Energy Modeling of Typical Commercial Buildings in Support of ASHRAE Building Energy Quotient Energy Rating Program (ASHRAE RP-1771)

Yingli Lou[a], Yunyang Ye[b], Yizhi Yang[a], Wangda Zuo[a,c,*], Gang Wang[d]

[a] Department of Architectural Engineering, Pennsylvania State University, University Park, PA, 16802, USA.

[b] Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder, Boulder, CO 80309, USA.

[c] National Renewable Energy Laboratory, Golden, CO, 80401, USA

[d] Civil, Architectural and Environmental Engineering Department, University of Miami, Coral Gables, FL, 33146, USA.

* Corresponding author. Email address: wangda.zuo@psu.edu (Wangda Zuo)

Abstract

In the practice of building energy performance evaluation, two types of rating systems are widely used in building energy performance evaluation: empirical baseline energy use intensity (EUI) for existing buildings and modeled baseline EUI for new buildings. Consequently, the baseline EUIs used by those systems are inconsistent. One example is ASHRAE's Building EQ *In Operation* and *As Designed*. To support the Building EQ, the ASHRAE RP-1771 project attempts to 1) make the baselines in both Building EQ *In Operation* and *As Designed* consistent, and 2) reconcile the Building EQ As Design with ASHRAE Standard 90.1 modeled baselines. After reviewing existing building data sources, we created sets of prototypical building energy models for 18 existing commercial building types based on commercial buildings energy consumption survey data. Then, we identified sensitive program design features (PDFs) for all building types. By developing adjustment factors of sensitive PDFs, we could adjust the empirical baseline EUI of Building EQ *In Operation* to match the modeled baseline EUI of Building EQ *As Designed*, with relative errors of less than 5%. To support building energy rating for new buildings, we developed a procedure to reconcile the modeled baseline EUIs of Building EQ and ASHRAE Standard 90.1, with relative errors of less than 5%.

Keywords: Building performance standard; commercial buildings; energy models for existing buildings; large-scale simulation.

Nomenclature

a_i	Adjustment factor of the sensitive program design feature i
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
b	Adjustment factor of EUI
Building EQ	Building energy quotient
CBECS	Commercial buildings energy consumption survey
DOE	U.S. Department of Energy
EPA	Environmental Protection Agency
EUI	Energy use intensity
$EUI_{90.1}$	Modeled 90.1 baseline EUI
EUI_{bEQ}	Modeled Building EQ As Design baseline EUI
EUI_{bEQ_cal}	Calculated Building EQ As Design baseline EUI
EUI_{emp}	Empirical baseline EUI for Building EQ *In Operation* rating
EUI_{mod}	Modeled baseline EUI for Building EQ *As Design* rating
EUI_{mod_cal}	Calculated building EQ's modeled baseline EUI
GAM	Generalized additive models
i	Program design feature i
k	Adjustment factor of EUI
LEED	Leadership in Energy and Environmental Design
LIN_REG	Linear regression
n	Total number of sensitive program design features
$N_{R^2 \geq 0.9}$	The number of sensitivity analysis methods whose $R^2 \geq 0.9$
$PCC^2_{LIN\_REG}$	The partial regression correlation coefficient squared, which is the sensitivity analysis results of the linear regression method
PDF	Program design feature
$PDF_{i,can}$	The value of sensitive program design feature i of a candidate building
$PDF_{i,def}$	The value of sensitive program design feature i of the prototypical building energy model for existing buildings
R^2	An indicator to evaluate the performance of the sensitivity analysis method
RP_REG	Recursive partitioning regression
RS_REG	Response surface regression
SHGC	Solar heat gain coefficient
$\hat{T}_{GAM}$	The sensitivity analysis results of generalized additive model
$\hat{T}_{RP\_REG}$	The sensitivity analysis results of recursive partitioning regression

$\hat{T}_{RS\_REG}$	The sensitivity analysis results of response surface regression

1. Introduction

In the practice of building energy performance evaluation, two types of rating systems are widely used: empirical baseline for existing buildings and modeled baseline for newly designed buildings. The ASHRAE Building EQ (ASHRAE 2023), EPA's ENERGY STAR program (EPA 2023), and ASHRAE Standard 100 (ASHRAE 2015) use the empirical approach with the baseline EUI based on existing building performance data, such as the DOE Commercial Building Energy Consumption Survey (CBECS) data (EIA 2006). By contrast, ASHRAE Standard 189.1 (ASHRAE 2014), ASHRAE Standard 90.1-2013 Addendum bm (ASHRAE 2013), LEED (USGBC 2023), and many other rating programs use the modeled approach with the simulated EUI baseline.

