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Evaluating the Energy Impact Potential of Energy Efficiency Measures for Retrofit Applications: A Case Study with U.S. Medium Office Buildings

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Abstract

Quantifying the energy savings of various energy efficiency measures (EEMs) for an energy retrofit project often necessitates an energy audit and detailed whole building energy modeling to evaluate the EEMs; however, this is often cost-prohibitive for small and medium buildings. In order to provide a defined guideline for projects with assumed common baseline characteristics, this paper applies a sensitivity analysis method to evaluate the impact of individual EEMs and to groups these into packages to produce deep energy savings for a sample prototype medium office building across 15 climate zones in the United States. We start with one baseline model for each climate zone and nine candidate EEMs with a range of efficiency levels for each EEM. Three energy performance indicators (EPIs) are defined, which are annual electricity use intensity, annual natural gas use intensity, and annual energy cost. Then, a Standard Regression Coefficient (SRC) sensitivity analysis method is applied to determine the sensitivity of each EEM with respect to the three EPIs, and the relative sensitivity of all EEMs are calculated to evaluate their energy impacts. For the selected range of efficiency levels, the results indicate that the EEMs with higher energy impacts (i.e., higher sensitivity) in most climate zones are high-performance windows, reduced interior lighting power, and reduced interior plug and process loads. However, the sensitivity of the EEMs also vary by climate zone and EPI; for example, improved opaque envelope insulation and efficiency of cooling and heating systems are found to have a high energy impact in cold and hot climates.

Key words: Energy Impact Evaluation, Energy Efficiency Measure, Medium Office, Energy Retrofit

1. Introduction

The 2012 Commercial Buildings Energy Consumption Survey (CBECS) shows that U.S. office buildings consume over 3×10^6 GJ of primary energy annually, and approximately 50% of this energy consumption is medium office buildings, which have floor areas from 1,000 m^2 to 10,000 m^2 (EIA 2017). Many studies have demonstrated that there is a great potential to reduce energy consumption by conducting existing building retrofits (Glazer 2016; Griffith et al. 2007; Thornton et al. 2011; Liu et al. 2011a; Liu et al. 2011b;

Moser et al. 2012; Wang et al. 2012). For instance, Thornton et al. (2011) concluded that the site energy savings for office buildings in the United States are approximately 25% by applying ASHARE Standard 90.1-2010 (ASHRAE 2010) instead of ASHARE Standard 90.1-2004 (ASHRAE 2004). To achieve energy savings during building retrofits, energy efficiency measures (EEMs) are adopted, which decrease the amount of energy needed while providing the same level of comfort or utility. However, the recommended EEMs often vary case by case, and it is important to select suitable EEMs for specific cases in order to optimize the retrofit by considering both energy and cost impacts.

Detailed building energy models are usually used in the retrofit projects for large buildings. However, these are often cost-prohibitive for smaller projects, such as medium office buildings. Instead, small retrofit projects typically rely on prescriptive methods for energy reduction strategies, which have their limitations. First, building owners often make independent retrofit decisions, but their knowledge may be limited in selecting EEMs that are most effective while minimizing cost. Second, building engineers have potential biases when selecting EEMs based on previous experience. Without comprehensive analyses, they tend to select some high-efficiency measures that from past projects demonstrated strong energy saving performance with the short payback periods; however, these techniques may not be suitable for the current project. Furthermore, by using prescriptive methods, it is possible to neglect some important factors, such as climates or occupancy schedules, and interactive relationships between EEMs. Therefore, the actual payback period of the energy retrofit of medium office buildings may be longer than expected.

To select appropriate EEMs with the highest energy saving potentials for small retrofit projects, it is useful to have readily available knowledge about which EEMs are most effective for the target building type and climate zone. A defined guideline can help various types of users – such as building owners, architects, and engineers – select prioritized EEMs in specific climate conditions. Before creating a defined guideline, we must answer two questions: (1) Which energy performance indicators (EPIs) do we use to quantify the cost effectiveness of EEMs? (2) Which method do we use to calculate these impacts?

For the first question, this study employs annual electricity use intensity and annual natural gas use intensity as EPIs for building energy use while annual energy cost for building energy cost. These EPIs support to evaluate an EEM's Return on Investment (ROI), which is one of the most critical metrics when deciding which EEMs to implement in building retrofit projects (Stadler et al. 2013). The ROI considers both energy cost savings and retrofit cost for building energy retrofit projects. While investments such as materials and installation costs are easily estimated, the evaluation of annual energy costs during the building's operation is more complicated. Therefore, this paper focuses on developing a methodology to evaluate annual energy costs during the building's operation.

Annual energy costs include electricity and natural gas costs. National average energy prices for electricity and natural gas are used, which represent a blended rate of energy pricing for both consumption and demand charges. To calculate ROI, users only need to obtain energy unit prices and initial investment costs from the market, while directly applying the climate-specific energy results herein to make final evaluations. Nowadays, the static natural gas pricing program is usually used in commercial buildings. However, evaluating annual electricity costs are less straight forward; there are several electricity pricing programs that vary across U.S. commercial building types and locations (Albadi and El-Saadany 2007; Doostizadeh and Ghasemi 2012; Joskow and Wolfram 2012). Currently, many areas in the United States use dynamic electricity pricing programs for commercial buildings, for which electricity costs need to consider both annual electricity consumption and monthly peak power load. Thus, this study also discusses the probability to consider the dynamic electricity pricing programs.

For the second question, there are multiple methods to guide EEM selection in retrofit applications, such as engineering judgement, building energy codes, and published guidelines. While these prescriptive methods are frequently used, their effectiveness can be limited by human biases and their generalized nature, as previously discussed. To this end, a guideline based on sensitivity analysis can provide unbiased recommendations that are appropriate for the target project location. Furthermore, such recommendations allow us to identify the interactive relationships between various EEMs. Existing research provides a rich set of references to identify effective EEMs for individual buildings by conducting sensitivity analysis (Breesch and Janssens 2010; Corrado and Mechri 2009; Delgarm et al. 2018; Eisenhower et al. 2012; Heo et al. 2012; Hygh et al. 2012; Li et al. 2018; NBI 2013; Nguyen and Reiter 2015; Pang and O'Neill 2018; Qiu et al. 2018; Sanchez et al. 2014; Spitz et al. 2012; Tian 2013; Tian et al. 2018; Tian et al. 2014; Wang and Zhao 2018). For example, based on 100,000 energy model simulations, the New Buildings Institute (NBI) developed a prescriptive guide for small to medium new construction projects that can achieve up to 40% energy savings over ASHRAE 90.1-2007/IECC 2009 (NBI 2013). Recently, global sensitivity analysis methods became popular since they consider both individual and interactive impacts of inputs to outputs (Tian 2013). This more accurately represents the impact of EEMs on EPIs, because multiple EEMs are often considered and implemented in retrofit projects. However, there is a lack of research to study the nationwide impacts of EEMs on EPIs by using global sensitivity analysis methods. To fill this gap, this paper conducts nationwide EEM research by using the Standard Regression Coefficient (SRC), one of the popular global sensitivity analysis methods (Storlie and Helton 2008; Tian et al. 2014).

The objective of this study is to evaluate the energy saving potentials of several EEMs through sensitivity analysis for retrofits of U.S. medium office buildings. This comprehensive defined guideline can help building owners identify promising EEMs in their given climate zone. These results can not only be used directly to evaluate energy saving potentials for a specific retrofit project, but they can also be applied for ROIs estimation. The remainder of this paper is structured as follows. Section 2 discusses the methodology. Section 3 describes the model preparation. Section 4 presents the analysis results for medium office buildings in 15 climate zones. Section 5 discusses the method to evaluate the energy saving impact of EEMs when dynamic electricity pricing programs are adopted. Lastly, Section 6 concludes with the findings of this paper and a discussion of future work.

2. Methodology

A building energy retrofit project usually has seven steps: (1) retrofit budgeting, (2) energy audit, (3) EEM saving prediction, (4) cost effectiveness evaluation, (5) retrofit plan decision, (6) retrofit construction or installation, and (7) post-retrofit performance and verification. To reduce the workload of onsite energy audits and energy cost saving predictions, this paper provides a methodology to evaluate the energy impact potential of EEMs on EPIs. Based on the results of this study, the number of candidate EEMs can be reduced during the onsite energy audit. Only the EEMs having high energy use and cost saving potentials need to be considered. Furthermore, the detailed building energy models are unnecessary for the energy cost saving prediction. The results of this study can be used as a reference to estimate the energy savings potential.

As shown in Figure 1, the methodology of this study consists of three steps: (1) preparation, (2) sensitivity analysis, and (3) energy impact evaluation. In the first step, we develop baseline models and select EEMs with a range of variations. In the second step, we generate parametric building models by using established sampling methods for the EEMs, conduct simulations, and calculate sensitivity indices for EPIs by using the SRC sensitivity analysis method. Lastly, we evaluate the energy impact potential of EEMs on EPIs based on the sensitivity indices calculated in Step 2.

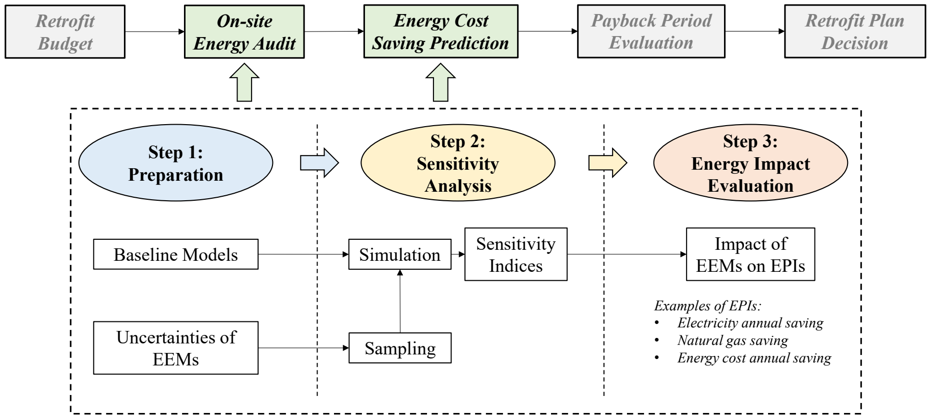


Figure 1. Methodology to evaluate the energy impact potential of EEMs on EPIs

2.1. Step 1: Preparation

This step consists of two tasks: establish representative baseline models for medium office buildings and develop candidate EEMs with their range of variations. Ye et al. (2019) reviewed a few sets of prototypical building energy models, developed by others. For example, the DOE Commercial Reference Building Models (DOE 2011), Commercial Prototype Building Models (DOE 2020), and OpenStudio-Standards Gem (NREL 2018) provide many prototypical building energy models for various U.S. commercial buildings. Furthermore, some researchers created prototypical building energy models for other commercial building types to complement the existing datasets, which are also suitable to be used as baseline models (Ye et al. 2018a; Ye et al. 2018b; Ye et al. 2019). Based on the required building types, vintages, and areas, for this study we selected the prototypical building models from these options (DOE 2020).

