Variance and Optimization in Nonresidential Building Simulation Receptacle Loads

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ABSTRACT

A key challenge in developing nonresidential building simulation models involves accurately quantifying receptacle load energy consumption. These loads come from personal computers, printers, kitchen appliances, and other equipment. Every newly constructed building has some mix of these loads, but it's difficult to predict the eventual consumption impacts for the simulation model. Thus, most modelers rely on guidance from ASHRAE or simulation modeling software.

Simulation models can be calibrated using post-occupancy billing data and generally reveal variance between the original estimates and actual receptacle load consumption. This variance can impact the amount of energy savings due to interactive effects with HVAC loads.

This paper provides data on the variance between reported and actual receptacle load values to provide insight into trends and impacts. The results from 33 calibrated simulation models from different building types are used to inform:

- Variance between the reported receptacle load values and the receptacle load values determined by calibrated simulation modeling
- Comparisons between calibrated simulation receptacle loads and ASHRAE Standard 90.1 Appendix G (2013) values by building type
- Examination of average variance in two EPA climate zones, and resulting impacts on HVAC loads

This information provides guidance on key common issues when evaluating nonresidential new construction programs. It also emphasizes the importance of conducting calibration with sufficient post-occupancy billing data to more accurately characterize impacts. Evaluators can share these data and recommendations with utility program administrators and simulation model developers to better inform prospective baseline and design simulation models, which will lead to improved program realization rates.

Introduction

Commercial buildings account for 18% of the total energy consumption in the United States (EPA 2009). Energy efficiency has a growing role in commercial new building design and construction. Developers and building owners increasingly realize that cost-effective energy efficiency improvements allow them to drive down tenant costs (USGBC 2015). This allows developers to lease spaces at a more competitive price, which enables tenants to obtain lower fixed costs. Building owners or tenants can also get marketing value by certifying buildings through Leadership in Energy and Environmental Design (LEED) or other similar rating systems that often require some degree of energy efficiency.

Utilities increasingly recognize the value that energy efficiency in new construction can provide in generating substantial energy savings. These savings often represent what would be a lost opportunity post-construction. Whole-building energy simulation models generally provide the most effective method for characterizing the performance and benefits of integrated design options.

Most utilities set the new construction program energy efficiency code baseline as the state or jurisdiction's prevailing energy code at the time the construction permit was issued. In general, the energy code is a version of the ASHRAE 90.1 Standard with various jurisdiction-specific amendments. A project developer is usually required to create a baseline simulation model using code requirements for the building envelope, space conditioning equipment efficiencies, lighting power density, and other factors, to reflect the same operational parameters and occupancy patterns as the final design building. The reported energy savings represent the difference between design model annual energy consumption and code baseline model energy consumption.

Receptacle loads (also referred to as “plug loads”) are rarely scrutinized as part of a new construction energy efficiency project and often not considered for energy efficiency opportunities. NREL (2013) has led detailed studies on methods to identify and reduce receptacle loads on-site, which is helpful because these receptacle loads may represent up to 12% of the total energy consumption in all United States office buildings (CBECS 2012). This provides a strong rationale to further investigate the sources and impacts of receptacle loads in new construction.

Another strong rationale to explore receptacle loads involves studies of building energy use intensity (EUI). For example, one early study of LEED buildings (Turner and Frankel 2008) compared the EUI between LEED buildings and national EUI data from CBECS. However, these studies lack detail on the actual receptacle loads, and therefore cannot be used to effectively assess whether differences in EUI result from actual energy efficiency improvements or from differences in receptacle loads. These types of studies could benefit from a thorough investigation of average receptacle loads for various building types.

Methods to Estimate Receptacle Loads

Receptacle loads represent a broad category of equipment that can be plugged into a wall socket. These include refrigerators, computers, coffee makers, vending machines, and many more. These also represent loads that often cannot be controlled by a building designer. As a result, receptacle loads can represent a large and growing portion of the building’s overall energy consumption as designers reduce the energy consumption of lighting, HVAC, and water heating loads. Simulation modeling programs, such as eQuest, report the building’s combined receptacle load as part of the output data under the category of “miscellaneous equipment.” Figure 1 shows an example in which the same miscellaneous equipment load represents 10% of baseline building consumption but 29% of calibrated, as-built consumption.