However, a study of LEED buildings (Turner et al. 2008) shows that the modeled baseline for new buildings results in a different estimate of energy use from the empirical baseline for existing buildings. An empirical baseline is usually created for a group of similar existing buildings in a similar climate, which represents the median of energy use for a group of buildings. By contrast, the modeled baseline is usually created for the individual newly designed building. A baseline model is created for individual new building to generate the modeled baseline. The baseline model typically has the same geometric shape, schedules of operation, heating and cooling set point temperatures, and other building operation inputs with the individual new building. Therefore, the empirical baseline and modeled baseline for one building is different in some cases, and thus a building does not receive the same rating from when it is designed to when it is operated.

The modeled baselines based on various building energy standards are different in some cases. The baseline model of the individual building is created based on building characteristics of individual buildings and building energy standards. Building energy standards set values for various building assets. For example, the R-value of the wall and the SHGC of the window. Some values of building assets of different buildings energy standards are different. Therefore, the modeled baselines could also be different.

ASHRAE's Building EQ rating system consists of these two types of rating system: Building EQ *In Operation* for existing buildings and Building EQ *As Design* for both new and existing buildings. The *In Operation* rating applies only to existing buildings because the energy performance of the candidate building is determined from measured energy use, typically the utility bills. *In Operation* rating compares actual building energy use based on metered energy information. The *As Designed* rating can apply to both new and existing buildings and is intended to only evaluate the building energy efficiency measures. The *As Designed* compares potential energy use based on the building's physical characteristics and systems with standardized energy use simulation. ASHRAE intends that the two ratings be consistent with each other. A candidate building should receive the same *As Designed* and *In Operation* rating under typical operating conditions or level of energy service.

To support the Building EQ, the ASHRAE RP-1771 attempts to 1) make the baselines in both Building EQ *In Operation* and *As Designed* consistent and 2) reconcile the Building EQ As Design with ASHRAE Standard 90.1 modeled baselines. This paper is organized as follows: Section 2 introduces the methodology including the creation of prototypical building energy models for existing buildings, reconciliation of Building EQ *In operation* with *As Design* baseline EUIs, and reconciliation of Building EQ As Design with ASHRAE Standard 90.1 modeled baseline EUIs; Sections 3 used pre-1980 medium office buildings as an example to show these three aspects; Section 4 illustrate the applications of this research in the building energy rating practice for both existing and new buildings; finally, Section 5 makes a conclusion.

2. Methodology

Fig.1 shows the methodology of ASHRAE RP-1771. Building characteristics data and operation information of existing buildings are very limited. Therefore, we need to develop the prototypical building energy models to represent existing buildings at first. Fifteen prototypical building energy models are developed for each type of buildings to represent 15 climate locations in the U.S. Then, using the prototypical building energy models as a starting point, large-scale energy models of existing buildings will be created. Based on the simulation results of the large-scale energy models, we will reconcile the Building EQ empirical and modeled baseline EUIs, and reconcile the Building EQ and ASHRAE Standard 90.1 modeled baseline EUIs. The following three subsections will introduce these steps in detail.