Sensitive EEMs for this paper are selected based on the rich collection of existing research surrounding the analysis of EEMs for various buildings and climate zones (Glazer 2016; Kneifel 2010; Wang et al. 2013; Wang et al. 2016; Wang et al. 2015; Moser et al. 2012). In addition, most jurisdictions in the United States have adopted energy codes for commercial buildings that are equivalent to or more stringent than ASHRAE Standard 90.1-2007 (ASHRAE 2007; DOE 2018). Furthermore, the Advanced Energy Design Guide (AEDG) from ASHRAE promotes building energy efficiency and provides high-efficiency measures (Bonnema et al. 2012). Thus, the uncertainties of the selected EEMs in this paper are identified by referring to ASHRAE Standard 90.1-2007 and AEDG.

2.2. Step 2: Sensitivity Analysis

Before identifying sensitive EEMs using the SRC method and calculating sensitivity indices, we initially follow four stages. First, we determine the number of building samples required to minimize the margin of error. Margin of error is a statistic expressing the results error caused by random sampling. Naturally, when the sample size becomes larger, the margin of error becomes smaller and the sensitivity results become more stable (Menberg et al. 2016; Mokhtari and Frey 2005; Nguyen and Reiter 2015; Iooss and Lemaître 2015). Iooss and Lemaître (2015) estimated the number of samples required for various sensitivity analysis methods. If the total number of variables is d, then the minimum number of samples required is on the scale of $10d$ for the SRC method. Second, we use the Latin Hypercube Sampling (LHS) method to select building samples, which is required with the SRC method (Stein 1987). Third, simulations for the selected building samples are conducted and the results are used to calculate their EPIs. This paper uses EnergyPlus, a full-scale building energy simulation program, to conduct simulations (DOE 2017). Fourth, we conduct uncertainty analysis to evaluate the EPI ranges of the building samples caused by the variations of the selected EEMs within their ranges. If the EPI range is lower than 50 MJ/m^2-yr for energy factors or 50 kW for whole building electric peak demand, we conclude that the EEM is not sensitive for the given EPI. If all selected EPIs have narrow ranges, it means that the building energy consumption is not significantly sensitive to the EEMs. If this occurs, we restart Step 1 (Preparation) to select other EEMs. Otherwise, we move to the final stage of calculating sensitivity indices.

We calculate sensitivity indices by using the SRC method. The SRC method uses a linear regression model to identify the relationship between EEMs and EPIs. The regression model is expressed as:

$$\left(\widehat{EPI}_i - \overline{EPI}\right)/\hat{s} = \sum_{j=1}^{m} \left(b_j \hat{s}_j/\hat{s}\right)\left(EEM_{ij} - \overline{EEM}_j\right)/\hat{s}_j = \sum_{j=1}^{m} SRC_j\left(EEM_{ij} - \overline{EEM}_j\right)/\hat{s}_j \qquad (1)$$

where m is the quantity of the EEMs; $\widehat{EPI}_i$ is the estimated value of one EPI for sample i, calculated based on the regression model; and EEM_{ij} is the value of EEM j in the sample i. The sample mean $\overline{EPI}$ corresponds to the value of one EPI, where $\overline{EPI} = \frac{1}{n}\sum_{i=1}^{n} EPI_i$, and n is the quantity of the building samples. The value $\overline{EEM}_j$ is the mean of EEM j in all the samples, where $\overline{EEM}_j = \frac{1}{n}\sum_{i=1}^{n} EEM_{ij}$. The standard deviation for one EPI is represented by $\hat{s}$, where $\hat{s} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(EPI_i - \overline{EPI})^2}$. $\hat{s}_j$ is the standard deviation for EEM_j, where $\hat{s}_j = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(EEM_{ij} - \overline{EEM}_j\right)^2}$. Lastly, SRC_j is the identified relationship between EEMs and EPIs.

The SRC regression model aims to minimize the Root Mean Square Error (RMSE) between the estimated value of one EPI from the regression models and the samples' values of the EPI calculated by EnergyPlus. The SRC of EEM j is $b_j\hat{s}_j/\hat{s}$, and $|b_j\hat{s}_j/\hat{s}|$ can be used as a measure of variable importance. In this paper, we refer to $|b_j\hat{s}_j/\hat{s}|$ as the sensitivity index, named as absolute SRC sensitivity index. The range of the absolute SRC sensitivity index is 0 to 1. If the absolute value is close to 1, the EEM is sensitive; if it is close to 0, the EEM is insensitive. To enhance the stability of the SRC results, the bootstrap method is used to resample the building samples (Tian et al. 2014). Based on the original sample set, we generate 1,000 sample sets by randomly sampling from the original sample set with replacement. Then, each bootstrap sample set will obtain a vector of absolute SRC sensitivity indices. The set of such vectors shows the sensitive ranges of individual EEMs while avoiding sampling biases.

2.3. Step 3: Energy Impact Evaluation

We use the sensitivity ratio to evaluate an individual EEM's energy impact on a specific EPI relative to the impacts of all selected EEMs. The sensitivity ratio can be calculated as follows:

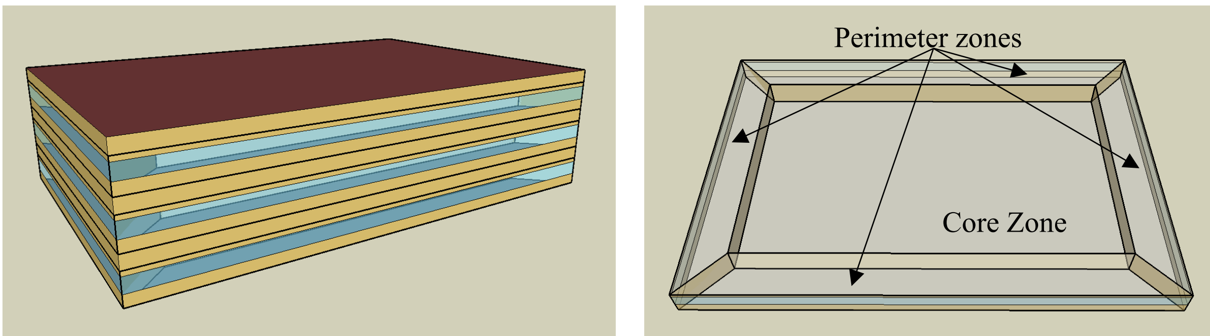
$$Sensitivity\ Ratio_{EPI_k,i} = \frac{SRC_{EPI_k,i}}{\sum_{j=1}^{n} SRC_{EPI_k,j}} \times 100\%, k = 1,2,3, i = 1,2,\dots,n \qquad (2)$$

where EPI_k is the type k of EPI, which in this paper includes annual electricity use intensity, annual natural gas use intensity, and annual energy cost; i represents EEM i; $SRC_{EPI_k,i}$ is the absolute SRC sensitivity index of EEM i for EPI k; and $\sum_{j=1}^{n} SRC_{EPI_k,j}$ is the sum of all EEMs' absolute SRC sensitivity indices for EPI k, with j representing the EEM index ($j = 1{:}n$).

The sum of sensitivity ratios for all selected EEMs is equal to 1, and the range of sensitivity ratios is between 0 and 1. If the sensitivity ratio is close to 1, then the EEM has a great impact on the EPI, and the uncertainty of the EPI is mainly caused by this EEM. If the sensitivity ratio is close to 0 or equal to 0, it means that the EEM has little or no impact on the EPI.

3. Model Preparation

This section introduces the preparation for medium office building models (i.e., Step 1 in Methodology). The baseline models of medium office buildings are selected from the DOE Commercial Prototype Building Models (DOE 2020). Figure 2 shows the geometry and thermal zones of the selected baseline models. The baseline models have rectangular shape and three stories. Each story contains five thermal zones (one core zone and four perimeter zones).



(a) Geometry (b) Thermal Zones

Figure 2. Geometry and thermal zones of the baseline medium office building models

Table 1 lists the key parameters of the baseline models of medium office buildings. There are 15 climate zones in the United States. The total floor area for prototype building is 4,980 m^2 with a 33% window-to-wall ratio. It has steel-frame exterior walls and insulation entirely above deck (IEAD) roofs. Furthermore, it uses packaged air conditioning units and VAV terminal boxes for all 15 climate zones.

Table 1. Key parameters of the baseline medium office building models (DOE 2020)

Parameter Name	**Value**		
Location (Climate Zone: Representative City)	1A: Honolulu 2A: Tampa 2B: Tucson 3A: Atlanta 3B: El Paso	3C: San Diego 4A: New York 4B: Albuquerque 4C: Seattle 5A: Buffalo	5B: Denver 6A: Rochester 6B: Great Falls 7: International Falls 8: Fairbanks
Total Floor Area	4,980 m^2 (50 m × 33.2 m)		
Aspect Ratio	1.5		
Number of Floors	3		
Window-to-Wall Ratio	33%		
Floor-to-Floor Height	3.96 m		
Exterior Walls	Steel-Frame Walls		
Roof	IEAD Roof		
Windows	Hypothetical Windows with Weighted (U-factor and SHGC vary by climate)		
Lighting Power Density	10.76 W/m^2		
Plug Load Density	8.07 W/m^2		
Central Heating	Packaged Air Conditioning Unit, Gas Furnace		
Cooling	Packaged Air Conditioning Unit, DX Cooling		

Parameter Name	Value
Air distribution system	VAV with Damper-controlled Terminal Boxes and Electric Reheating Coils
Service Water Heating	Storage Tank, Natural Gas Water Heater

Figure 3 shows the annual electricity and natural gas use intensities by end-use for the baseline medium office building models. The annual electricity use intensities are approximately 450 to 500 megajoule (MJ)/m^2-yr in all 15 climate zones. The interior lighting and equipment consume approximately 50% of electricity. The cooling system consumes more electricity in climate zones 1 through 3 compared to other climate zones. On the contrary, the heating system consumes more electricity in climate zones 5 through 8 compared to other climate zones. The annual natural gas use intensities are lower than 20 MJ/m^2-yr in most of the hot and warm climates, such as climate zones 1A, 2A, and 3B. The heating system consumes the most natural gas in cold climates, such as climate zones 6A, 7, and 8. The water system only consumes approximately 17 MJ/m^2-yr of natural gas in all 15 climate zones, which is only a small portion in the total energy consumption.