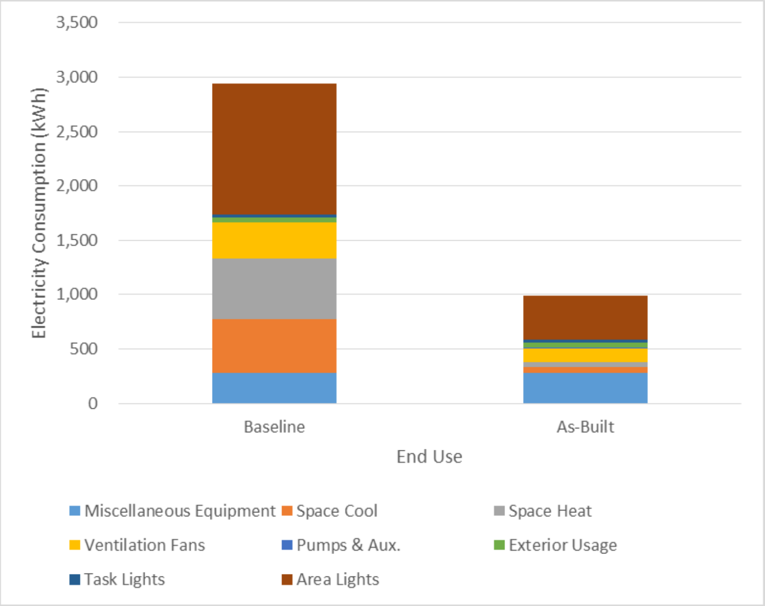
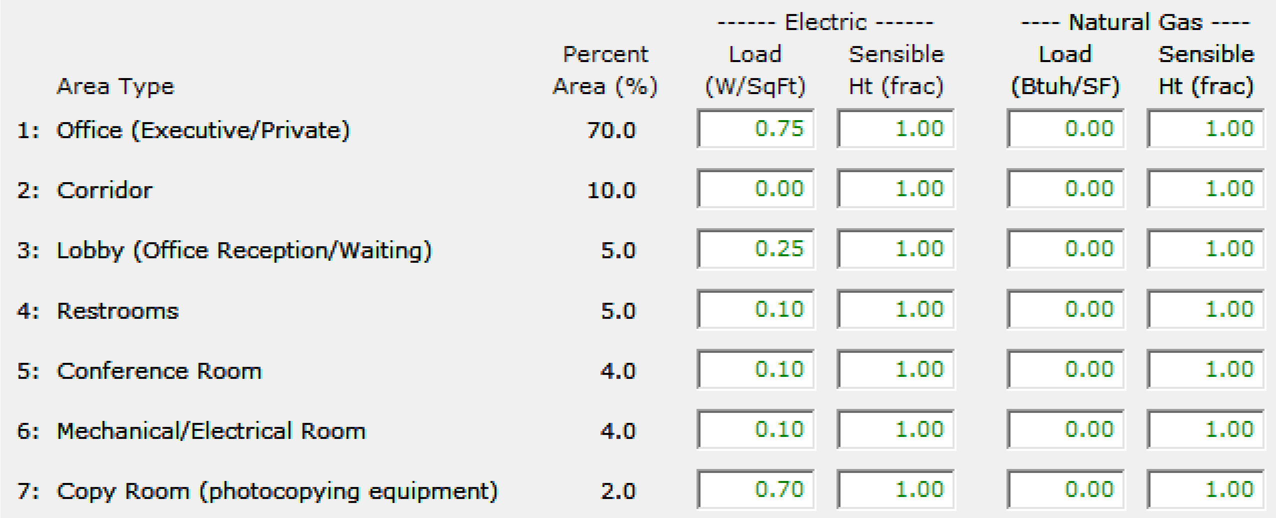


Figure 1. Example building with baseline and design loads. *Source:* Cadmus

Simulation modelers face another challenge in trying to estimate how many and what type of receptacle loads will be present throughout a building. Clients may try to estimate the eventual number of workstations, printers, and kitchens, but it's difficult to estimate the total receptacle load in advance.

To overcome this issue, ASHRAE 90.1 Appendix G provides guidance; however, an Appendix G model is not intended for comparison with actual consumption, but is a modeling protocol aimed at creating consistent relative comparisons for LEED Energy and Atmosphere Credit 1 points. This resource lists acceptable receptacle power densities in watts per square foot (W/ft^2) for various building types, such as health/institutional, hotel/motel, office, and schools. However, the listings of receptacle power densities only includes a small portion of building types, and is missing some types that represent a large portion of new building stock, such as high-rise multifamily. As a result, modelers must develop their own estimates of multifamily receptacle power density, either based on estimates from clients or experiential guidance (Fuertes and Schiavon 2014).

eQuest also provides default miscellaneous electric load values by space type for different building types, as well as the estimated percentage of a building area that each space type is expected to represent. Figure 2 shows default values for miscellaneous electric load by space type for a two-story office building.