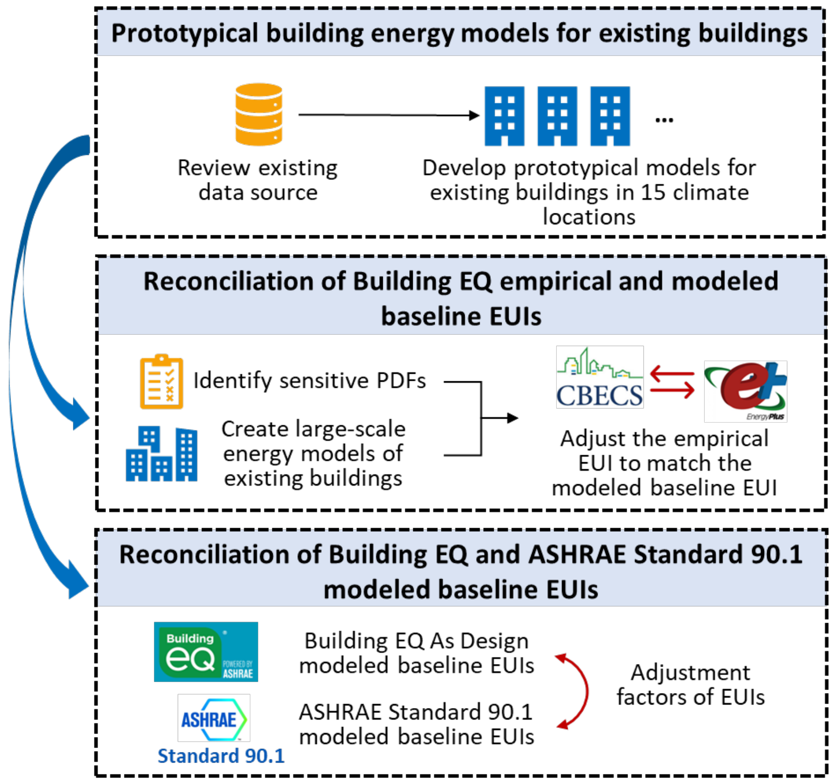

Fig.1. Methodology of ASHRAE RP-1771.

2.1. Prototypical building energy models for existing buildings

A comprehensive literature review is first conducted to summarize energy-related data for U.S. commercial buildings. We reviewed existing building data sources of U.S. commercial buildings and identified the recommended classification of building types and sensitive input variables, including program design features, building operation inputs, building assets, and building operation influenced by assets. More detailed information can be found in our previous publication (Ye, Zuo, et al. 2019).

Based on the data of existing commercial buildings, a method of creating prototypical building energy models for existing commercial buildings is proposed, which includes six steps: identify the model inputs, collect related data, clean the data, convert the data into model inputs, conduct the simulation, and calibrate the building energy models. More detailed information is illustrated in our previous publication (Lou et al. 2023; Ye et al. 2020; Ye, Hinkelman, et al. 2019).

2.2. Reconciliation of Building EQ's empirical and modeled baseline EUIs

An empirical baseline is usually created for a group of similar existing buildings while modeled baseline is usually created for individual buildings, which takes account of many program design features (PDFs), for example, the total floor area, floor-to-floor height. Therefore, there is a difference between the empirical and modeled baseline.

We plan to obtain an adjusted empirical baseline for a candidate building (EUI_{emp_adj}) by adding the Building EQ's empirical baseline (EUI_{emp}) with an adjustment for sensitive PDFs, as shown in equation (1). The EUI_{emp_adj} is objective to be consistent with Building EQ's modeled baseline EUIs (EUI_{mod}).

$$EUI_{emp\_adj} = EUI_{emp} + \sum_{1}^{n} a_i(PDF_{i,can} - PDF_{i,def}), \tag{1}$$

where, a_i is the adjustment factor developed in this study for the sensitive PDF i; The n is the number of sensitive PDFs; $PDF_{i,can}$ is the value of sensitive PDF i for a candidate building; and $PDF_{i,def}$ is the default value of sensitive PDF i, which will be determined in this research. The procedure to calculate adjustment factors of sensitive PDFs is shown in Fig.2.

