers. In reality, some base load due to lighting and equipment is always present. Thus, sizing HVAC systems with zero base load is a conservative approach that typically leads to slight oversizing.
- The OpenStudio default sizing factors of 1.25 for cooling and 1.15 for heating were used. Sizing factors greater than 1 provide an additional margin of safety in the case of extreme weather or unusually high internal loads.
- The default non-coincident plant sizing routine was used for all models. This means HVAC systems are sized based on the sum of zone loads, regardless of when they occur. Coincident sizing is the peak sum of all loads at any given time, typically represented in design sizing by assuming a diversity factor of ~70% on the non-coincident load sum. Non-coincident sizing is another conservative approach that further contributes to oversizing of HVAC equipment.

Unmet hours, part-load ratios, and several other validation checks were used to analyze system sizing. A preliminary run of 1,500 simulations was conducted to identify any major sizing issues or QA/QC flags.

- Unmet Hours
  - Out of 1,500 data points, 0.4% exceeded the unmet hours threshold of 600 (300 heating unmet hours, 300 cooling unmet hours) during occupied hours with a temperature tolerance of 2°F;
  - Packaged single-zone HVAC systems (corresponds to small office) were the most common system experiencing high unmet hours;
  - As expected, climate zones with extreme weather conditions experienced either high cooling unmet hours (i.e., Miami) or high heating unmet hours (i.e., Duluth, Fairbanks), but not both;
  - Most occupied unmet hours occurred during the morning or evening hours, when temperature setpoints and occupancy levels were undergoing sharp changes. Generally, during the middle of the workday, the HVAC system maintained its temperature setpoints.
    - This indicates that schedules were the main cause of unmet hours, as opposed to improper system sizing.

        - To account for this, the start time of the HVAC availability schedules was moved up by one hour, such that the HVAC system is fully running before the building reaches maximum occupancy.

- PLRs
    - A summary of the different HVAC components analyzed for the PLR QA/QC check is below. Not all components apply to all building sizes and HVAC system types, which is indicated in parentheses.
        - Chillers (Large Office only): PLRs reach 0.6-0.8 during maximum load conditions, indicating slight oversizing. This is reasonable considering the factors listed above that contribute to oversizing of the cooling system.
        - Cooling Towers (Large Office only): PLRs rise above 0.9 at times, indicating undersizing. This is a result of oversimplified condenser loop logic. The default setting is a constant 70°F temperature setpoint in the condenser loop, causing the cooling tower to operate near or at full load to decrease the water temperature to 70°F. This is unrealistic at warmer times of year when the water temperature does not need to be as low as 70°F. To resolve this issue, we have implemented more complex logic in which the condenser loop setpoint adjusts based on outdoor air temperature, replacing the constant 70°F setpoint.
        - Boilers (Large Office, Medium Office): PLRs are typically under 0.5, indicating significant oversizing. This is not a major concern, considering the factors listed above that contribute to oversizing of the heating system. In addition, boilers in real buildings tend to be oversized as a precaution because the cost of boilers increases minimally with capacity.
        - Electric Reheat Coils: PLRs are typically under 0.5, indicating significant oversizing. This is not a major concern because oversized heating coils do not affect the energy consumption results for the building.
        - Direct Expansion Cooling Coils (Medium Office only): PLRs reach 0.6-0.8 during maximum load conditions, indicating slight oversizing. This is reasonable, considering the factors listed above that contribute to oversizing of the cooling system.
        - Gas Heating Coils (Small Office only): PLRs are typically under 0.5, indicating significant oversizing. This is not a major concern because oversized heating coils do not affect the energy consumption results for the building.
        - Electric Backup Heating Coils (Small Office only): PLRs are zero at nearly all times, indicating that the backup coils are rarely used. This is to be expected and is not a concern.

- Validation. Checked pressure drops across fans, validated that economizers turn on/off with heating and cooling loads, and ensured HVAC energy usage versus temperature follows an expected relationship.

- Fan Pressure Rise
  - The fan pressure rise variable was examined for each HVAC system type to ensure values are reasonable. This model parameter was taken directly from the OpenStudio-Standards library, so the fan pressure rise in our models is consistent with typical engineering practice. The fan pressure rise ranges for each HVAC system type are as follows:
    - VAV with Reheat: 5.58-6.32 in H_2O
    - VAV with PFP Boxes: 5.58-6.32 in H_2O
    - PVAV with Reheat: 4.00-6.32 in H_2O
    - PVAV with PFP Boxes: 5.58-6.32 in H_2O
    - PSZ-AC: 2.5 in H_2O
    - PSZ-HP: 2.5 in H_2O
- Economizers
  - The default schedule for economizers is set to "Always On," meaning economizers operate whenever the outdoor air is a suitable temperature and condition. This ensures economizers will turn on or off whenever necessary to meet the heating and cooling loads most efficiently.
- HVAC Energy Use Versus Temperature
  - To ensure the HVAC systems were operating as intended and responding properly to outdoor temperature, we tracked HVAC energy use versus outdoor air drybulb temperature for each climate zone and HVAC system type. We expect heating energy to be inversely related to outdoor temperature and cooling energy to be directly related. In addition, warmer climate zones should use more cooling, while colder climate zones should use more heating.
    - In Figure 4, we show a large building in Burlington, Vermont, with a VAV with reheat (electric cooling, fossil fuel heating) HVAC system. The heating energy well exceeds cooling, which is to be expected in a cold climate such as Burlington.
    - Figure 5 shows a medium-sized building in El Paso, Texas, with a PVAV with PFP boxes (electric cooling, electric heating) system. The cooling energy well exceeds heating, which is to be expected in a warm climate such as El Paso.
    - Figure 6 is a small building in Chicago, Illinois, with a packaged single-zone heat pump (electric cooling, electric heating) system. Significant heating and cooling loads are present at different times of year, which is to be expected in a moderate climate such as Chicago.