		------ Electric ------		---- Natural Gas ----	
Area Type	Percent Area (%)	Load (W/SqFt)	Sensible Ht (frac)	Load (Btuh/SF)	Sensible Ht (frac)
1: Office (Executive/Private)	70.0	0.75	1.00	0.00	1.00
2: Corridor	10.0	0.00	1.00	0.00	1.00
3: Lobby (Office Reception/Waiting)	5.0	0.25	1.00	0.00	1.00
4: Restrooms	5.0	0.10	1.00	0.00	1.00
5: Conference Room	4.0	0.10	1.00	0.00	1.00
6: Mechanical/Electrical Room	4.0	0.10	1.00	0.00	1.00
7: Copy Room (photocopying equipment)	2.0	0.70	1.00	0.00	1.00

Figure 2. eQuest miscellaneous equipment power density default values for an office building. *Source:* Cadmus

Similar to ASHRAE, these values from eQuest may represent acceptable averages, but do not necessarily reflect the accurate load of a particular building. The only effective ways to accurately determine a building's miscellaneous power consumption are post-occupancy, and involve either a detailed receptacle load survey or calibration of the as-designed simulation model with utility billing data. While comparison studies between these two methods could not be found, such a comparison could yield valuable data on the efficacy of calibrated simulation modeling analysis. The following section summarizes a calibrated simulation analysis, building on previous work in this area (Cropp, Lee, and Castor 2014).

Post-Occupancy Model Calibration Process

Cadmus conducts impact evaluations following a new construction project being approved for an energy efficiency program. With these types of evaluations, we calculate the actual energy savings achieved by a sample of projects, to ensure that the energy efficiency program is cost-effective for ratepayers.

To verify reported program participation and estimate gross energy savings in the impact evaluation, we estimate changes in gross energy consumption between calibrated baseline and as-built simulation models. Given that these evaluations are for new construction programs, and that there is no prior basis for estimating energy consumption and savings, we build our calibration process on the original energy models submitted to demonstrate incentive compliance. Figure 3 provides an overview of the calibration process.

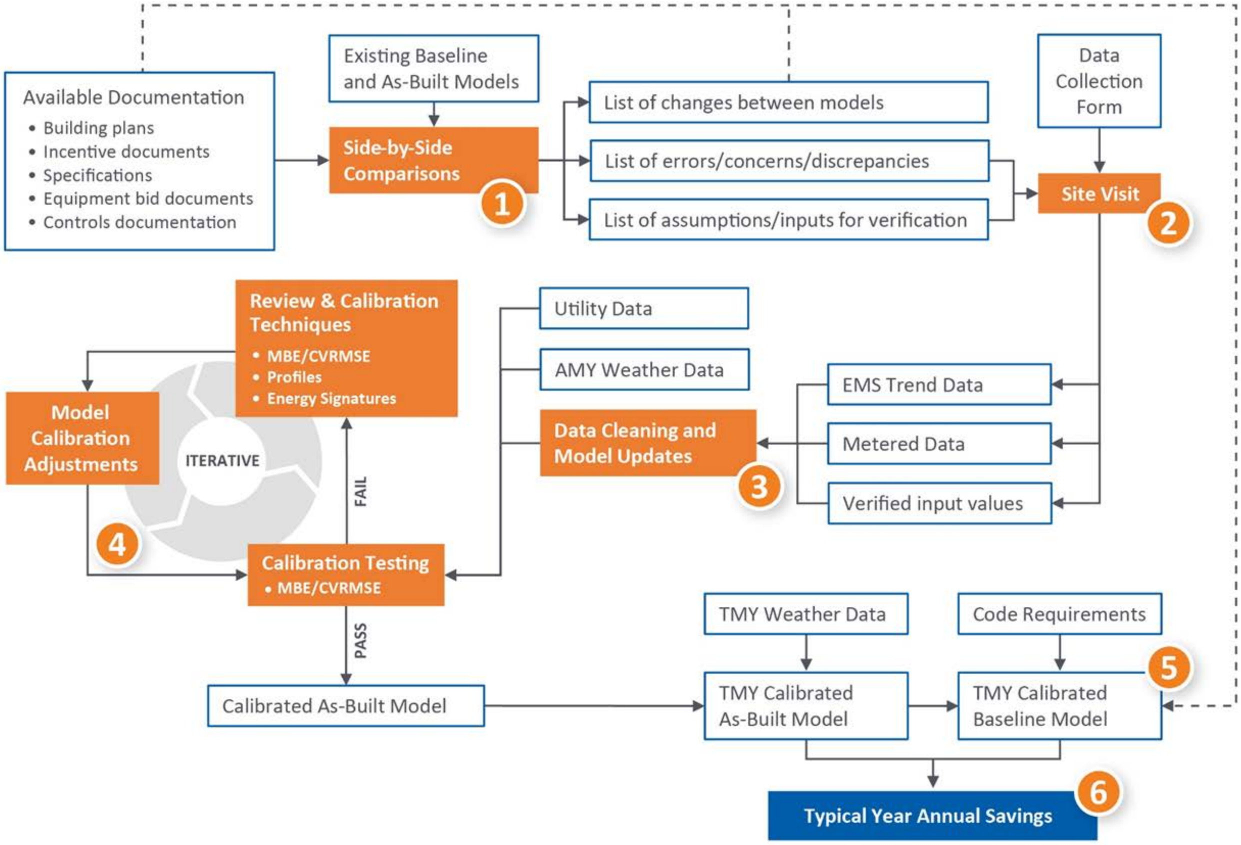


Figure 3. General overview of whole-building model calibration process. *Source:* Cadmus