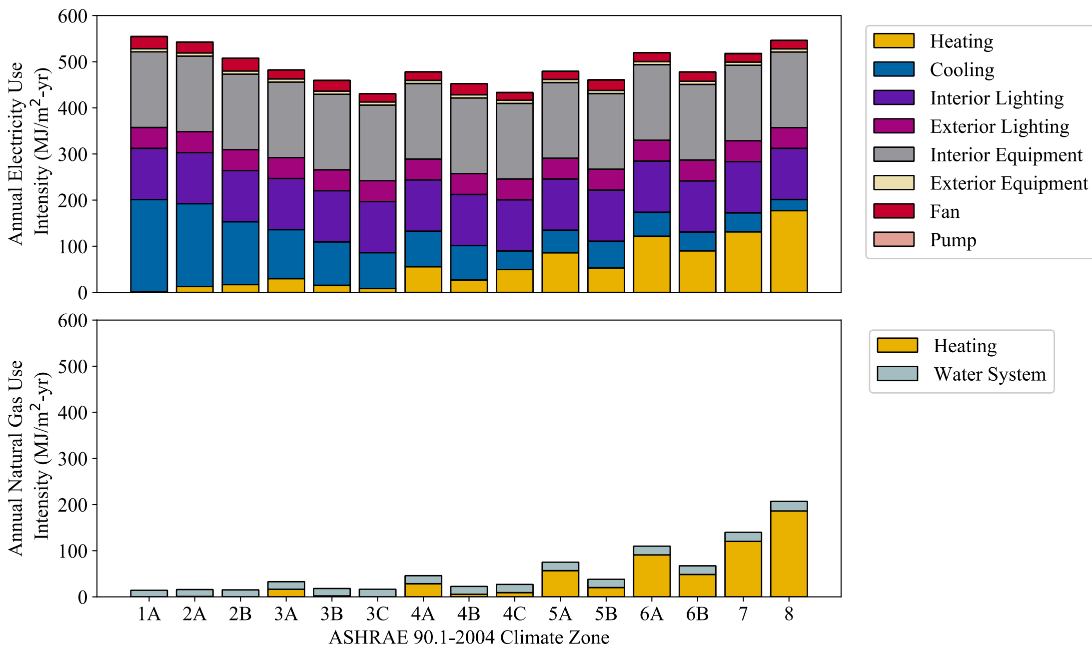


Figure 3. Annual electricity and natural gas use intensities by end-use for the baseline medium office building models

Based on the outcomes of existing research (Glazer 2016; Kneifel 2010; Wang et al. 2013; Wang et al. 2016; Wang et al. 2015), we select nine EEMs, which potentially have significant impacts on the EPIs for the medium office buildings across all climate zones. Then, based on ASHRAE Standard 90.1-2007 (ASHRAE 2007) and AEDG (Bonnema et al. 2012), we determine possible ranges (uncertainties) of these EEMs in existing U.S. medium office buildings. Table 2 lists the range of the nine selected EEMs, which are all uniformly distributed (Eisenhower et al. 2012).

Table 2. Uncertainties of the nine selected EEMs

No.	EEM	Variable	Units	Range
1	Add wall insulation	Wall Insulation U-value	W/m^2-K	1A: [0.28, 0.96]; 2A and 2B: [0.28, 0.96]; 3A, 3B, and 3C: [0.28, 0.58]; 4A, 4B, and 4C: [0.28, 0.42]; 5A and 5B: [0.20, 0.42]; 6A and 6B: [0.18, 0.42]; 7: [0.18, 0.42]; 8: [0.18, 0.42]
2	Add roof insulation	Roof Insulation U-value	W/m^2-K	1A: [0.28, 0.38]; 2A and 2B: [0.23, 0.29]; 3A, 3B, and 3C: [0.23, 0.29]; 34A, 4B, and 4C: [0.20, 0.29]; 5A and 5B: [0.20, 0.29]; 6A and 6B: [0.20, 0.29]; 7: [0.16, 0.29]; 8: [0.16, 0.29]
3	Replace windows (U-factor)	Window U-factor	W/m^2-K	1A: [3.18, 5.78]; 2A and 2B: [2.56, 4.60]; 3A, 3B, and 3C: [2.33, 2.85]; 4A, 4B, and 4C: [2.16, 2.65]; 5A and 5B: [1.99, 2.65]; 6A and 6B: [1.99, 2.65]; 7: [1.87, 2.49]; 8: [1.42, 2.49]
4	Replace windows (SHGC)	SHGC (all)	-	1A: [0.25, 0.31]; 2A and 2B: [0.25, 0.29]; 3A, 3B, and 3C: [0.25, 0.29]; 4A, 4B, and 4C: [0.26, 0.43]; 5A and 5B: [0.26, 0.43]; 6A and 6B: [0.35, 0.43]; 7: [0.40, 0.43]; 8: [0.40, 0.43]
5	Replace interior lighting fixtures with higher-efficiency fixtures	Lighting Power Density	W/m^2	[8.07, 10.76] for all climate zones
6	Replace office equipment with higher-efficiency equipment	Plug Load Density	W/m^2	[5.92, 8.07] for all climate zones
7	Replace heating system with higher-efficiency system	Heating Efficiency	-	[0.80, 0.90] for all climate zones
8	Replace cooling system with higher-efficiency system	Coefficient of Performance	-	[3.23, 3.37] for all climate zones
9	Replace service hot water system with higher-efficiency system	Hot Water Efficiency	-	[0.81, 0.90] for all climate zones

Wall insulation, roof insulation, and window U-factor and SHGC are climate dependent. In ASHARE Standard 90.1-2007 and AEDG, wall insulation U-value, roof insulation U-value, and window U-factor are smaller in colder climate zones (e.g. climate zones 7 and 8) than in warmer climate zones (e.g. climate zones 1A and 2A), while SHGC is larger in colder climate zones. The other five variables listed in Table 2 have the same requirement for all climate zones and are considered to be climate independent. Therefore, this paper includes the different ranges of values for EEMs 1 to 4 in different climate zones and the same range for EEMs 5 to 8 in all climate zones.

This paper uses the required and recommended values in ASHARE Standard 90.1-2007 and AEDG as the upper and lower boundaries for the EEMs' ranges. The detailed upgrading strategies could be found in AEDG (Bonnema et al. 2012). For example, lighting power density could be lowered by replacing incandescent lamps with light-emitting diodes (LED). It is important to note that this approach does not encapsulate the full potential range of EEM values for available technologies. For example, cooling system COP (EEM 8) values above 3.37 are possible with some air conditioning technologies, such as radiant cooling. However, the purpose of this study was not to evaluate the the full extent of individual EEMs for medium office retrofits, but to comprehensively evaluate the energy savings of typical EEM ranges while considering their individual and interactive impacts, as well as multiple climate zones.

4. Results

The methodology described in Section 2 is applied in order to provide unbiased and climate-specific evaluation of EEM impact potentials on the three selected EPIs. The subsections below correspond to the subsections above. Subsection 4.1 shows the results of sensitivity analysis (i.e., Step 2 in methodology). And, subsection 4.2 shows the results of the energy impact evaluation (i.e., Step 3 in methodology).

4.1. Sensitivity Analysis

Since there are nine variables ($d = 9$) in this study, we will need at least 90 samples for each climate zone when applying the SRC method. In order to get a stable result, the sample sizes were selected based on the point when the standard deviation of the sensitivity indices stabilized. Our results show that each climate zone needs 500 samples. The number of samples is higher than the estimated value, which ensures the sensitivity analysis results are independent of sample size.

By using the LHS method, 7,500 building samples are selected. As described in the methodology, we conduct simulations using EnergyPlus 8.6, collect annual electricity and natural gas use intensities, and conduct uncertainty analysis for these two EPIs in order to quantify the impact of EEM uncertainties across all 15 climate zones. The boxplot results are shown in Figure 4. The five horizontal lines for each boxplot from the highest to the lowest indicate the maximum, third quartile (75^{th} percentile), median, first quartile (25^{th} percentile), and minimum values, respectively.

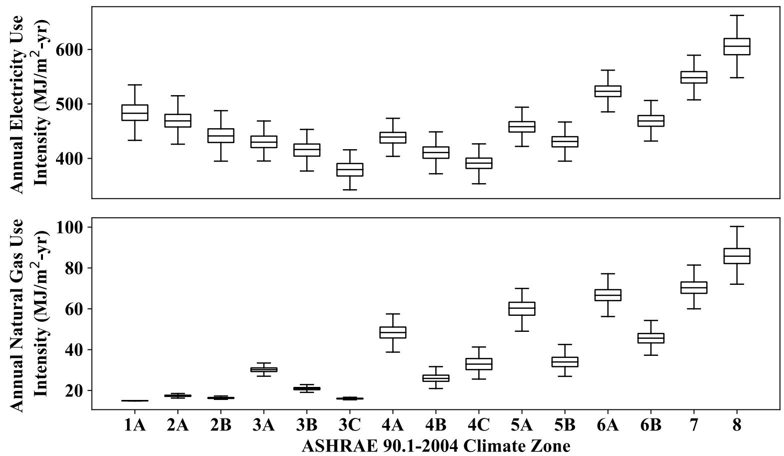


Figure 4. Uncertainties of annual electricity and natural gas use intensities for medium office buildings in the 15 climate zones

The uncertainties of these two EPIs represent the energy use saving potential for existing medium office buildings in different climate zones. Both the climates' temperatures (correlated to the numerical zone listings 1 through 8) and humidity (correlated to the letter keys A through C, as defined by the ASHRAE climate zones) affect the uncertainties of the EPIs. Based on Figure 4, the annual electricity use intensity ranges approximately from 250 to 750 MJ/m^2-yr. Furthermore, the uncertainties of this EPI for the buildings in all 15 climate zones are in the range of approximately 200 MJ/m^2-yr, which indicates that these 9 EEMs notably impact this EPI for all 15 climate zones.

The annual natural gas use intensity ranges approximately from 10 to 100 MJ/m^2-yr. Contrary to the annual electricity use intensity results, the range of the annual natural gas use intensity greatly vary across climate zones. In the hot and warm climates, such as climate zones 1A, 2A, and 2B, the range of annual natural gas use intensity is close to 0, while the range is higher than 20 MJ/m^2-yr in cold climates, such as climate zones 7 and 8. Thus, it is unnecessary to evaluate the impacts of EEMs on annual natural gas use intensity in the hot climates. This paper only focuses on climate zones 4 through 8 for the impacts on annual natural gas use intensity.

Furthermore, we calculate the annual energy cost based on the annual electricity and natural gas use. The U.S. average unit prices for electricity and natural gas are used. The electricity unit price is $28.78/1,000 MJ and the natural gas unit price is $6.69/1,000 MJ. Figure 5 shows the uncertainties of annual energy cost in the 15 climate zones.