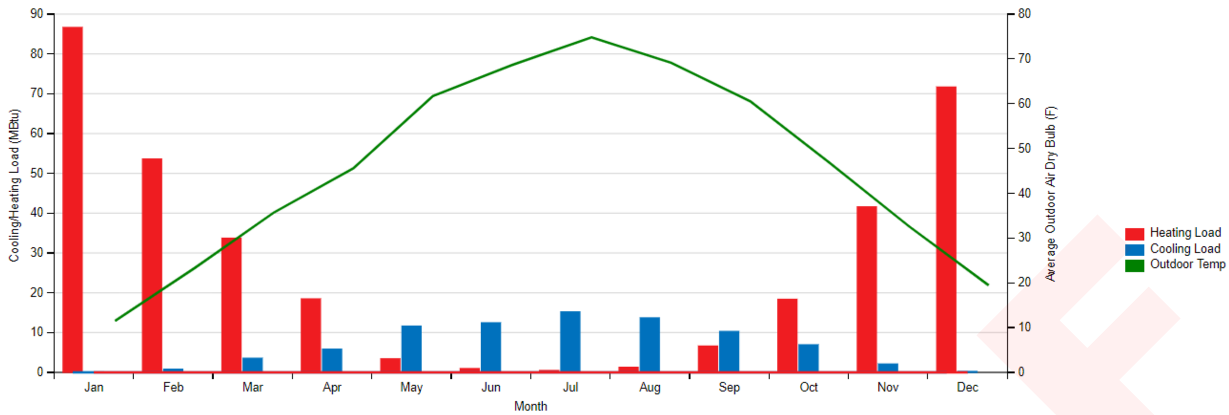


Figure 4. HVAC energy use vs. temperature for large building, Burlington, Vermont, fossil fuel heating

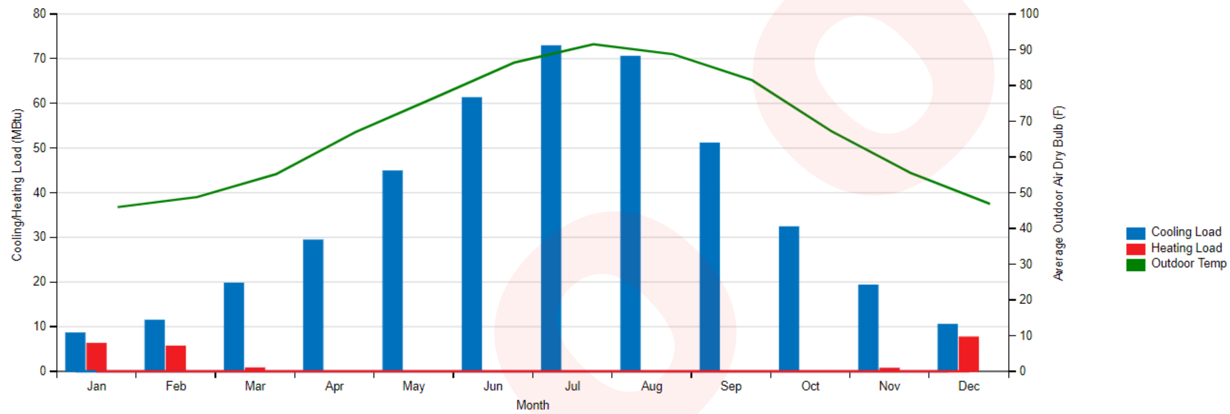


Figure 5. HVAC energy use vs. temperature for medium building, El Paso, Texas, electric heating

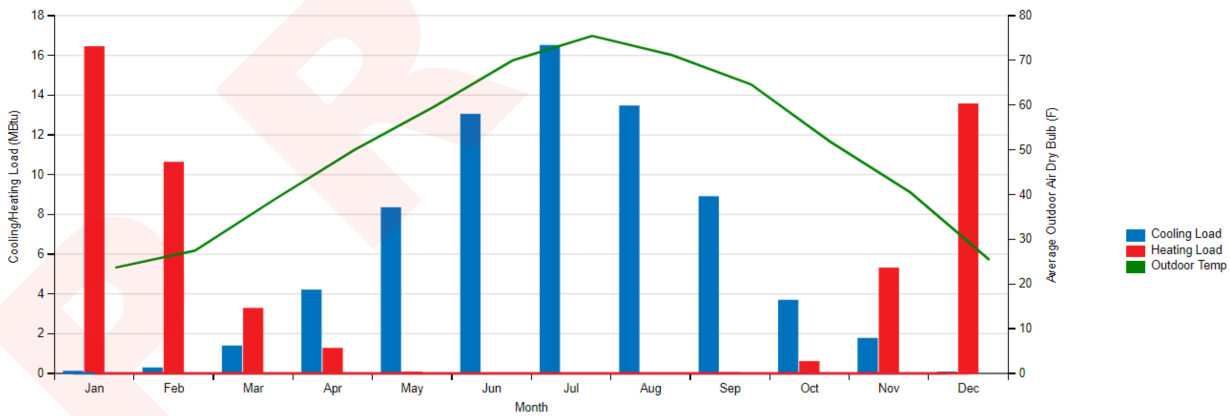


Figure 6. HVAC energy use vs. temperature for small building, Chicago, Illinois, electric heating

4.1.2 Internal Loads

Additional QA/QC checks related to internal loads and schedules were applied during the analysis process. Internal load densities are calculated from the tenant's survey inputs for equipment, lighting, and number of workers; however, the schedules for internal loads must be inferred by the *Create Parametric Schedules* measure from the number of weekly operating hours entered by the tenant. The following QA/QC checks ensured the internal loads and schedules are reasonable and operating as intended:

- Internal Load Schedules
  - Equipment, lighting, and occupancy follow the schedules generated by the *Create Parametric Schedules* measure. For a given number of operating hours per week, the measure generates typical internal load schedules for an office space.
  - Examples of equipment, lighting, and occupancy schedules are shown below for 62, 40, and 32 operating hours per week, respectively. The measure generates separate schedules for weekdays, Saturdays, and Sundays based on the logic described in Subsection 3.1.3.
    - The model with 62 weekly operating hours, as shown in Figure 7, assumes office equipment is in use for long hours on Monday through Friday. In addition, equipment is in full use for part of Saturday to reach 62 working hours per week.
    - Figure 8 represents the lighting schedule for a typical 40-hour work week. It assumes normal work hours for Monday through Friday. Some lighting is used on Saturday; however, it is far from the maximum load.
    - Figure 9 shows the parametric occupancy schedule for a 32-hour work week. This schedule assumes shortened workdays for Monday through Friday and low occupancy on Saturday and Sunday.
  - In the previously mentioned figures, the weekday, Saturday, and Sunday profiles (black lines) for internal loads are the schedules generated by the *Create Parametric Schedules* measure for 62, 40, and 32 hours per week. The weekly simulation graphs (orange/blue lines) show the OpenStudio output for equipment electric energy (Wh), lighting electric energy (Wh), and occupant count corresponding to each of the three schedule sets. The simulation outputs match the internal load profiles in each case, verifying OpenStudio is correctly applying the internal load parametric schedules to the models.