To assess the results from 33 calibrated simulation models from different building types, Cadmus implemented the following steps (in chronological order) to transform original simulation models into calibrated models:

1. Side-by-side comparisons: We reviewed the original models received from the program staff to confirm whether the modeled measures matched the incented measures, both qualitatively and in magnitude. In instances where incented measures were not collectively modeled to account for interactive effects, we aggregated efficiency measures within one model to address interactive effects. We notified program staff and requested accurate models whenever modeled savings did not match the reported savings.

2. Site visits: In preparation for site visits, we identified any unusual consumption trends seen in the billing data (where available in advance) so that we could assess possible reasons during site visits and interviews with the site contact. Site contacts often had valuable insight on unusual

consumption trends based on operations rather than design. We conducted site visits to verify the modeled inputs such as envelope construction, energy system operational parameters, building operational schedules, and energy-efficient measure characteristics (such as quantities, capacities, and efficiencies) and to confirm whether the metered end-uses match the modeled end uses. We sampled spaces to estimate the typical installed lighting power density. Where accessible, we obtained energy management system trend data to better understand more detailed equipment operation cycles and set points. Wherever accessible, we documented the installation of energy efficiency measures by taking photographs of the physical measure and of nameplates indicating the rated equipment capacity and efficiency.

3. Data cleaning and model updates: Following the site visits, we updated the model with the verified values and actual meteorological year weather data for the appropriate location and time period. Cadmus used various tools, including Excel macros and custom Python packages, to facilitate data management and processing. Our model calibration process included aligning and scaling time series data, generating load shapes, converting raw metered data to formats suitable for analysis, and conducting batch detailed analysis for graphical and statistical comparison techniques.

4. Model calibration adjustments: We input verified values, then tested statistical calibration, comparing model results with utility and metered data. We incrementally calibrated the models using site verified data to simulate performance within ±10% of the metered data and to have no more than ±20% variance in actual versus calibrated energy on a monthly basis. The most common site-verified modifications included extending occupancy and system operations schedules, thermostat set points, and control set points, as well as adjusting the lighting power densities, plug loads, and equipment efficiencies. In a few instances, the calibration effort included adding energy end-uses such as elevators, exterior lights, or commercial kitchen appliances that were not originally modeled but reflected consumption in the building utility meter. Accounting for such non-incentivized building systems helped bridge the gap between the calibrated and actual energy consumption of the building and mimicked the associated interactive effects on incented measures.

5. Final model adjustments: Once we had satisfactorily calibrated the as-built model to match billing data, we revised the baseline models to match the operational parameters (schedules, receptacle loads, set points) of the calibrated as-built model. Finally, we calculated the typical annual evaluated savings for the project by running the models using typical meteorological year weather data.

The resulting model calibration often displayed the difference between reported and evaluated receptacle power load as a simple displacement, as shown in Figure 4. The monthly electricity consumption curves generally maintain a similar shape, but are offset from one another by the variance in base load, which is often the receptacle load.