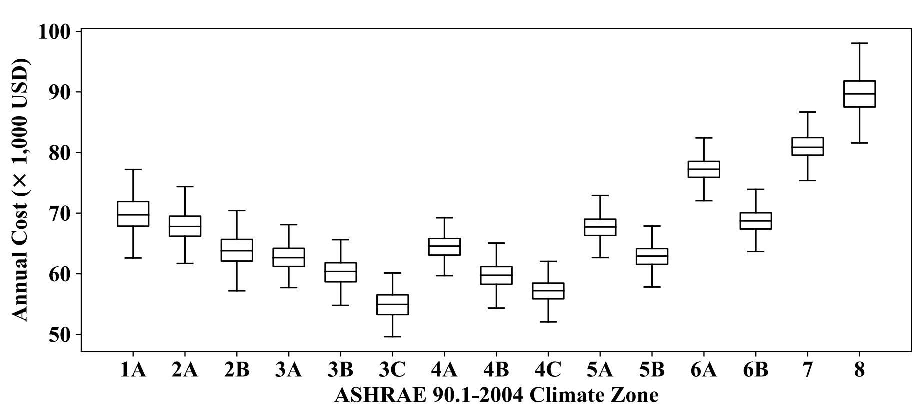


Figure 5. Uncertainties of annual energy cost for medium office buildings in the 15 climate zones

The annual energy cost ranges approximately from $50,000 to $100,000. The uncertainties of this EPI for the buildings in all 15 climate zones ranges by approximately $15,000. Similar to the impacts of these EEMs to annual electricity use intensity, the notable impacts of selected EEMs to annual energy cost are shown for all 15 climate zones. This is because in each building the electricity unit price is greatly higher than the natural gas unit price and the annual electricity use is greatly higher than the natural gas use.

Since the uncertainties in annual electricity use intensity are approximately 200 MJ/m^2-yr in all 15 climate zones, we conduct sensitivity analysis for all zones. Then, we calculate the absolute SRC sensitivity index for this EPI. Table 3 shows the sensitivity analysis results of the nine EEMs for this EPI in all 15 climate zones. The absolute SRC sensitivity index indicates the relative sensitivity of the nine EEMs. Each bootstrap sample set generates one value of the absolute SRC sensitivity index for a certain EEM. Thus, based on multiple bootstrap sample sets, we obtain a set of values for the EEMs' absolute SRC sensitivity indices. Table 3 provides the median value (SRC) and the confidence interval (C.I.) of the absolute SRC sensitivity index. For the SRC results, the red shading in the cells indicates increasingly higher values. This means darkly shaded EEM and climate-zone combinations are sensitive to annual electricity use intensity, while, unshaded and lightly shaded ones are insensitive.

Table 3. Absolute SRC sensitivity index for annual electricity use intensity

EEM	Climate Zone		1	2	3	4	5	6	7	8
Add wall insulation	**A**	SRC[1]	0.08	0.11	0.11	0.10	0.20	0.25	0.30	0.30
		C.I.[2]	[0.08,0.09]	[0.10,0.12]	[0.11,0.12]	[0.09,0.10]	[0.19,0.21]	[0.23,0.26]	[0.29,0.33]	[0.29,0.32]
	B	SRC		0.13	0.09	0.06	0.16	0.24		
		C.I.		[0.12,0.14]	[0.08,0.09]	[0.06,0.07]	[0.15,0.17]	[0.23,0.25]		
	C	SRC			0.04	0.08				
		C.I.			[0.04,0.05]	[0.08,0.09]				
Add roof insulation	**A**	SRC	0.02	0.02	0.04	0.10	0.14	0.16	0.24	0.21
		C.I.	[0.02,0.03]	[0.01,0.03]	[0.04,0.04]	[0.10,0.11]	[0.13,0.15]	[0.15,0.17]	[0.22,0.25]	[0.20,0.22]
	B	SRC		0.02	0.03	0.07	0.11	0.15		
		C.I.		[0.01,0.03]	[0.03,0.03]	[0.06,0.08]	[0.11,0.12]	[0.14,0.16]		
	C	SRC			0.02	0.09				
		C.I.			[0.02,0.02]	[0.08,0.09]				
Replace windows (U-factor)	**A**	SRC	0.26	0.28	0.09	0.17	0.33	0.38	0.46	0.75
		C.I.	[0.25,0.28]	[0.27,0.30]	[0.09,0.10]	[0.16,0.18]	[0.32,0.35]	[0.36,0.40]	[0.44,0.49]	[0.72,0.78]
	B	SRC		0.35	0.07	0.10	0.27	0.37		
		C.I.		[0.33,0.37]	[0.06,0.07]	[0.10,0.11]	[0.26,0.29]	[0.36,0.40]		
	C	SRC			0.03	0.15				
		C.I.			[0.03,0.03]	[0.14,0.16]				
Replace windows (SHGC)	**A**	SRC	0.11	0.02	0.01	0.15	0.14	0.10	0.04	0.04
		C.I.	[0.10,0.12]	[0.02,0.03]	[0.00,0.01]	[0.15,0.16]	[0.13,0.15]	[0.09,0.10]	[0.03,0.04]	[0.03,0.05]
	B	SRC		0.02	0.01	0.19	0.13	0.07		
		C.I.		[0.01,0.03]	[0.00,0.01]	[0.19,0.20]	[0.12,0.14]	[0.07,0.08]		
	C	SRC			0.00	0.24				
		C.I.			[0.00,0.00]	[0.23,0.25]				
Replace interior lighting fixtures with higher-efficiency fixtures	**A**	SRC	0.56	0.59	0.61	0.59	0.58	0.56	0.52	0.38
		C.I.	[0.53,0.58]	[0.57,0.61]	[0.58,0.63]	[0.56,0.62]	[0.55,0.61]	[0.54,0.59]	[0.49,0.54]	[0.35,0.39]
	B	SRC		0.55	0.62	0.59	0.59	0.55		
		C.I.		[0.52,0.57]	[0.59,0.64]	[0.57,0.62]	[0.56,0.61]	[0.53,0.58]		
	C	SRC			0.63	0.59				
		C.I.			[0.60,0.65]	[0.56,0.61]				
Replace office equipment with higher-efficiency equipment	**A**	SRC	0.74	0.77	0.76	0.74	0.69	0.66	0.59	0.41
		C.I.	[0.70,0.76]	[0.74,0.80]	[0.73,0.79]	[0.71,0.78]	[0.66,0.72]	[0.64,0.69]	[0.56,0.62]	[0.39,0.43]
	B	SRC		0.69	0.78	0.74	0.72	0.66		
		C.I.		[0.66,0.72]	[0.76,0.81]	[0.71,0.77]	[0.68,0.75]	[0.63,0.69]		
	C	SRC			0.78	0.72				
		C.I.			[0.75,0.81]	[0.68,0.73]				
	A	SRC	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

EEM	Climate Zone		1	2	3	4	5	6	7	8
Replace heating system with higher-efficiency system		C.I.	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]	[0.00,0.00]	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]
	B	SRC		0.00	0.00	0.00	0.00	0.00		
		C.I.		[0.00,0.01]	[0.00,0.01]	[0.00,0.00]	[0.00,0.01]	[0.00,0.01]		
	C	SRC			0.00	0.00				
		C.I.			[0.00,0.00]	[0.00,0.01]				
Replace cooling system with higher-efficiency system	A	SRC	0.11	0.11	0.07	0.05	0.04	0.04	0.03	0.01
		C.I.	[0.10,0.12]	[0.10,0.12]	[0.07,0.07]	[0.04,0.05]	[0.03,0.04]	[0.04,0.05]	[0.03,0.04]	[0.01,0.02]
	B	SRC		0.08	0.07	0.06	0.05	0.04		
		C.I.		[0.07,0.08]	[0.06,0.07]	[0.05,0.06]	[0.04,0.05]	[0.03,0.04]		
	C	SRC			0.05	0.03				
		C.I.			[0.05,0.05]	[0.03,0.04]				
Replace service hot water system with higher-efficiency system	A	SRC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		C.I.	[0.00,0.01]	[0.00,0.01]	[0.00,0.00]	[0.00,0.00]	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]
	B	SRC		0.00	0.00	0.00	0.00	0.00		
		C.I.		[0.00,0.01]	[0.00,0.00]	[0.00,0.00]	[0.00,0.01]	[0.00,0.01]		
	C	SRC			0.00	0.00				
		C.I.			[0.00,0.00]	[0.00,0.01]				

[1] SRC is the median value of the absolute SRC sensitivity index.
[2] C.I. is confidence interval of the absolute SRC sensitivity index.

As shown in Table 3, most of the EEM sensitivities vary across climate zones. For example, adding wall insulation has a higher SRC in climate zones 5 - 8 than in climate zones 1 through 4. This means that the wall insulation is more important in cool and cold area (climate zones 5 through 8) than in warm and hot area (climate zones 1 through 4). Furthermore, replacing interior lighting fixtures with higher-efficiency fixtures and replacing office equipment with higher-efficiency equipment have the highest SRC in all climate zones except climate zone 8. Replacing windows (U-factor) is the most sensitive EEM to annual electricity use intensity in climate zone 8. The ranges of C.I. are all lower than 0.07; this low number indicates that the sensitivity level of each EEM in all climate zones can be quantified using the median SRC value only. While the first four EEMs are climate dependent, there are some differences in the trends between insulation sensitivity (add wall and roof insulation) and glazing sensitivity (replace windows) across climates. For example, the EEMs for adding wall and roof insulation are more sensitive in the cold climates (e.g. climate zones 7 and 8) than in the hot climates (e.g. climate zones 1 and 2). Further, replacing windows based on U-factor is sensitive in both hot and cold climates, but not sensitive in mild climates (e.g. climate zones 3 and 4). Replacing windows based on SHGC has varied absoluted SRC, which is mainly caused by the different climate-dependent ranges, rather than demonstrated sensitivity across climate zones.

Table 4 shows the sensitivity analysis results of the nine EEMs for annual natural gas use intensity. Since the uncertainties of the annual natural gas intensity in climate zones 1 through 3 are below the 50 MJ/m^2-yr threshold, this paper only focuses on climate zones 4 through 8 for this EPI. Similarly, we provide the median value (SRC) and the C.I. of the absolute SRC sensitivity index in the table.