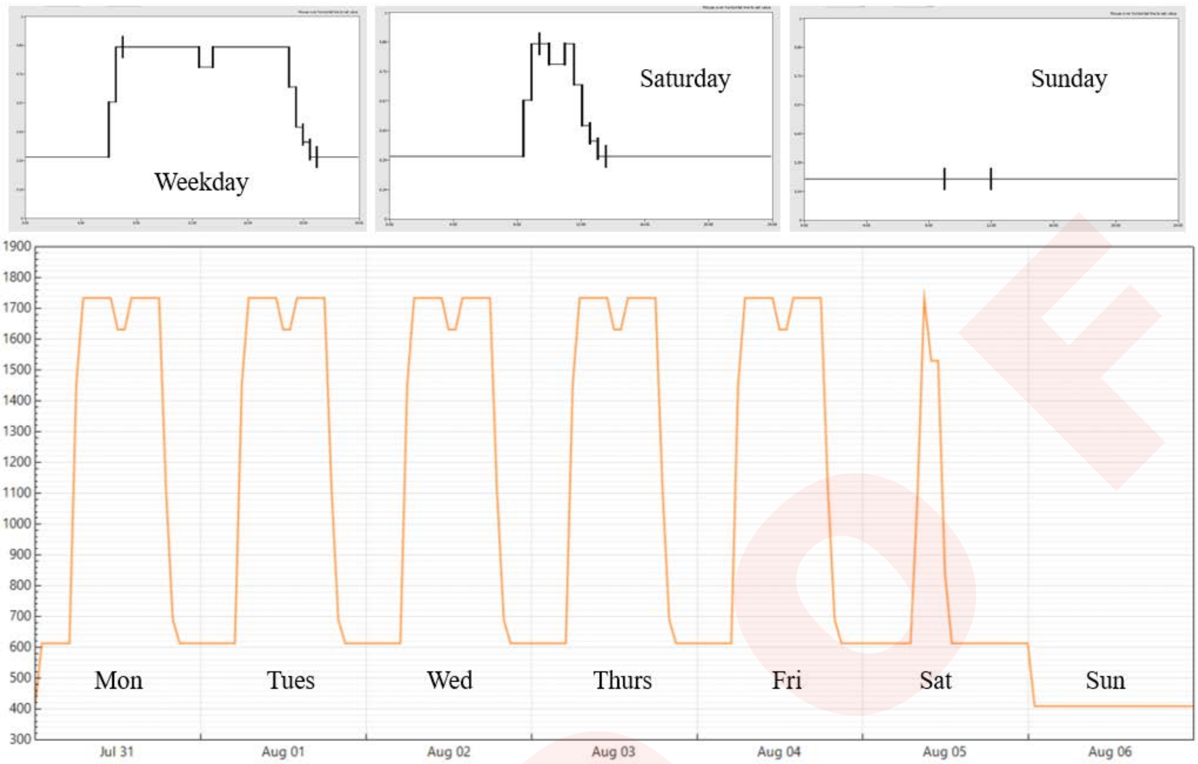


Figure 7. Parametric Electric Equipment Schedule, 62 hours/week

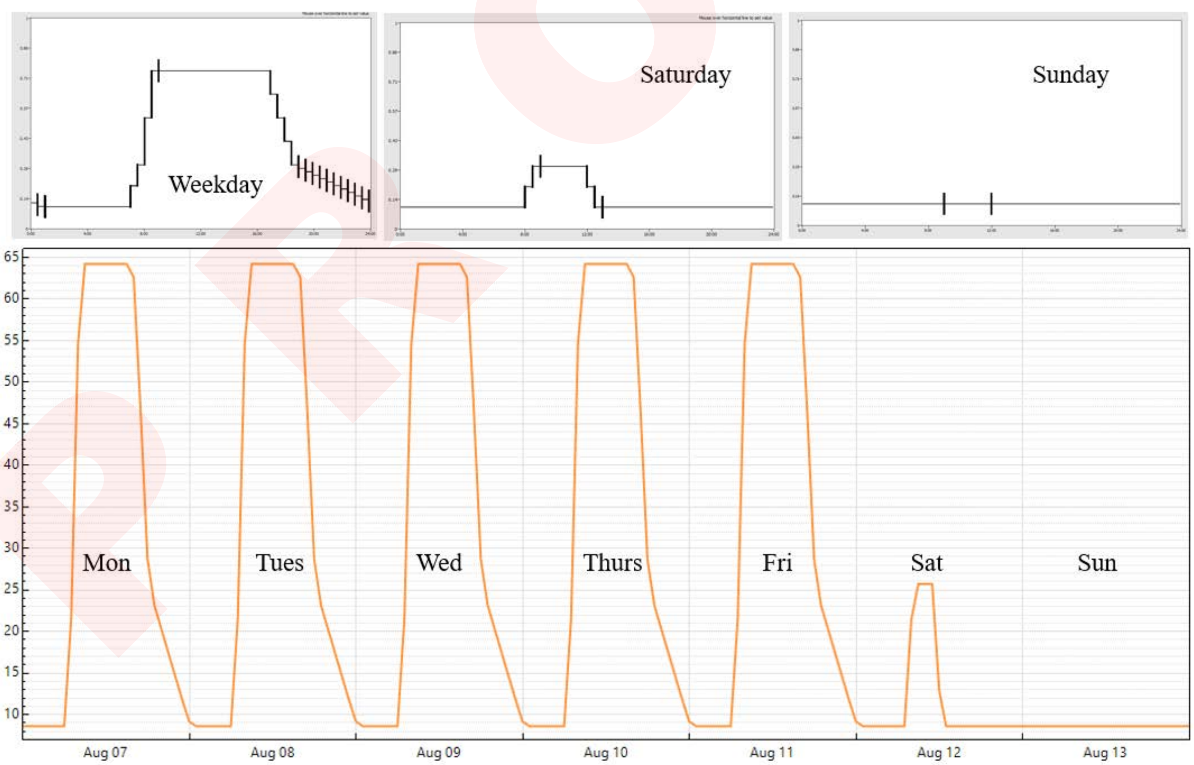


Figure 8. Parametric Lighting Schedule, 40 hours/week

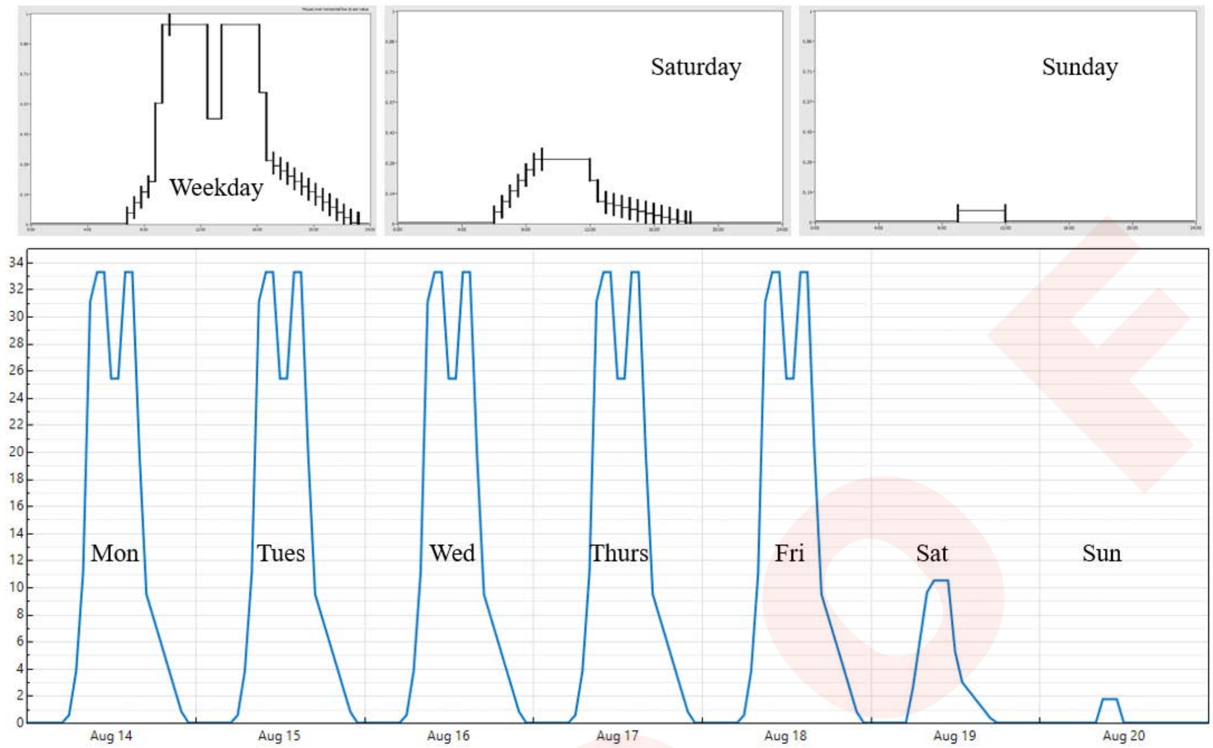


Figure 9. Parametric Occupancy Schedule, 32 hours/week

- Weekend Schedules
  - The goal of this QA/QC check was to ensure that internal load fractions and schedules for weekends and weekdays are operating as expected throughout the year. DView, a time series visualization tool often paired with OpenStudio, was used to generate heat maps corresponding to the three parametric schedules from the previous QA/QC check.
  - The heat maps shown below provide a way to visualize the equipment, lighting, and occupancy schedules during each day (vertical axis), as well as throughout the entire year (horizontal axis). The dark blue sections at the top and bottom of each map represent the nighttime, when minimal internal loads are present. The dark blue vertical stripes represent each weekend throughout the year, during which internal loads are much lower than weekdays. This confirms that the building models exhibit the expected behavior on weekends throughout the year.
      - Figure 10 corresponds to the Parametric Electric Equipment Schedule from Figure 7 for a 62-hour work week;
      - Figure 11 corresponds to the Parametric Lighting Schedule from Figure 8 for a 40-hour work week; and
      - Figure 12 corresponds to the Parametric Occupancy Schedule from Figure 9 for a 32-hour work week.
  - The steps that occur around March and November represent the one-hour adjustment for daylight saving time.