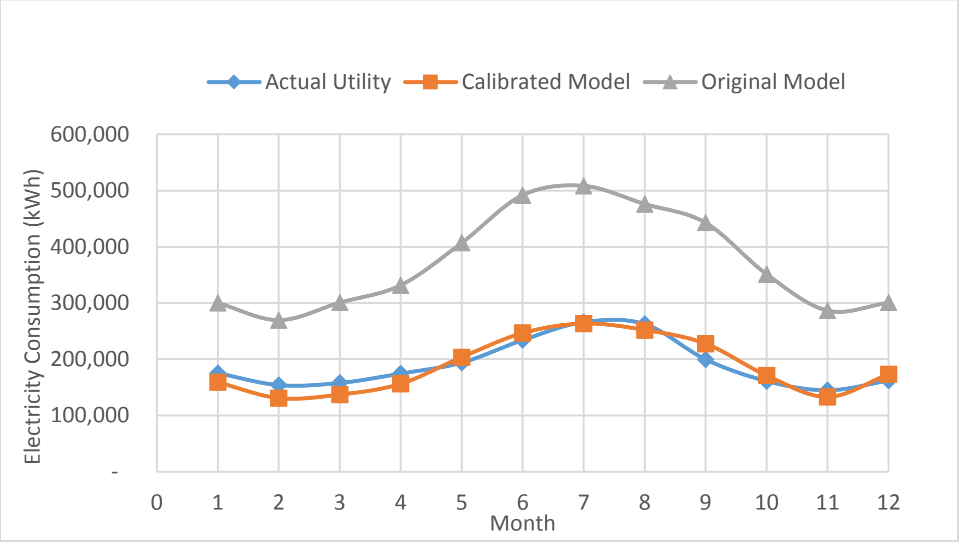


Figure 4. Comparison of original model consumption with utility billing data and calibrated model consumption. *Source:* Cadmus

Study Projects

This paper examines the calibrated simulation model results for 28 LEED new construction projects in EPA Climate Zone 4 (temperate marine environment) and five new construction projects in EPA Climate Zone 2 (hot, dry environment). The projects represent a range of building types, as shown in Table 1.

Table 1. Number of buildings in study by building type and climate zone

Building Type	Zone 2 Building Frequency	Zone 4 Building Frequency
Assembly	1	--
Automotive	--	1
Health/Institutional	--	1
Hotel/Motel	1	1
Infrastructure	--	1
Multifamily	1	6
Office	--	8
School	1	9
Warehouse	1	1
Total	5	28

Source: Cadmus

The results presented in this paper are primarily focused on the three building types for which we had the most data—multifamily, office, and schools—although there were variances within each of these building types due to the various building subtypes. For example, the school population included university classroom buildings, university residence halls, elementary schools, and one high school. We classified the remaining projects outside the three primary building types as the "other" category for the miscellaneous equipment load comparisons in the following section.

Miscellaneous Equipment Load Comparisons

To compare miscellaneous equipment loads, Cadmus reviewed the results of proposed and calibrated design models in eQuest. The proposed models represent the original simulation models developed prior to building construction, often relying on the ASHRAE defaults for receptacle power density. eQuest records outputs for the miscellaneous equipment power density in kilowatt-hours per square foot (kWh/ft^2) for the entire building. We used this value for comparison purposes rather than as the receptacle power density since most buildings included various power densities by space type within the building (e.g., classrooms, corridors, storerooms). In some cases, the simulation modeler applied a weighted average estimated power density across the entire building.

In most cases, the impact evaluation results indicated that calibrated miscellaneous equipment power density varied from the proposed power density based on actual equipment quantities, specifications, and operational parameters. Figure 5 shows the comparison of power density between the proposed receptacle and the calibrated simulation modeling. The trend line provides a hypothetical visual representation of a 100% realization rate, in which the calibrated consumption would equal the proposed consumption. Many projects achieved a realization rate below 100% (shown below the trend line), indicating that the calibrated power density is less than the proposed value. The data exclude two large outliers that would obscure the plotted scale results for smaller projects: one hospital with intensive loads and one office with an unusually high miscellaneous power density.

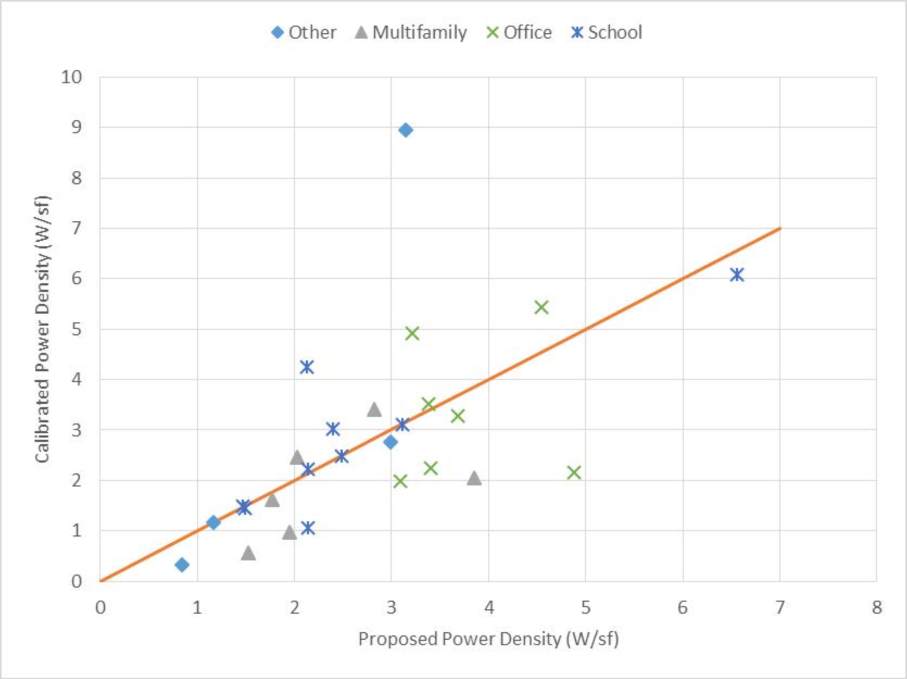


Figure 5. Comparison of proposed versus calibrated design receptacle power density in W/ft^2. *Source:* Cadmus