Table 4. Absolute SRC sensitivity index for annual natural gas use intensity

EEM	Climate Zone		4	5	6	7	8
Add wall insulation	A	SRC[1]	0.00	0.00	0.01	0.01	0.01
		C.I.[2]	[0.00,0.01]	[0.00,0.01]	[0.01,0.02]	[0.00,0.01]	[0.01,0.02]
	B	SRC	0.00	0.01	0.03		
		C.I.	[0.00,0.01]	[0.00,0.02]	[0.03,0.04]		
	C	SRC	0.03				
		C.I.	[0.02,0.04]				
Add roof insulation	A	SRC	0.08	0.08	0.11	0.14	0.07
		C.I.	[0.07,0.08]	[0.07,0.09]	[0.10,0.12]	[0.13,0.15]	[0.07,0.08]
	B	SRC	0.03	0.05	0.09		

EEM	Climate Zone		4	5	6	7	8
		C.I.	[0.02,0.04]	[0.04,0.06]	[0.09,0.10]		
	C	SRC	0.04				
		C.I.	[0.04,0.05]				
Replace windows (U-factor)	A	SRC	0.04	0.08	0.09	0.13	0.31
		C.I.	[0.03,0.04]	[0.07,0.09]	[0.08,0.10]	[0.13,0.14]	[0.29,0.32]
	B	SRC	0.04	0.09	0.06		
		C.I.	[0.03,0.05]	[0.08,0.10]	[0.05,0.06]		
	C	SRC	0.00				
		C.I.	[0.00,0.01]				
Replace windows (SHGC)	A	SRC	0.73	0.71	0.44	0.22	0.19
		C.I.	[0.70,0.76]	[0.68,0.73]	[0.42,0.47]	[0.21,0.23]	[0.18,0.20]
	B	SRC	0.73	0.74	0.54		
		C.I.	[0.70,0.76]	[0.70,0.76]	[0.52,0.57]		
	C	SRC	0.77				
		C.I.	[0.74,0.80]				
Replace interior lighting fixtures with higher-efficiency fixtures	A	SRC	0.45	0.46	0.58	0.62	0.58
		C.I.	[0.43,0.47]	[0.43,0.48]	[0.55,0.60]	[0.59,0.65]	[0.55,0.60]
	B	SRC	0.46	0.48	0.57		
		C.I.	[0.44,0.48]	[0.46,0.50]	[0.55,0.61]		
	C	SRC	0.41				
		C.I.	[0.39,0.44]				
Replace office equipment with higher-efficiency equipment	A	SRC	0.39	0.40	0.50	0.54	0.50
		C.I.	[0.37,0.42]	[0.38,0.42]	[0.47,0.52]	[0.51,0.57]	[0.48,0.52]
	B	SRC	0.40	0.41	0.50		
		C.I.	[0.38,0.42]	[0.39,0.43]	[0.47,0.52]		
	C	SRC	0.36				
		C.I.	[0.34,0.38]				
Replace heating system with higher-efficiency system	A	SRC	0.31	0.36	0.45	0.47	0.53
		C.I.	[0.30,0.33]	[0.34,0.37]	[0.43,0.48]	[0.45,0.50]	[0.50,0.55]
	B	SRC	0.19	0.21	0.31		
		C.I.	[0.17,0.20]	[0.20,0.23]	[0.30,0.33]		
	C	SRC	0.19				
		C.I.	[0.18,0.20]				
Replace cooling system with higher-efficiency system	A	SRC	0.00	0.00	0.00	0.00	0.00
		C.I.	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]
	B	SRC	0.00	0.00	0.00		
		C.I.	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]		
	C	SRC	0.00				
		C.I.	[0.00,0.01]				
Replace service hot water system with higher-efficiency system	A	SRC	0.02	0.02	0.01	0.01	0.01
		C.I.	[0.01,0.03]	[0.01,0.02]	[0.01,0.02]	[0.01,0.02]	[0.00,0.01]
	B	SRC	0.02	0.01	0.02		
		C.I.	[0.01,0.03]	[0.00,0.02]	[0.01,0.02]		
	C	SRC	0.01				
		C.I.	[0.01,0.02]				

[1] SRC is the median value of the absolute SRC sensitivity index.
[2] C.I. is confidence interval of the absolute SRC sensitivity index.

Replacing windows with different SHGC is the most sensitive EEM in climate zones 4 and 5, while replacing interior lighting fixtures with higher-efficiency fixtures is the most sensitive in climate zones 7 and 8. By comparing with the results in Table 3, Table 4 shows some different trends. For example, the replacement of a heating system with a higher-efficiency system is sensitive to annual natural gas use intensity, while it is insensitive to annual electricity use intensity. Furthermore, the window U-factor is more sensitive than window SHGC for annual electricity use intensity, while the opposite is true for annual natural gas use intensity. Since the combinations of U-factor and SHGC for windows are naturally dependent on available products, it is necessary to select a window by considering both impacts. Lastly, the replacement of a service hot water system with a higher-efficiency system is insensitive to annual natural gas intensity because of the low energy consumption, as shown in Figure 3.

Furthermore, Table 5 shows the sensitivity analysis results of the nine EEMs for annual natural gas use intensity. Similarly, we provide the median value (SRC) and the C.I. of the absolute SRC sensitivity index in the table.

Table 5. Absolute SRC sensitivity index for annual energy cost

EEM	Climate Zone		1	2	3	4	5	6	7	8
Add wall insulation	**A**	SRC[1]	0.08	0.11	0.11	0.10	0.21	0.26	0.32	0.31
		C.I.[2]	[0.08,0.09]	[0.10,0.11]	[0.11,0.12]	[0.10,0.11]	[0.20,0.22]	[0.24,0.27]	[0.30,0.33]	[0.29,0.33]
	B	SRC		0.13	0.09	0.06	0.17	0.25		
		C.I.		[0.12,0.14]	[0.08,0.09]	[0.06,0.07]	[0.16,0.18]	[0.23,0.26]		
	C	SRC			0.04	0.08				
		C.I.			[0.04,0.05]	[0.08,0.09]				
Add roof insulation	**A**	SRC	0.02	0.02	0.04	0.10	0.14	0.16	0.24	0.20
		C.I.	[0.02,0.03]	[0.02,0.02]	[0.04,0.04]	[0.10,0.11]	[0.13,0.15]	[0.14,0.16]	[0.22,0.25]	[0.19,0.22]
	B	SRC		0.02	0.03	0.07	0.12	0.15		
		C.I.		[0.01,0.03]	[0.03,0.03]	[0.07,0.08]	[0.11,0.12]	[0.14,0.17]		
	C	SRC			0.02	0.09				
		C.I.			[0.02,0.02]	[0.08,0.10]				
Replace windows (U-factor)	**A**	SRC	0.26	0.28	0.10	0.18	0.36	0.40	0.49	0.78
		C.I.	[0.25,0.28]	[0.27,0.30]	[0.09,0.10]	[0.17,0.19]	[0.34,0.37]	[0.38,0.42]	[0.47,0.52]	[0.74,0.81]
	B	SRC		0.35	0.07	0.11	0.29	0.39		
		C.I.		[0.33,0.36]	[0.06,0.07]	[0.10,0.11]	[0.27,0.30]	[0.37,0.42]		
	C	SRC			0.03	0.16				
		C.I.			[0.03,0.03]	[0.15,0.17]				
Replace windows (SHGC)	**A**	SRC	0.11	0.02	0.01	0.11	0.09	0.07	0.02	0.03
		C.I.	[0.10,0.12]	[0.02,0.03]	[0.00,0.01]	[0.11,0.12]	[0.08,0.10]	[0.07,0.08]	[0.02,0.03]	[0.02,0.04]
	B	SRC		0.02	0.01	0.17	0.09	0.04		
		C.I.		[0.01,0.03]	[0.00,0.01]	[0.17,0.18]	[0.09,0.10]	[0.04,0.05]		
	C	SRC			0.00	0.21				
		C.I.			[0.00,0.00]	[0.20,0.22]				
Replace interior fixtures with higher-efficiency fixtures	**A**	SRC	0.56	0.59	0.61	0.59	0.57	0.55	0.50	0.35
		C.I.	[0.54,0.58]	[0.56,0.62]	[0.58,0.63]	[0.56,0.62]	[0.54,0.59]	[0.52,0.57]	[0.47,0.52]	[0.33,0.37]
	B	SRC		0.55	0.62	0.59	0.58	0.54		
		C.I.		[0.52,0.57]	[0.59,0.64]	[0.56,0.62]	[0.55,0.60]	[0.52,0.57]		
	C	SRC			0.62	0.59				
		C.I.			[0.60,0.65]	[0.56,0.62]				
Replace office equipment with higher-efficiency equipment	**A**	SRC	0.74	0.77	0.76	0.75	0.69	0.66	0.58	0.39
		C.I.	[0.71,0.76]	[0.74,0.80]	[0.73,0.79]	[0.73,0.78]	[0.67,0.72]	[0.63,0.68]	[0.55,0.60]	[0.36,0.41]
	B	SRC		0.70	0.78	0.74	0.72	0.66		
		C.I.		[0.67,0.72]	[0.75,0.81]	[0.72,0.76]	[0.69,0.75]	[0.62,0.69]		
	C	SRC			0.78	0.73				
		C.I.			[0.75,0.81]	[0.70,0.75]				
Replace heating coil with higher-efficiency coil	**A**	SRC	0.01	0.00	0.01	0.02	0.03	0.03	0.03	0.03
		C.I.	[0.00,0.01]	[0.00,0.01]	[0.01,0.01]	[0.01,0.02]	[0.02,0.03]	[0.02,0.03]	[0.03,0.04]	[0.02,0.03]
	B	SRC		0.00	0.00	0.01	0.01	0.02		
		C.I.		[0.00,0.01]	[0.00,0.00]	[0.00,0.01]	[0.00,0.02]	[0.01,0.03]		
	C	SRC			0.00	0.01				
		C.I.			[0.00,0.00]	[0.00,0.01]				
Replace cooling coil with higher-efficiency coil	**A**	SRC	0.11	0.11	0.07	0.05	0.04	0.04	0.03	0.01
		C.I.	[0.10,0.12]	[0.10,0.11]	[0.07,0.08]	[0.05,0.06]	[0.04,0.05]	[0.04,0.05]	[0.03,0.04]	[0.01,0.02]
	B	SRC		0.08	0.07	0.06	0.05	0.04		
		C.I.		[0.07,0.09]	[0.06,0.07]	[0.05,0.06]	[0.04,0.05]	[0.03,0.04]		
	C	SRC			0.05	0.03				
		C.I.			[0.05,0.05]	[0.03,0.04]				
Replace service hot water system with higher-efficiency system	**A**	SRC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		C.I.	[0.00,0.01]	[0.00,0.01]	[0.00,0.00]	[0.00,0.01]	[0.00,0.01]	[0.00,0.00]	[0.00,0.01]	[0.00,0.01]
	B	SRC		0.00	0.00	0.00	0.00	0.00		
		C.I.		[0.00,0.01]	[0.00,0.00]	[0.00,0.01]	[0.00,0.01]	[0.00,0.01]		
	C	SRC			0.00	0.00				
		C.I.			[0.00,0.00]	[0.00,0.01]				

[1] SRC is the median value of the absolute SRC sensitivity index.
[2] C.I. is confidence interval of the absolute SRC sensitivity index.