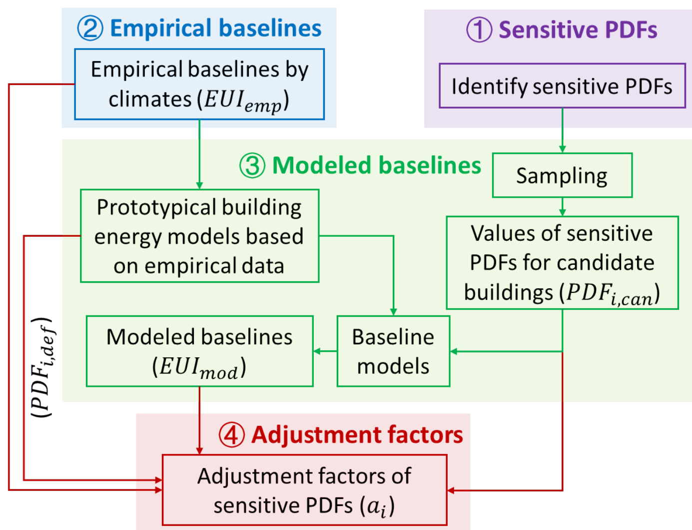

Fig.2. Methodology of reconciling the Building EQ's empirical and modeled baseline EUIs

<u>Step 1: Identify sensitive PDFs to EUI using four different sensitivity analysis methods</u>: Linear Regression (LIN_REG), Response Surface Regression (RS_REG), Generalized Additive Models (GAM), and Recursive Partitioning Regression (RP_REG) (Storlie et al. 2009; Storlie and Helton 2008b, 2008a). Some sensitivity analysis methods have difficulty in identifying certain types of relationship (Helton et al. 2006; Tian 2013). For example, LIN_REG cannot identify the relationship except the linear one. Also, some sensitivity analysis overfit the data, and identify the sensitive inputs which are not the truly sensitive ones. Thus, we analyze the results from all four methods, and then identify the sensitive PDFs.

We use "credits" to count the sensitive degree of each possible sensitive PDF. For each method, the credit of each possible sensitive PDF ranges from 0 to 1. When the credit closes to 1, the PDF is highly sensitive to EUI, and if the model input is changed, the EUI will be changed greatly. When the credit closes to 0, the PDF is not or weakly sensitive to EUI, and if the model input is changed, the EUI will almost keep the value. Table 1 shows the way to calculate the credits of the four sensitivity analysis methods.

Table 1. Criteria to identify the sensitive PDFs

Condition	Credit	Condition	Credit
$PCC^2_{LIN\_REG} > 0.1$	1	$PCC^2_{LIN\_REG} \leq 0.1$	$3 \times \left(\frac{PCC^2_{LIN\_REG}}{0.1}\right)^2 - 2 \times \left(\frac{PCC^2_{LIN\_REG}}{0.1}\right)^3$
$\hat{T}_{RS\_REG} > 0.1$	1	$\hat{T}_{RS\_REG} \leq 0.1$	$3 \times \left(\frac{\hat{T}_{RS\_REG}}{0.1}\right)^2 - 2 \times \left(\frac{\hat{T}_{RS\_REG}}{0.1}\right)^3$
$\hat{T}_{GAM} > 0.1$	1	$\hat{T}_{GAM} \leq 0.1$	$3 \times \left(\frac{\hat{T}_{GAM}}{0.1}\right)^2 - 2 \times \left(\frac{\hat{T}_{GAM}}{0.1}\right)^3$
$\hat{T}_{RP\_REG} > 0.1$	1	$\hat{T}_{RP\_REG} \leq 0.1$	$3 \times \left(\frac{\hat{T}_{RP\_REG}}{0.1}\right)^2 - 2 \times \left(\frac{\hat{T}_{RP\_REG}}{0.1}\right)^3$

Note: $PCC^2_{LIN\_REG}$ is the partial regression correlation coefficient squared, which is the sensitivity analysis results of the linear regression method; $\hat{T}$ is the estimated value to reflect the total proportion of the uncertainty in the EUIs. $\hat{T}_{RS\_REG}$, $\hat{T}_{GAM}$, and $\hat{T}_{RP\_REG}$ is the sensitivity analysis results of response surface regression, generalized additive models, and recursive partitioning regression methods.