Despite the limited sample, it is possible to identify some trends based on results by building type. Tables 2 through 4 show the results for the three predominant building types in the sample. For comparison, we examined the proposed receptacle power density input by the simulation modeler for the predominant space type or whole building for each model. We normalized that based on the miscellaneous equipment power density values output by eQuest. We calculated the calibrated receptacle power density using the following equation:

$$CRpd = PRpd\ x\ \frac{CMEpd}{PMEpd}$$

Where:

CRpd = calibrated design model receptacle power density in W/ft^2
PRpd = proposed design model receptacle power density in W/ft^2
CMEpd = calibrated design miscellaneous equipment power density in kWh/ft^2
PMEpd = proposed design miscellaneous equipment power density in kWh/ft^2

Table 2. Comparison of receptacle power densities for multifamily buildings

Conditioned Area (ft^2)	Receptacle Power Density	
	Proposed (W/ft^2)	Calibrated (W/ft^2)
40,500	1.44	0.77
106,655	3.50	4.23
231,709	1.20	0.44
401,000	0.73	0.67
505,000	0.61	0.74

Source: Cadmus

The list in Table 2 excludes two multifamily buildings for which published receptacle power density data was not readily available. The multifamily receptacle power density estimates primarily reflect the modeler's experiential assumptions, in combination with client estimates of receptacle loads. In general, the actual multifamily receptacle loads were lower than the modeled estimates, indicating the modelers often overestimated the receptacle loads present in multifamily units. The data included one obvious outlier: a low-income multifamily housing project with an on-site medical clinic, which may have distorted the resulting miscellaneous equipment power density of 4.23 W/ft^2. Excluding this outlying project, we calculated the multifamily building area-weighted average receptacle power density as 0.66 W/ft^2.

Table 3. Comparison of receptacle power densities for office buildings

Conditioned Area (ft^2)	Receptacle Power Density	
	Proposed (W/ft^2)	Calibrated (W/ft^2)
33,200	0.71	0.72
42,765	1.00	1.53
85,000	0.75	0.78
142,468	1.00	0.64
143,120	0.95	0.85
260,000	1.10	0.49
309,012	1.77	2.12

Source: Cadmus

The list in Table 3 excludes one office building for which receptacle power density data was not readily available. For the simulation models in our sample, the original simulation modeler rarely relied on the office building power density estimate of 0.75 W/ft^2 from the ASHRAE 90.1 Appendix G guidelines.

Instead, they generally relied on experiential data, estimating power density as a function of building type and size. The modelers further refined their estimates with assumptions on computing power density. An office building that includes a large server room resulted in the highest power density of all office buildings in the sample, at 2.12 W/ft^2. We calculated the office building area-weighted average receptacle power density as 1.13 W/ft^2. Without the two relatively large outliers with significant server loads, the weighted average value is 0.65 W/ft^2. These results imply that the ASHRAE 90.1 Appendix G value may be reasonable for general office environments, but larger values in the range of 1.5 to 2.0 W/ft^2 may be more appropriate when the building incorporates server closets or relatively high computing power requirements.

Table 4. Comparison of receptacle power densities for school buildings

Conditioned Area (ft^2)	Receptacle Power Density	
	Proposed (W/ft^2)	Calibrated (W/ft^2)
27,000	0.75	0.75
57,945	0.70	1.40
68,700	0.50	0.46
70,000	1.00	1.04
92,400	1.00	0.97

Source: Cadmus

The list in Table 4 excludes four school buildings for which receptacle power density data was not readily available. As with office buildings, models of school buildings were rarely based on the guideline of 0.50 W/ft^2 from ASHRAE 90.1 Appendix G. Despite the range of building types, the results were roughly consistent and indicate the ASHRAE 90.1 Appendix G guideline is much too low to be reasonable. We calculated the school area-weighted average receptacle power density as 0.94 W/ft^2.

Interactive Effects Between Receptacle Loads and HVAC

The variance between proposed and calibrated receptacle load values has little impact on LEED Energy and Atmosphere Credit 1 points. However, these receptacle loads also generate significant amounts of waste heat that interact with the building HVAC system. These interactive effects can then impact the energy savings resulting from the difference between code baseline and energy-efficient equipment. Large variances in receptacle loads could potentially change the building requirements for space conditioning relative to original HVAC equipment sizing. We conducted a sensitivity analysis of the impacts of varying receptacle load on space cooling, ventilation, and space heating in both project regions. Figure 6 and 7 show the results of varying miscellaneous equipment power density on representative buildings in Climate Zones 2 and 4, respectively.