Due to the electricity domination in the buildings, the absolute SRC sensitivity indices for annual energy cost are similar to the indices for annual electricity use intensity. Since the EEMs related to the window, interior fixtures, and office equipment have the high indices for both annual electricity and natural gas use intensities, the indices for these here are higher in most of the climate zones compared with the indices for annual electricity use intensity.

4.2. Energy Impact Evaluation

By using the SRC sensitivity analysis, we calculated the absolute SRC sensitivity indices of all nine selected EEMs for the three EPIs. This subsection calculates the sensitivity ratio based on the sensitivity indices in order to evaluate the energy impact of these EEMs. Figure 6 shows the sensitivity ratios of the nine selected EEMs for annual electricity use intensity in the 15 climate zones.

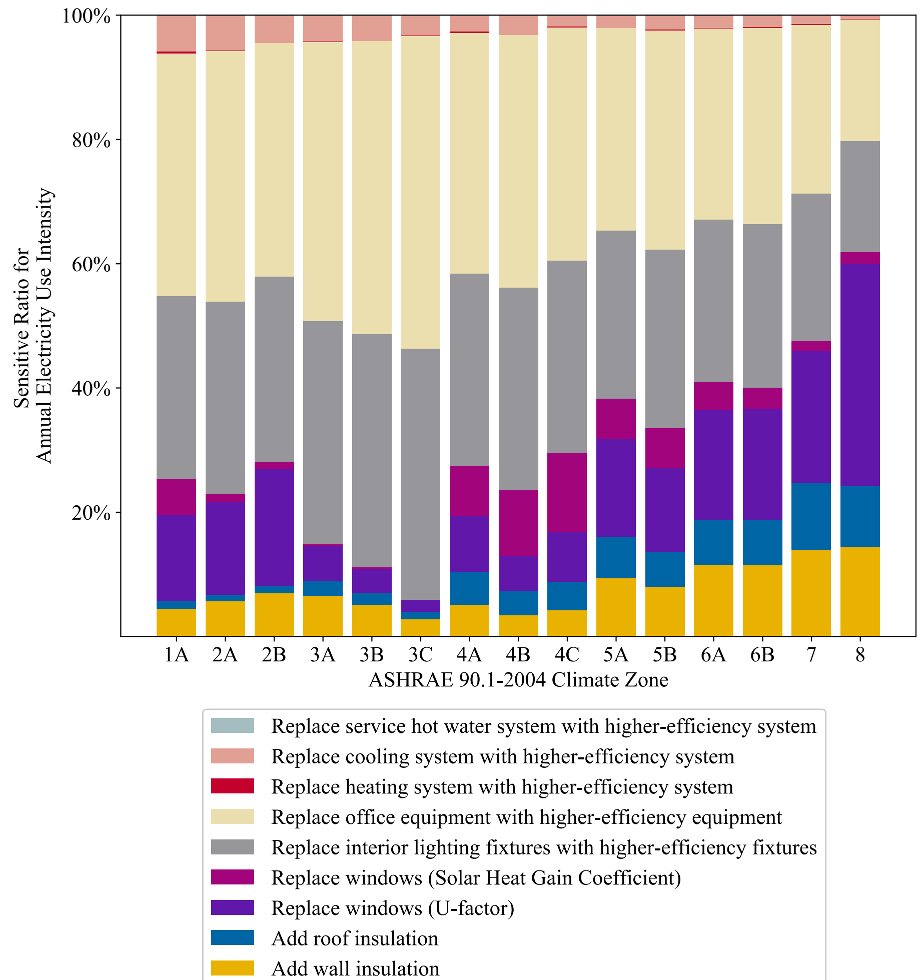


Figure 6. Sensitivity ratio of the nine EEMs for annual electricity use intensity in the 15 climate zones

Generally, replacing interior lighting fixtures with higher-efficiency fixtures, replacing office equipment with higher-efficiency equipment, and replacing windows (U-factor and SHGC) are the three EEMs with the highest sensitivity ratios in most climate zones. Furthermore, different climate zones have some varied features for the sensitivity ratios. For example, adding wall insulation and adding roof insulation have higher sensitivity ratios in cold climates, such as climate zones 7 and 8, indicating higher importance for this EEM in cold climates. However, replacing the cooling system with a higher-efficiency system is more sensitive in hot climate zones, such as climate zones 1A, 2A, and 2B. It is interesting for windows, the SHGC is more sensitive in mild climate zones, such as climate zones 4A, 4B, and 4C, while the U-factor is more sensitive in hot climate zones (1A, 2A, and 2B) and cold climate zones (5A, 5B, 6A, 6B, 7, and 8). During a building energy retrofit project, if windows need to be replaced to reduce annual electricity use intensity, the U-factor should be a key evaluator in the hot and cold climate zones, while the SHGC should be a key evaluator in the mild climate zones. Based on the results shown in Figure 6, replacing the heating system with a higher-efficiency system and replacing the service hot water system with a higher-efficiency system have insensitive ratios for the annual electricity use intensity in all 15 climate zones. Thus, if a building energy retrofit project needs to reduce the electricity energy consumption, these two EEMs are not good options to select.

Based on the analysis for Figure 4, the uncertainties of annual natural gas use intensity are close to 0 in climate zones 1 through 3. Thus, we only calculate the absolute SRC sensitivity indices for this EPI in the remaining nine climate zones. Based on these sensitivity indices, Figure 7 shows the sensitivity ratios of the nine selected EEMs for annual natural gas use intensity.

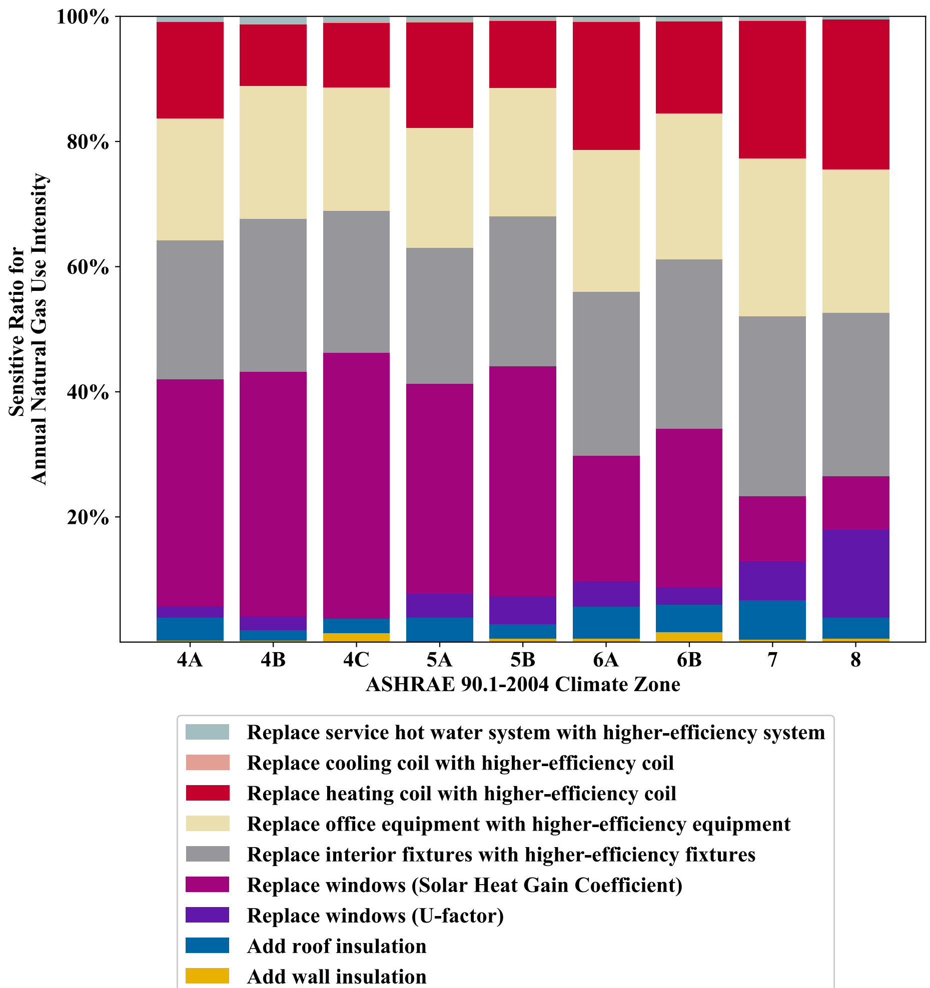


Figure 7. Sensitivity ratio of the nine EEMs for annual natural gas use intensity in climate zones 4A through 8

Generally, the highest sensitivity ratios in these nine climate zones are replacing windows (U-factor and SHGC), replacing interior lighting fixtures with higher-efficiency fixtures, replacing office equipment with higher-efficiency equipment, and replacing heating system with higher-efficiency system. Replacing windows is more sensitive in the mild climate zones (4A, 4B, and 4C) than in the cold climate zones (5A, 5B, 6A, 6B, 7, and 8). It is noticeable that replacing windows with different U-factors has higher sensitive ratios in cold climate zones than in mild climate zones; on the contrary, replacing windows with different SHGC is more sensitive in mild climate zones than in cold climate zones. Relatively, the other three major contributors have similar sensitive ratios in all nine climate zones. Besides these four EEMs, adding wall insulation and adding roof insulation also have small contributions in these climate zones. No contribution is made by replacing the cooling system with a higher-efficiency system and replacing the service hot water system with a higher-efficiency system. This is because the cooling system uses electricity instead of natural gas and service hot water system only consumes a small portion of energy in a building, which has been shown in Figure 3.

Based on these sensitivity indices, Figure 8 shows the sensitivity ratios of the nine selected EEMs for annual energy cost. The results are similar to the ratios for annual electricity use intensity. Since some EEMs, e.g. replacing heating coil with higher-efficiency coil, are sensitive for annual natural gas use intensity in climate zones 4 through 8, the sensitive ratios of annual energy cost for these EEMs are higher than the ratios for annual electricity use intensity in these climate zones.