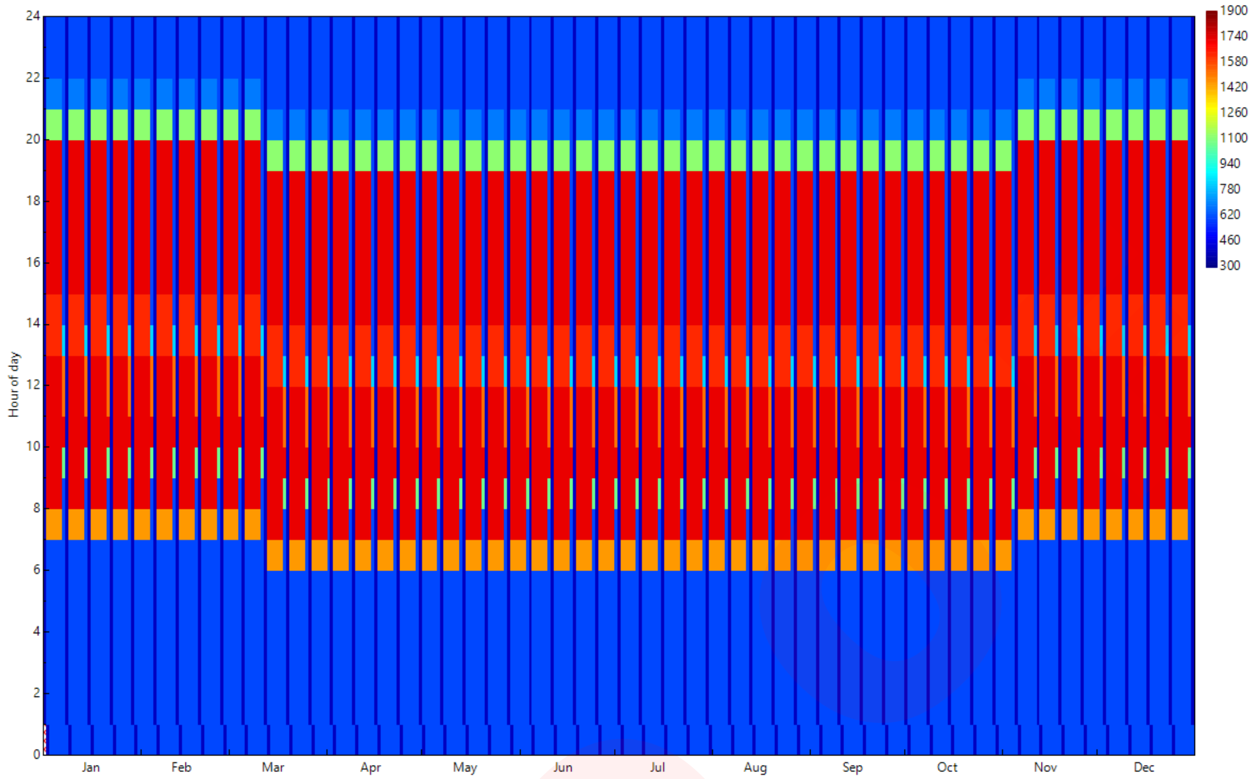


Figure 10. Heat map for Parametric Electric Equipment Schedule, 62 hours/week

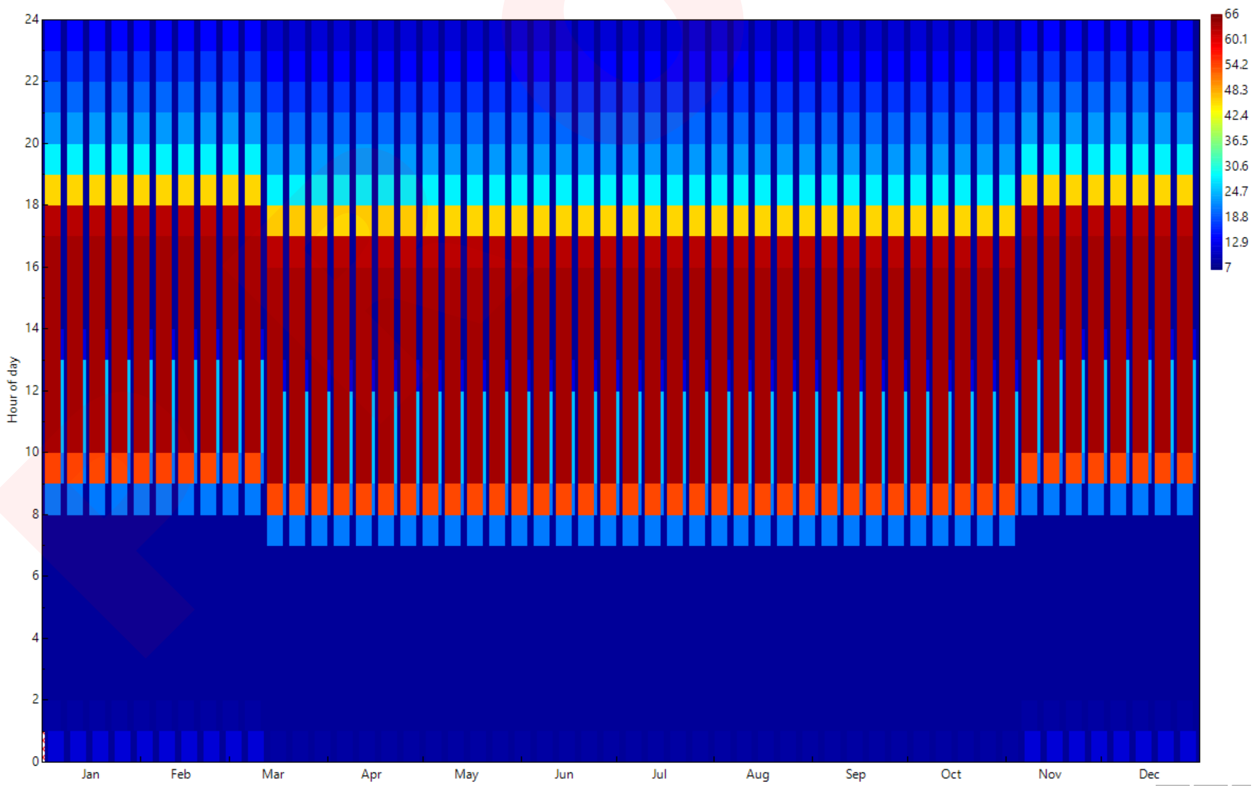


Figure 11. Heat map for Parametric Lighting Schedule, 40 hours/week

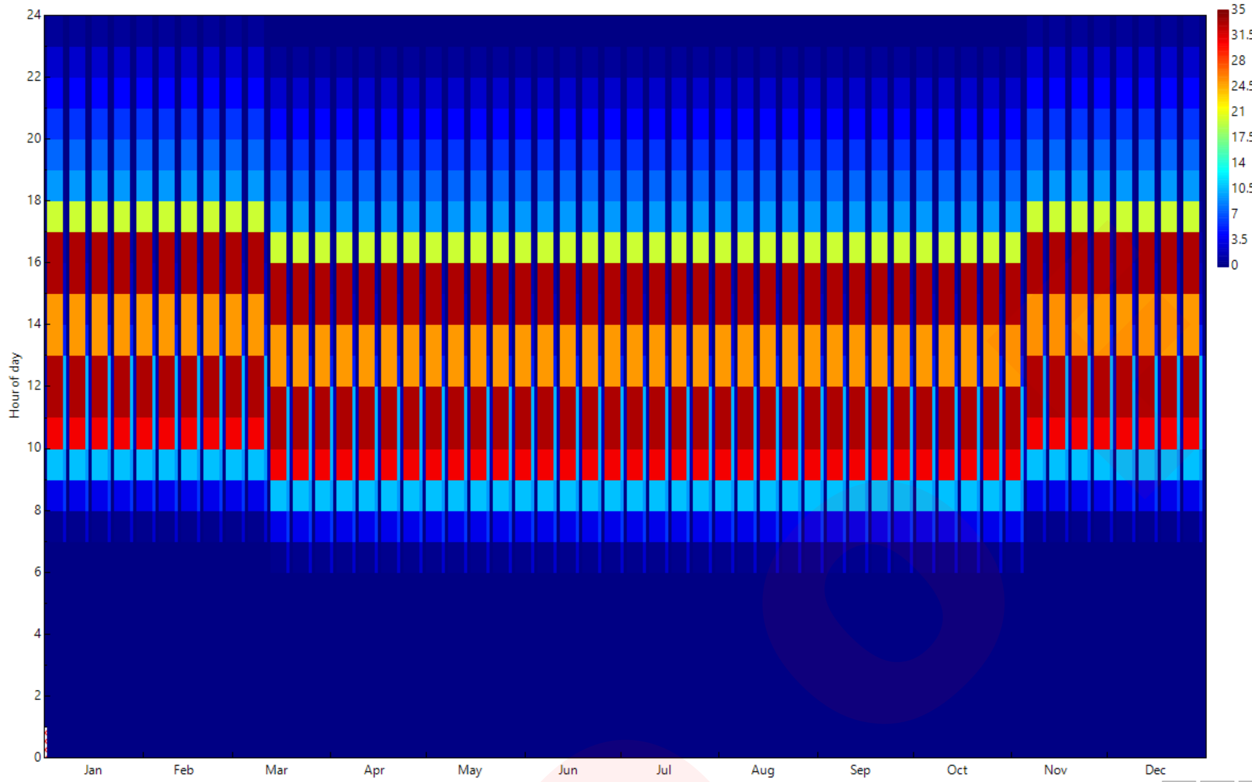


Figure 12. Heat map for Parametric Occupancy Schedule, 32 hours/week

4.2 Full Simulation

4.2.1 Number of Simulations

The preliminary QA/QC simulation consisted of 1,500 data points. No major concerns arose as a result of the QA/QC. The final step for the project was to complete a full run for each of the 15 climate zones. We first conducted a large run of 100,000 data points with the Chicago weather file. The goal was to determine an ideal number of simulations sufficient to generate a comprehensive parameter space of building models without using an excessive amount of computing time and power. We ran a regression analysis on the Chicago data set to evaluate the R-squared value as a function of the number of data points simulated. The results are shown in Figure 13.

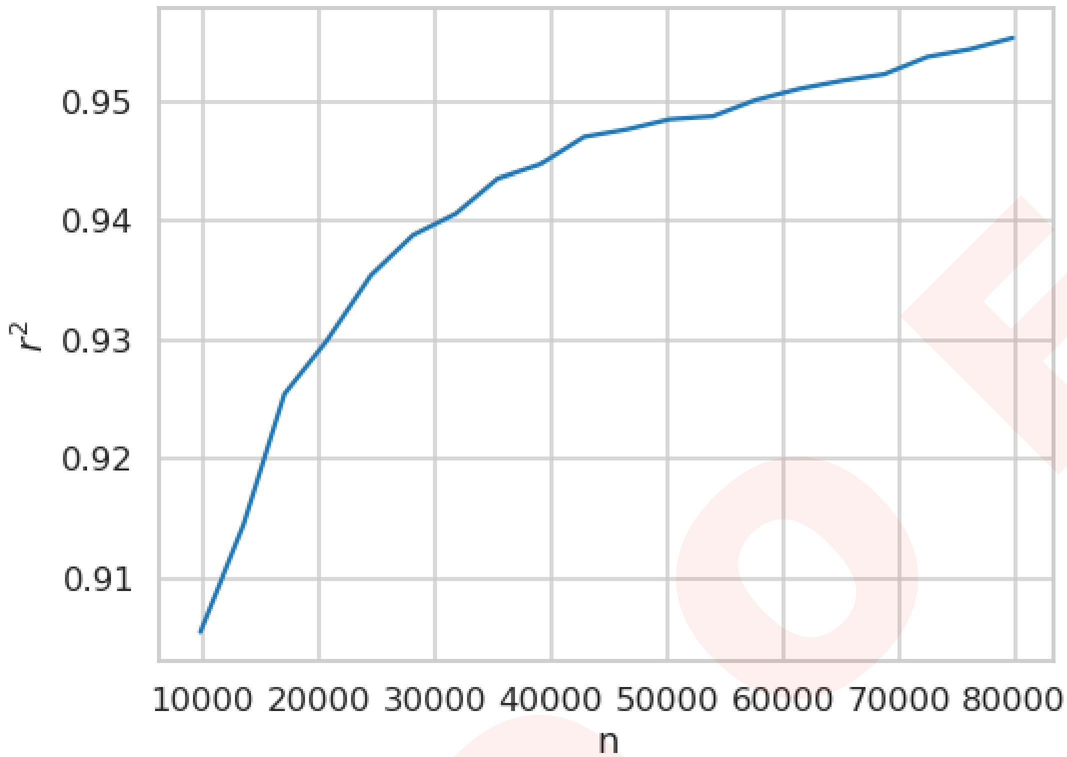


Figure 13. R-squared vs. number of data points, generated from Chicago 100,000-data point simulation

We see that the R-squared value is over 90% for any number of simulations over 10,000. This indicates that the random forest and lookup tables generated for 10,000 or more data points will include a 90% coverage of the parameter space. We decided to select 20,000 data points for our remaining simulations, which corresponds to an R-squared value of 0.93. Beyond 20,000, the R-squared value does not increase rapidly; we would need to triple the number of simulations to 60,000 to reach an R-squared of 0.95. Thus, the final simulation consisted of 20,000 data points for each of the 15 weather file locations—a total of 300,000 simulations. The simulations were completed on Amazon Web Service's Elastic Compute Cloud (EC2).

4.2.2 Parameter Bins

A set of 20,000 simulations was run for each of the 15 weather locations. For each weather file, a random forest regression model was generated. A lookup table was then built from each random forest model using a Python script. The purpose of the lookup tables is to represent every combination of building parameters that could be entered by a tenant. While including every possible combination of inputs is not practical due to file size limitations, the lookup tables generated have enough rows such that most combinations of tenant inputs will have an exact or at least a close match in the database of building models. This way, when a tenant fills out the online survey, the Tenant Estimation Tool accesses the lookup tables to identify the closest match and outputs the energy consumption values for that model.

When the lookup tables are generated, the script ranks the model parameters according to how much impact they have on the total energy consumption of the tenant space being modeled.