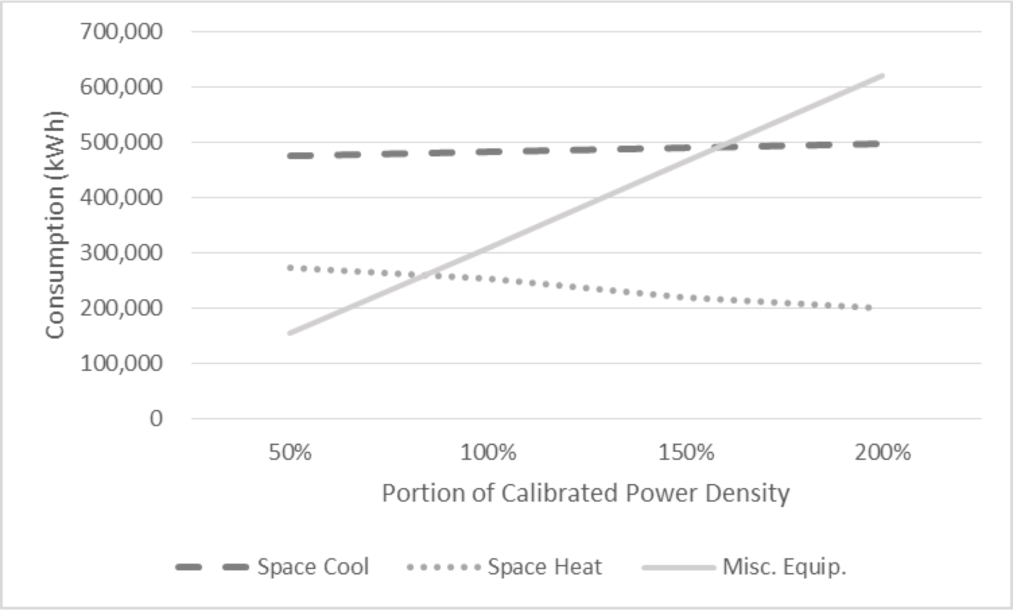


Figure 6. Impact of varying miscellaneous equipment power density on HVAC loads in Climate Zone 2 building.
Source: Cadmus

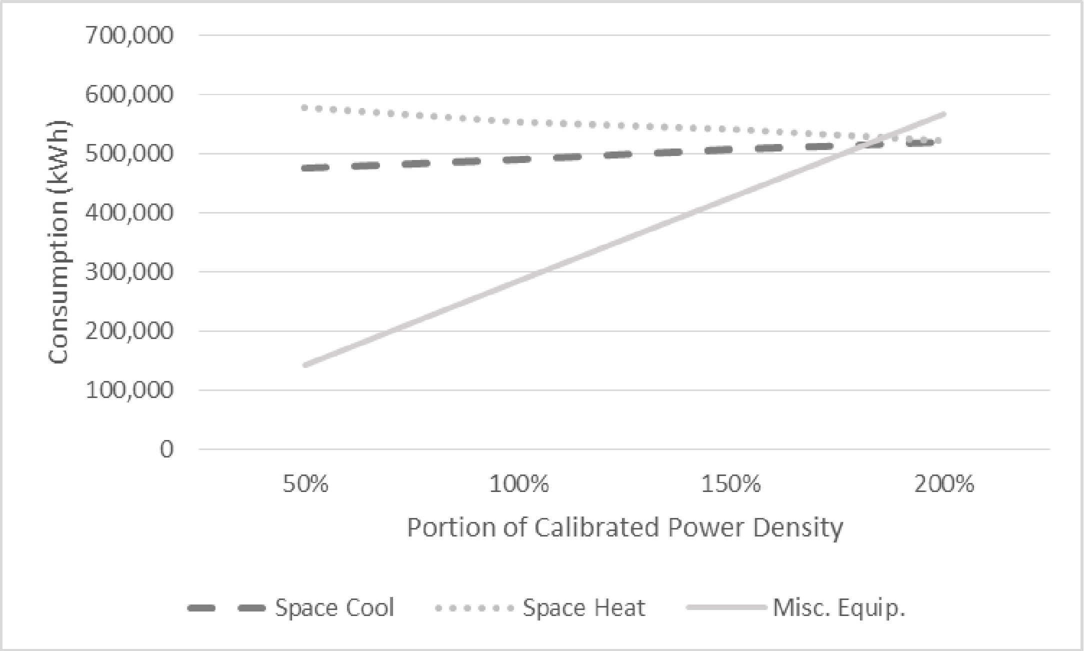


Figure 7. Impact of varying miscellaneous equipment power density on HVAC loads in Climate Zone 4 building.
Source: Cadmus

These variances in miscellaneous equipment power density alter the energy savings due to differences in code baseline and installed equipment energy efficiency parameters. The resulting impacts on energy savings for a representative building in Climate Zone 4 are shown in Figure 8.