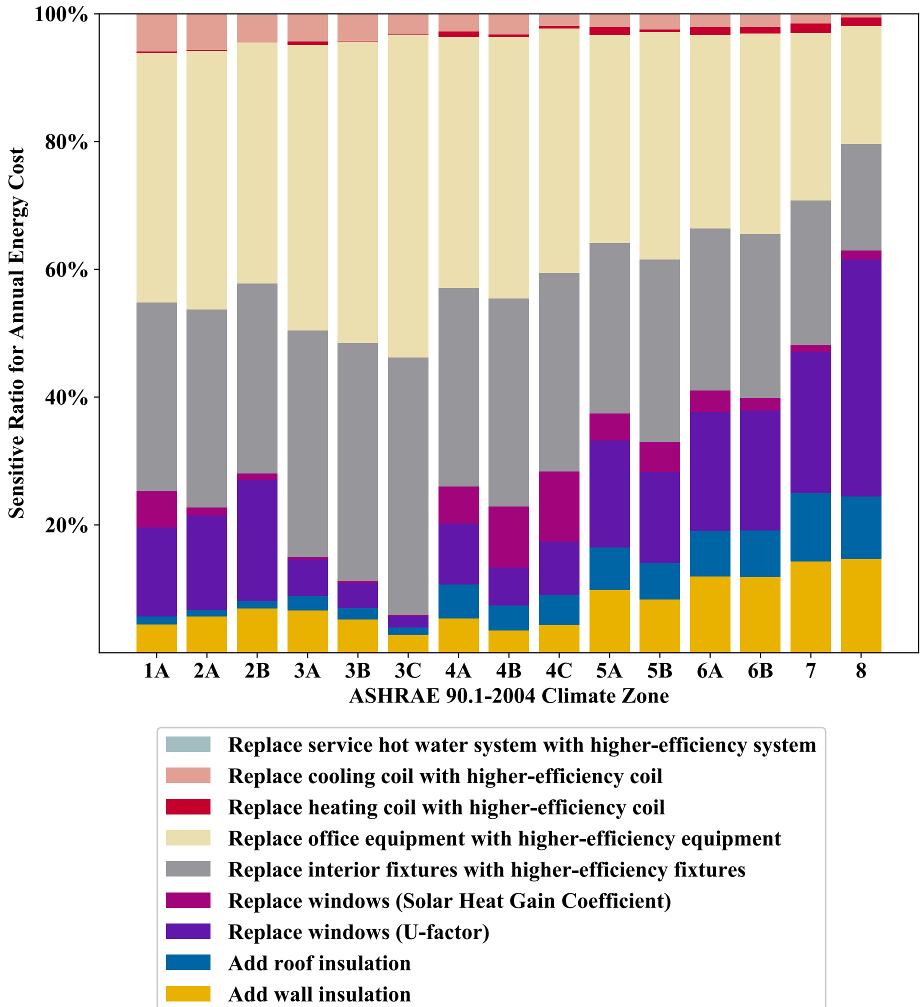


Figure 8. Sensitivity ratio of the 9 EEMs for annual energy cost in the 15 climate zones

5. Discussion

Dynamic electricity pricing programs are usually adopted in commercial buildings, such as medium office buildings. The methodology proposed in this paper is also able to evaluate the energy cost saving potentials of EEMs when a dynamic electricity pricing program. For example, some dynamic electricity pricing programs need not only the annual electricity use but also need the monthly peak power load for a building. In this case, the proposed methodology can set the monthly peak loads as a new EPI and calculate the sensitivity of selected EEMs to this EPI. Based on the models introduced in Section 3, Figure 9 shows the sensitivity ratios of the nine selected EEMs for monthly peak power load in the 15 climate zones. The 12 subfigures are included to show the sensitivity ratios in all 12 months in a year.

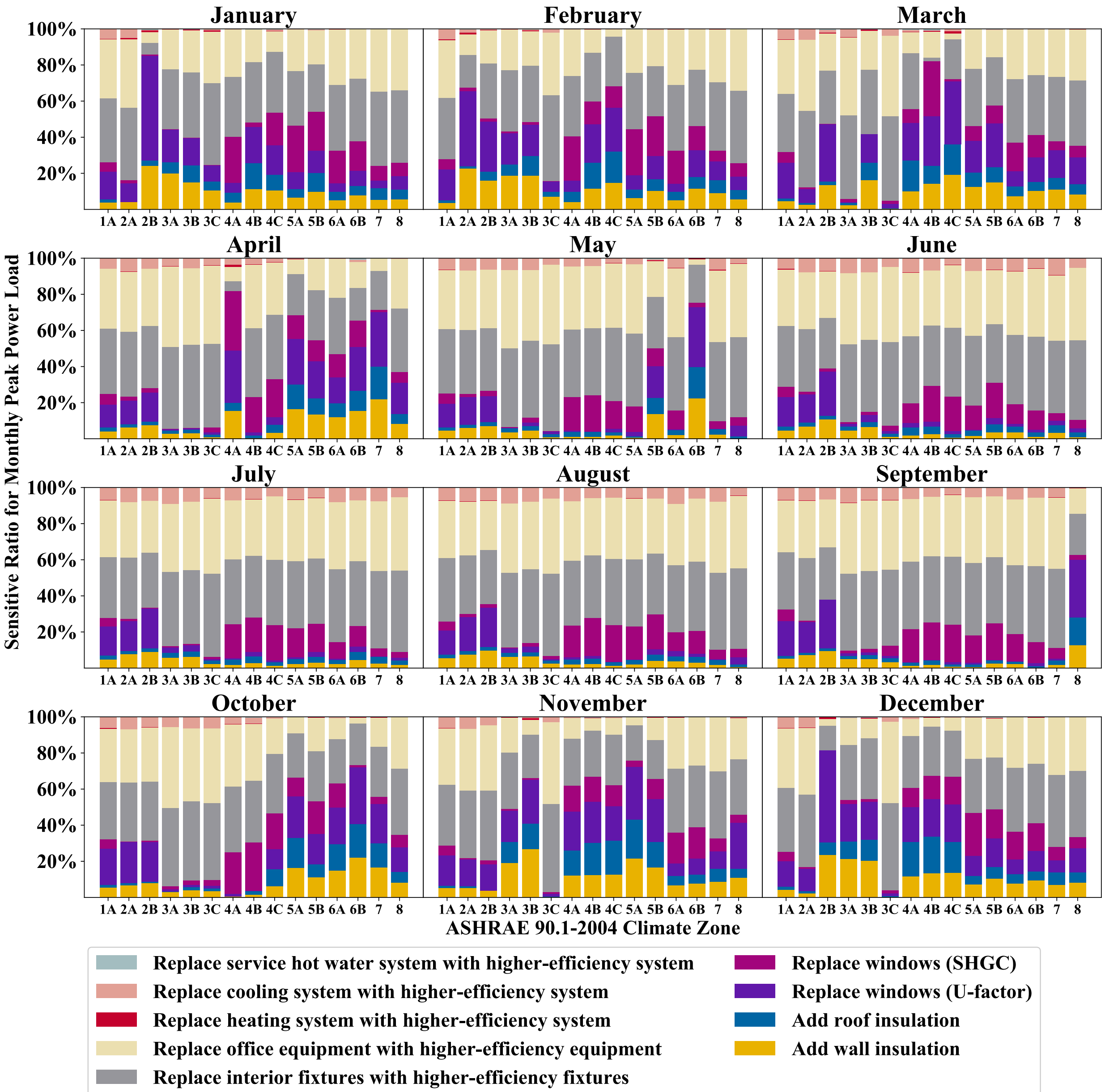


Figure 9. Sensitivity ratio of the 9 EEMs for monthly peak power load in the 15 climate zones

For EEMs, the results show that replacing interior lighting fixtures with higher-efficiency fixtures and replacing office equipment with higher-efficiency equipment both have highly sensitive ratios in most of months and climate zones. Replacing the heating system with a higher-efficiency system and replacing the service hot water system with a higher-efficiency system have sensitive ratios close to 0 in all months and climate zones. This is because the heating system and service hot water system use natural gas and do not affect the electricity power load.

For climate zones, the sensitive ratios of some EEMs depend on climate zones. For example, in January, replacing windows with different U-factors is responsible for approximately 60% of sensitive ratio in climate zone 2B, but it is lower than 20% in all other climate zones. In April, replacing windows with different SHGC is approximately 30% of sensitive ratio in climate zone 4A, but lower than 20% in all other climate zones. These results indicate the importance of considering climate impacts when addressing peak power loads for building energy retrofits.

For month-to-month comparison, the results show that the sensitive ratios of some EEMs change on a monthly basis. For instance, adding wall insulation has higher sensitive ratios in most climate zones during winter (January, February, and December) than in summer (June, July, and August). Furthermore, reducing internal loads (replacing interior lighting fixtures with higher-efficiency fixtures and replacing office equipment with higher-efficiency equipment) tends to contribute more to the ratios during summer (June, July, and August).

These results allow users to more easily quantify annual cost savings of one or more common EEMs for medium office retrofits. Because of the nationwide global sensitivity analysis and prototype building energy modeling performed in this study, even novice users can accuately evaluate EPIs for their case studies. For example, ROI – the ratio between annual cost savings for energy consumption and cost of investment – is a popular EPI in the selection of the EEMs for retrofit applications, which was previously discussed in the introduction. This paper provides the eight most common EEMs for medium office retrofits. From these eight options, users can select which EEMs they are interested in investigating and gather the investment costs easily from the market or existing documents, such as RSMeans (Gordian 2020). This paper's results can then be used directly to calculate the annual cost saving, bypassing the need for users to perform detailed building energy modeling to assess their building retrofit options. In a static electricity pricing program case, if the local electricity and natural gas unit prices are similar to the U.S. average values (electricity: $28.78/1,000 MJ; natural gas: $6.69/1,000 MJ), Figures 5 and 8 can be used to estimate the annual cost saving for energy consumption; otherwise, Figures 4, 6, and 7 can be used. In a dynamic electricity pricing program case, Figure 9 is also needed. These figures allow users to more readily calculate ROI for their medium office retrofits in their given climate zone and electricity pricing program.

6. Conclusion

This paper provides the energy saving potentials of nine EEMs to advise EEM selections in retrofit projects. To fulfill the target, three EPIs are selected for this research, which are annual electricity use intensity, annual natural gas use intensity, and annual energy cost. Then, we conduct sensitivity analyses of typical U.S. medium office buildings in the 15 climate zones. Generally, the most sensitive EEMs in most situations involves replacing windows, replacing interior lighting fixtures with higher-efficiency fixtures, and replacing office equipment with higher-efficiency equipment. However, some results vary by climate zone and EPI. For example, EEMs for envelope insulation improvement (e.g., adding wall insulation) are more sensitive in cold climate zones (e.g., climate zone 8). Another example is that replacing the heating system with a higher-efficiency system is sensitive to annual gas use intensity in climate zones 4 through 8, while it is insensitive to the other two EPIs. The outcomes summarized in this paper can help building owners and architects select EEMs during existing medium office building retrofits. This information can be use directly to advise energy improvements, but it can also be applied in financial evaluations, such as ROI estimation.