These rankings decide how many “bins” are generated for each model parameter in the lookup tables. Because there are practical limits on the size of the lookup tables, statistical data binning (also referred to as quantization) is used. Depending on the importance of the model parameter, anywhere from 3-10 bins are created, grouping values within a certain interval and representing them by one, often central, value. Each resulting lookup table contains approximately 130 million rows, representing 130 million combinations of tenant inputs.

Figure 14 and Figure 15 show the model parameter importance rankings for two climate zones, Baltimore and Miami. For all climate zones, the floor area of the tenant space had the biggest impact on the annual energy consumption. Because tenant floor area has the largest impact on the results, this parameter was given the largest number of bins for the lookup tables. The remaining model parameters, however, varied in importance based on the climatic conditions of the different locations. In Baltimore, WWR and HVAC system type were the second and third most important parameters; however, in Miami, where cooling loads are very significant, HVAC system type has a very big impact on a building’s energy consumption.

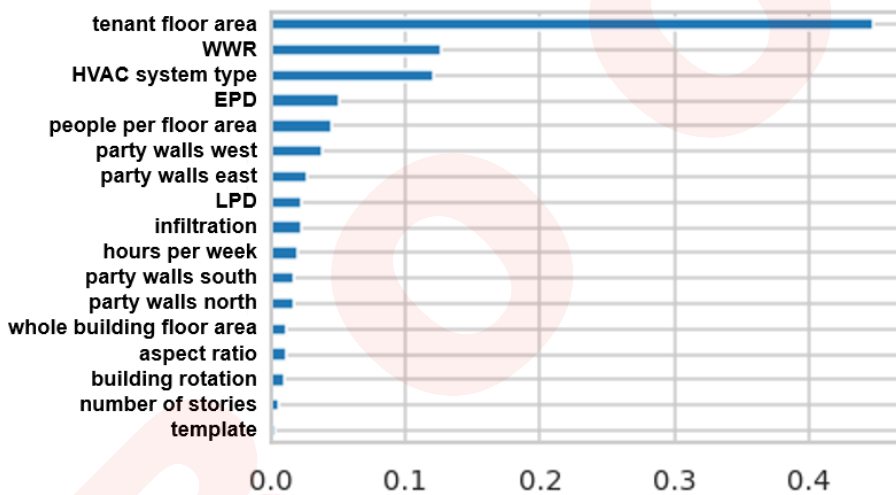


Figure 14. Model parameter importance, Baltimore

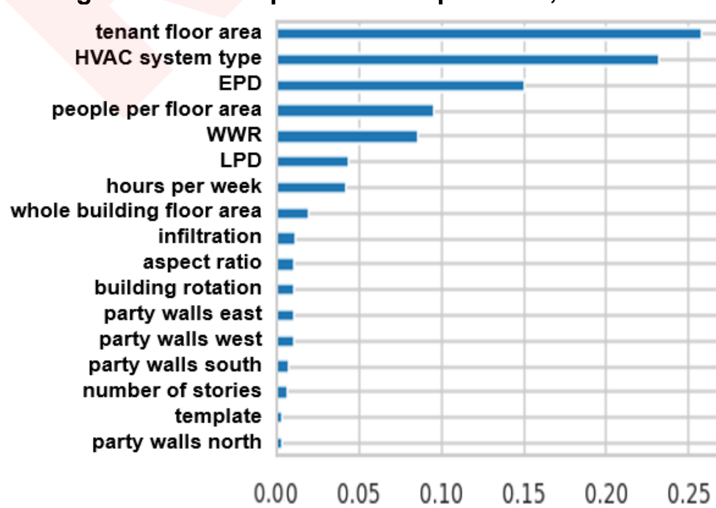


Figure 15. Model parameter importance, Miami

Building models in this project have 17 varying parameters, which are listed in Figure 14 and Figure 15 and summarized in Table 9 and Table 10. These parameters are derived from the tenants' inputs in the online survey. While some survey inputs map directly to model inputs, some require transformations to map to the fields in the lookup tables and retrieve the energy consumption predictions. The parameters were mapped to the correct lookup table row based on the following binning criteria:

1. Location: Use the Postal Code input to look up the climate zone in *climate_zone_lookup.csv*, then determine the corresponding representative city for this climate zone. This identifies which lookup table to use.
2. Exterior Exposure: Map the Building orientations for which the tenant floor/suite has exterior exposure (N/S/E/W) inputs to the lookup fields as follows. The lookup fields are 0 and 1; a "Y" (YES exterior exposure) in the input form maps to 0 in the lookup table (0 party walls); a "N" (NO exterior exposure) in the input form maps to 1 in the lookup table (1 party wall) (See Table 11).

Table 11. Exterior Exposure Lookup Fields

Web Form Input	Lookup Column Name
Building orientations for which tenant floor/suite has exterior exposure—East	*create_bar_from_building_type_ratios.party_wall_stories_east*
Building orientations for which tenant floor/suite has exterior exposure—South	*create_bar_from_building_type_ratios.party_wall_stories_south*
Building orientations for which tenant floor/suite has exterior exposure—West	*create_bar_from_building_type_ratios.party_wall_stories_west*
Building orientations for which tenant floor/suite has exterior exposure—North	*create_bar_from_building_type_ratios.party_wall_stories_north*

3. Number of Floors: Map the Total Number of Conditioned Floors in the Building input to the *tenant_star_whole_building_sizing.num_stories_above_grade* lookup column, as shown in Table 12.

Table 12. Number of Floors Lookup

Web Form Input	Lookup Value
1-3	2
4-5	6
>5	10

4. Vintage: Map the Year Building was Built input to the *create_bar_from_building_type_ratios.template* lookup column, as shown in Table 13.

Table 13. Vintage Lookup

Web Form Input	Corresponding Template	Lookup Value
2004 < x <= 2007	90.1-2004	0
1980<= x <= 2004	DOE Ref 1980-2004	1
< 1980	DOE Ref Pre-1980	2
2007< x <= 2010	90.1-2007	3
> 2013	90.1-2013	4
2010 < x <= 2013	90.1-2010	5

5. HVAC System: Use the What is the heating fuel for the building?, Building Gross Floor Area (sq. ft), and Total Number of Conditioned Floors in the Building inputs to determine

the value for the *create_typical_building_from_model_2.system_type* lookup column, as shown in Table 14.