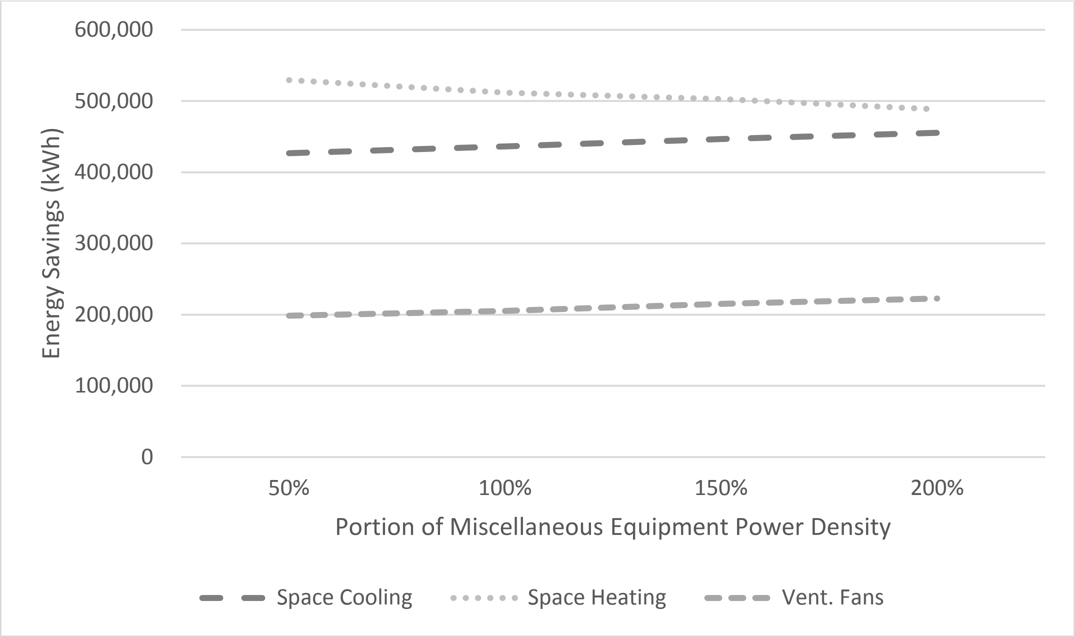


Figure 8. Impact of varying miscellaneous equipment power density on energy savings by end use. *Source:* Cadmus

For Climate Zone 4, a heating-dominant region, doubling the miscellaneous equipment loads actually causes a slight increase in overall energy savings of 1%. This is mainly driven by the difference between baseline and installed cooling equipment efficiency. Space heating savings decline, since the plug loads result in inefficient waste heat that offsets the space heating from a more efficient source.

Conclusions

In the course of numerous commercial new construction impact evaluations, we have identified that receptacle loads are a less scrutinized portion of building loads. These loads represent equipment that generally does not have an energy-efficient option, and therefore they represent a larger portion of building energy consumption as designers and builders work to meet increasing energy efficiency targets through state energy codes and programs such as LEED.

Simulation modelers have a variety of guidance on estimating building receptacle loads, such as ASHRAE 90.1 Appendix G and default values in eQuest. However, most modelers appear to rely extensively on a combination of customer-provided data and experiential assumptions in defining their estimates of receptacle load power density.

Cadmus' study of 33 new construction models calibrated with post-occupancy utility billing data revealed that the estimated receptacle power density rarely matched the actual values. We used the available study data to determine reasonable estimates of receptacle power density based on weighted averages. Those values are shown in Table 5.

Table 5. Recommended weighted average receptacle power density by building type

Building Type	Receptacle Power Density (W/ft^2)
Multifamily	0.66
Office with Large Computing Load	1.13
Office	0.65
School	0.94

Source: Cadmus

However, this was a relatively limited data set. Many consulting firms conduct third-party evaluation of utility energy efficiency programs, which often include calibrated simulation modeling on nonresidential new construction. The data from these various evaluations could be reviewed for consistency of methods, then combined into a much larger and more robust dataset to further inform factors such as the appropriate values for receptacle load power density.

After identifying accurate values for receptacle loads, the next step for building owners and energy efficiency program staff involves finding opportunities to reduce consumption from these loads. NREL (2013) has led detailed studies on methods to identify and reduce receptacle loads on-site that represent an important step in this direction.

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