The range of EEMs in this paper are defined by literature review. Therefore, the EPIs of specific buildings may vary by specific pre-retrofit conditions. In the future, the same procedure can be applied to determine sensitive EEMs for other U.S. commercial buildings. With the large aging building stock in the United States and heavy energy consumption by buildings, quantitative evaluation such as these can help existing buildings systematically identify where their greatest energy saving potentials lie.

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Reference

Albadi, Mohamed H, and Ehab F El-Saadany. 2007. Demand response in electricity markets: An overview. Paper presented at the 2007 IEEE power engineering society general meeting.

ASHRAE. 2004. "Standard 90.1-2004, Energy standard for buildings except low rise residential buildings." *The American Society of Heating, Refrigerating and Air-Conditioning Engineers*.

ASHRAE. 2007. "Standard 90.1-2007, Energy standard for buildings except low rise residential buildings." *The American Society of Heating, Refrigerating and Air-Conditioning Engineers*.

ASHRAE. 2010. "Standard 90.1-2010, Energy standard for buildings except low rise residential buildings." *The American Society of Heating, Refrigerating and Air-Conditioning Engineers*.

Bonnema, Eric, Matt Leach, Shanti Pless, B Liu, W Wang, B Thornton, and J Williams. 2012. "50% Advanced Energy Design Guides." In.: National Renewable Energy Lab.(NREL), Golden, CO (United States).

Breesch, Hilde, and Arnold Janssens. 2010. "Performance evaluation of passive cooling in office buildings based on uncertainty and sensitivity analysis." *Solar energy* 84 (8):1453-67.

Corrado, Vincenzo, and Houcem Eddine Mechri. 2009. "Uncertainty and sensitivity analysis for building energy rating." *Journal of building physics* 33 (2):125-56.

Delgarm, Navid, Behrang Sajadi, Khadijeh Azarbad, and Saeed Delgarm. 2018. "Sensitivity analysis of building energy performance: a simulation-based approach using OFAT and variance-based sensitivity analysis methods." *Journal of Building Engineering* 15:181-93.

DOE. "Commercial Reference Building Models." https://energy.gov/eere/buildings/commercial-reference-buildings.

DOE. "EnergyPlus." https://energyplus.net/.

DOE. "Status of State Energy Code Adoption." https://www.energycodes.gov/status-state-energy-code-adoption.

DOE. "Commercial Prototype Building Models." https://www.energycodes.gov/commercial-prototype-building-models.

Doostizadeh, Meysam, and Hassan Ghasemi. 2012. "A day-ahead electricity pricing model based on smart metering and demand-side management." *Energy* 46 (1):221-30.

EIA. "2012 Commercial Buildings Energy Consumption Survey." https://www.eia.gov/consumption/commercial/data/2012/.

Eisenhower, B, Z O'Neill, V Fonoberov, and I Mezić. 2012. "Uncertainty and sensitivity decomposition of building energy models." *Journal of Building Performance Simulation* 5 (3):171-84.

Glazer, J. 2016. "Development of Maximum Technically Achievable Energy Targets for Commercial Buildings." *ASHRAE*.

Gordian. "Construction Cost Estimating Software: Rsmeans Data." https://www.rsmeans.com.

Griffith, B, N Long, P Torcellini, R Judkoff, D Crawley, and J Ryan. 2007. "Assessment of the technical potential for achieving net zero-energy buildings in the commercial sector." *National Renewable Energy Laboratory (NREL), Golden, CO.*

Heo, Yeonsook, Ruchi Choudhary, and GA Augenbroe. 2012. "Calibration of building energy models for retrofit analysis under uncertainty." *Energy and Buildings* 47:550-60.

Hygh, Janelle S, Joseph F DeCarolis, David B Hill, and S Ranji Ranjithan. 2012. "Multivariate regression as an energy assessment tool in early building design." *Building and Environment* 57:165-75.

Iooss, Bertrand, and Paul Lemaître. 2015. "A review on global sensitivity analysis methods." In *Uncertainty management in simulation-optimization of complex systems*, 101-22. Springer.

Joskow, Paul L, and Catherine D Wolfram. 2012. "Dynamic pricing of electricity." *American Economic Review* 102 (3):381-85.

Kneifel, Joshua. 2010. "Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings." *Energy and Buildings* 42 (3):333-40.

Li, Hangxin, Shengwei Wang, and Howard Cheung. 2018. "Sensitivity analysis of design parameters and optimal design for zero/low energy buildings in subtropical regions." *Applied Energy* 228:1280-91.

Liu, Guopeng, Bing Liu, Weimin Wang, Jian Zhang, Rahul A Athalye, Dave Moser, Eliot Crowe, Nick Bengtson, Mark Effinger, and Lia Webster. 2011a. "Advanced energy retrofit guide office buildings." In.: Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Liu, Guopeng, Bing Liu, Jian Zhang, Weimin Wang, Rahul A Athalye, Dave Moser, Eliot Crowe, Nick Bengtson, Mark Effinger, and Lia Webster. 2011b. "Advanced Energy Retrofit Guide Retail Buildings." In.: Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Menberg, Kathrin, Yeonsook Heo, and Ruchi Choudhary. 2016. "Sensitivity analysis methods for building energy models: Comparing computational costs and extractable information." *Energy and Buildings* 133:433-45.

Mokhtari, Amirhossein, and H Christopher Frey. 2005. "Review and recommendation of methods for sensitivity and uncertainty analysis for the Stochastic Human Exposure and Dose Simulation (SHEDS) models: Volume II: evaluation and recommendation of methodology for conducting sensitivity analysis in probabilistic models." *Alion Science and Technology: Durham, NC* 1:1-99.

Moser, Dave, Guopeng Liu, Weimin Wang, and Jian Zhang. 2012. "Achieving Deep Energy Savings in Existing Buildings through Integrated Design." *ASHRAE Transactions* 118 (2).

NBI. 2013. "New Construction Guide: A prescriptive guide to achieve significant, predictable energy savings in new commercial buildings." In. Vancouver, WA (United States): New Buildings Institute (NBI).

Nguyen, Anh-Tuan, and Sigrid Reiter. 2015. A performance comparison of sensitivity analysis methods for building energy models. Paper presented at the Building Simulation.

NREL. "openstudio-standards gem." https://github.com/NREL/openstudio-standards.

Pang, Zhihong, and Zheng O'Neill. 2018. "Uncertainty quantification and sensitivity analysis of the domestic hot water usage in hotels." *Applied Energy* 232:424-42.

Qiu, Shunian, Zhengwei Li, Zhihong Pang, Weijie Zhang, and Zhenhai Li. 2018. "A quick auto-calibration approach based on normative energy models." *Energy and Buildings* 172:35-46.

Sanchez, D Garcia, Bruno Lacarrière, Marjorie Musy, and Bernard Bourges. 2014. "Application of sensitivity analysis in building energy simulations: Combining first-and second-order elementary effects methods." *Energy and Buildings* 68:741-50.

Spitz, Clara, Laurent Mora, Etienne Wurtz, and Arnaud Jay. 2012. "Practical application of uncertainty analysis and sensitivity analysis on an experimental house." *Energy and Buildings* 55:459-70.

Stadler, Michael, Maximillian Kloess, Markus Groissböck, Gonçalo Cardoso, Ratnesh Sharma, Mohammad C Bozchalui, and Chris Marnay. 2013. "Electric storage in California's commercial buildings." *Applied Energy* 104:711-22.

Stein, Michael. 1987. "Large sample properties of simulations using Latin hypercube sampling." *Technometrics* 29 (2):143-51.

Storlie, Curtis B, and Jon C Helton. 2008. "Multiple predictor smoothing methods for sensitivity analysis: Description of techniques." *Reliability Engineering & System Safety* 93 (1):28-54.

Thornton, B, M Rosenberg, E Richman, W Wang, Y Xie, J Zhang, H Cho, V Mendon, R Athalye, and B Liu. 2011. "Achieving the 30% goal: Energy and cost savings analysis of ASHRAE Standard 90.1-2010." *Pacific Northwest National Laboratory (PNNL), Richland, WA (US)*.

Tian, Wei. 2013. "A review of sensitivity analysis methods in building energy analysis." *Renewable and Sustainable Energy Reviews* 20:411-9.

Tian, Wei, Pieter de Wilde, Zhanyong Li, Jitian Song, and Baoquan Yin. 2018. "Uncertainty and sensitivity analysis of energy assessment for office buildings based on Dempster-Shafer theory." *Energy Conversion and Management* 174:705-18.

Tian, Wei, Jitian Song, Zhanyong Li, and Pieter de Wilde. 2014. "Bootstrap techniques for sensitivity analysis and model selection in building thermal performance analysis." *Applied Energy* 135:320-8.

Wang, N, S Goel, and A Makhmalbaf. 2013. "Commercial Building Energy Asset Score System: Program Overview and Technical Protocol (Version 1.1)." *Pacific Northwest National Laboratory (PNNL), Richland, WA*.

Wang, N, S Goel, A Makhmalbaf, and N Long. 2016. "Development of building energy asset rating using stock modelling in the USA." *Journal of Building Performance Simulation*:1-15.

Wang, N, S Goel, V Srivastava, and A Makhmalbaf. 2015. "Building Energy Asset Score Program Overview and Technical Protocol (Version 1.2)." *Pacific Northwest National Laboratory (PNNL), Richland, WA*.

Wang, Weimin, Jian Zhang, Dave Moser, Guopeng Liu, Rahul Athalye, and Bing Liu. 2012. "Energy and Cost Savings of Retro-Commissioning and Retrofit Measures for Large Office Buildings." *Proceedings of SimBuild* 5 (1):496-503.

Wang, Zhaoxia, and Jing Zhao. 2018. "Optimization of passive envelop energy efficient measures for office buildings in different climate regions of China based on modified sensitivity analysis." *Sustainability* 10 (4):907.

Ye, Yunyang, Kathryn Hinkelman, Jian Zhang, Wangda Zuo, and Gang Wang. 2019. "A methodology to create prototypical building energy models for existing buildings: A case study on US religious worship buildings." *Energy and Buildings* 194:351-65.

Ye, Yunyang, Gang Wang, and Wangda Zuo. 2018a. "Creation of a Prototype Building Model of College and University Building." In *the 4th International Conference on Building Energy and Environment (COBEE2018)*, pp.373-8. Melbourne, Australia.

Ye, Yunyang, Gang Wang, Wangda Zuo, Peilin Yang, and Keya Joshi. 2018b. "Development of a Baseline Building Model of Auto Service and Repair Shop." In *2018 ASHRAE Building Performance Analysis Conference and SimBuild (BPACS2018)*, pp. 573-80. Chicago, IL.