Table 14. HVAC System Lookup

Web Form Inputs	Corresponding System Type	Lookup Value
Heating fuel = electric Floor area <= 25,000 Floors = 1-3	PSZ-HP	1
Heating fuel = electric Floor area > 25,000 and <= 150,000 Floors = 1-3 or 4-5	PVAV with PFP boxes	0
All other buildings with Heating Fuel = electric	VAV with PFP boxes	2
Heating fuel = fossil fuel Floor area <= 25,000 Floors = 1-3	PSZ-AC wit gas coil heat	3
Heating fuel = fossil fuel Floor area > 25,000 and <= 150,000 Floors = 1-3 or 4-5	PVAV with reheat	5
All other buildings with Heating Fuel = fossil fuel	VAV with reheat	4

6. Building Floor Area: Map the Building Gross Floor Area (sq. ft) input to the *tenant_star_whole_building_sizing.total_bldg_floor_area* lookup column, as shown in Table 15.

Table 15. Building Floor Area Lookup

Web Form Input	Lookup Value
< 52,500	30,000
52,500 <= x < 105,000	75,000
105,000 <= x < 150,000	135,000
>= 150,000	165,000

7. Tenant Suite Floor Area: Map the Tenant Suite Usable Floor Area (sq. ft) input to the *tenant_star_whole_building_sizing.total_bldg_floor_area* lookup column, as shown in Table 16.

Table 16. Tenant Suite Floor Area Lookup

Web Form Input	Lookup Value
< 7,500	5,000
7,500 <= x < 12,500	10,000
12,500 <= x < 17,500	15,000
17,500 <= x < 22,500	20,000
22,500 <= x < 27,500	25,000
27,500 <= x < 32,500	30,000
32,500 <= x < 37,500	35,000
37,500 <= x < 42,500	40,000
42,500 <= x < 47,500	45,000
>= 47,500	50,000

8. Weekly Operating Hours: Map the Weekly Operating Hours input to the *create_parametric_schedules.hoo_per_week* lookup column, as shown in Table 17.

Table 17. Weekly Operating Hours Lookup

Web Form Input	Lookup Value
< 35	30
35 <= x < 45	40
45 <= x < 55	50
55 <= x < 65	60
>= 65	70

9. Window-Wall Ratio: Map the Percent of tenant suite exterior walls which are glass input to the *create_bar_from_building_type_ratios.wwr* as shown in Table 18.

Table 18. Window-Wall Ratio Lookup

Web Form Input	Lookup Value
0-1%	0.05
2-10%	0.05
11-25%	0.18
26-50%	0.36
51-75%	0.63
76-100%	0.88

10. Occupancy: Divide the Number of Workers on Main Shift input by the Tenant Suite Usable Floor Area (sq. ft) input, and map the resulting occupancy density to the *tenant_star_internal_loads.people_per_floor_area* lookup column, as shown in Table 19.

Table 19. Occupancy Lookup

Web Form Input (# workers/tenant floor area)	Lookup Value
< 0.0054	0.0005
0.0054 <= x < 0.015	0.01025
>= 0.015	0.02

11. Convert the calculated site LEUI from the Lighting information section from kWh/sq. ft to kBtu/sq. ft, and multiply by the site-to-source conversion factor:

    new_value = LEUI * 3.412 * 2.8

    Map this new value to the *tenant_star_internal_loads.lpd* lookup column, as shown in Table 20

Table 20. LEUI Lookup

Web Form Input	Lookup Value
< 3	2
3 <= x < 5	4
5 <= x < 7	6
7 <= x < 9	8
>= 9	10

12. Equipment: Map the calculated EPD from the Equipment Information tab to the *tenant_star_internal_loads.epd* lookup column, as shown in Table 21.

Table 21. Equipment Lookup

Web Form Input	Lookup Value
< 0.225	0.05
0.225 <= x < 0.6	0.4
0.6 <= x < 1	0.8
1 <= x < 1.6	1.2
>= 1.6	2

5 Conclusions and Future Work

The goal of this work was to provide an online tool through which office building tenants could estimate their energy consumption based on a limited number of inputs. The development of this tool is part of a larger effort by the EPA to recognize tenants for their commitment to energy efficiency and environmental stewardship. This document outlines the modeling and analysis behind the online tool. The lookup tables generated from hundreds of thousands of simulations allow the web tool to access the nearest energy consumption results for any combination of user inputs. As mentioned in previous sections, simulation time and file size put a practical limit on the number of parameter bins that could be generated for the lookup tables. Each additional parameter bin effectively doubles the size of the lookup tables, and it becomes very difficult to downsample the analysis. The resolution of each variable was chosen wisely based on feedback from the Technical Review Committee and how much effect each variable had on the results. As a result, not every single combination of inputs was directly modeled, but rather the most similar model in the parameter space was used to generate outputs.

The simulation results have gone through some minimal verification and validation thus far, as described in the previous sections. The EnergyPlus physics-based simulation engine has been used and validated by engineers and architects for many years. Thorough testing and validation methodologies have been developed and adopted by ASHRAE in order to evaluate the accuracy of whole building energy simulation software, including EnergyPlus. (ASHRAE 2017; Judkoff & Neymark 2006). Thus, we are confident that the energy consumption results will be realistic for the inputs given. The larger question in this project is whether the online survey contains enough information to accurately model the user's office building. The answer to this question relies on Step 2 of the ENERGY STAR for Tenants recognition program: "meter energy use." In order to fully verify the accuracy of the online tool, we must compare tenants' results from the Tenant Estimation Tool to their actual meter data. This will give us insight into which aspects of the tool are accurately predicting energy consumption and which can be further improved.

After analyzing the results of the first iteration of the tool, we identified several areas for improvement, listed in Section 2.5. We made several important changes to this version of the tool, primarily with the equipment and HVAC, which we believe will result in more accurate energy consumption estimates. Once the tenants have completed Step 2 and provided sufficient meter data, we can confirm whether our modifications to the tool have improved its accuracy. Thus, our next steps include creating a series of checks to be evaluated once the new tool is online and the tenants have begun reporting their meter data. The purpose of these checks is to compare and analyze the results reported by the tool for a particular building to the actual energy consumption of the building.

Currently, the Tenant Estimation Tool only supports office buildings. However, the EPA has discussed the possibility of the expanding the ENERGY STAR for Tenants tool to include additional building types. This would require creating a similar online tool, with survey inputs adjusted to better represent the selected building type. The same modeling and simulation process would be done to generate the new lookup tables for each building type.

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