After calculating the credits of the four sensitivity analysis methods, we need to sum up all the credits. In this study, the criteria to determine the sensitive model inputs are:

$$Total\ Credits \times \frac{4}{N_{R^2 \geq 0.9}} \geq 1.25, \text{ sensitive model input}$$

$$Total\ Credits \times \frac{4}{N_{R^2 \geq 0.9}} < 1.25, \text{ not sensitive model input}$$

where $N_{R^2 \geq 0.9}$ is the number of the sensitivity analysis methods whose $R^2 \geq 0.9$. R^2 is an indicator to evaluate the performance of the sensitivity analysis method. $R^2 \geq 0.9$ means that the sensitivity analysis results are credible.

Step 2: Develop Building EQ's empirical baselines based on survey data. The median EUI of one type of commercial building is calculated based on the energy consumption data in the 2003 CBECS. Then, we calculated empirical baseline EUIs for 15 climate locations by multiplying the median EUI with climate adjustment factors provided by ASHRAE Standard 100.

Step 3: Create baseline models for candidate buildings. Using the prototypical building energy model created in subsection 2.1 as a starting point, the baseline models for candidate buildings are created by modifying the values of sensitive PDFs ($PDF_{i,can}$). Then, modeled baseline (EUI_{mod}) is generated for each candidate building by running baseline models.

Step 4: Calculate the adjustment factors (a_i) to adjust the empirical baselines (EUI_{emp}) to get calculated the modeled baseline (EUI_{mod_cal}). The EUI_{mod_cal} is objective to be consistent with modeled baselines (EUI_{mod}). For each climate zone, empirical baselines (EUI_{emp}) are constant for all candidate buildings. However, modeled baseline (EUI_{mod}) are unique for each candidate building because the values of PDFs ($PDF_{i,can}$) are different. We use the $PDF_{i,can}$ as the independent variable and use EUI_{mod} as the dependent variable to create regression models. Then we obtained the best a_i which can minimize the sum of the absolute difference of EUI between the modeled baselines (EUI_{mod}) and the calculated one from regression models (EUI_{mod_cal}).

2.3. Reconciliation of Building EQ As Design and ASHRAE Standard 90.1 modeled baseline EUIs

Modeled EUI is used as a baseline for evaluating building's energy performance when we design a building. However, molded baselines based on different standards are different. For example, modeled Building EQ As Design EUI and modeled ASHRAE Standard 90.1 EUI are different. This subsection will investigate the relationships between the modeled Building EQ baseline EUIs and modeled 90.1 baseline EUIs. Following are the definitions of five terms used in this research.

- Building EQ baseline models: building energy models developed based on empirical data. This research uses the CBECS 2003 data.
- Modeled Building EQ baseline EUI: EUI generated by running the Building EQ baseline models.
- 90.1 baseline models: building energy models developed based on ASHRAE standards 90.1. This research uses the ASHRAE standard 90.1-2004.
- Modeled 90.1 baseline EUI: EUI generated by running the 90.1 baseline models.
- Calculated Building EQ baseline EUI: EUI calculated by using the Modeled 90.1 baseline EUI and adjustment factors developed in this research.

Model inputs of baseline models can be classified into four categories: program design features, building operation inputs, building assets, and building operation influenced by assets. This research considers three model input categories: (1) program design features (e.g., floor-to-floor height), (2) building operation inputs (e.g., occupied hour), and (3) building assets (e.g., wall insulation).

Since program design features and building operation inputs should not affect building energy performance evaluation, the modeled baselines focus on the energy efficiency features (building assets). Both the designed building models and baseline building models should use the same program design features and building operation inputs. Therefore, the creation of baseline models follows three principles: (1) model inputs related to program design features are the values of designed building; (2) model inputs related to building operation are recommended values since the designed building does not have operation information yet; and (3) model inputs related to building assets are standardized values (e.g., ASHRAE Standard 90.1). Following these three principles, Building EQ baseline models and 90.1 baseline models can be developed according to Table 2.

Table 2. Development of Building EQ and 90.1 baseline models

Model Inputs Category	**Building EQ Baseline Models**	**90.1 Baseline Models**
Program design features	Values of designed building	

Model Inputs Category	Building EQ Baseline Models	90.1 Baseline Models
Building assets	Recommended values based on prototypical building energy models for existing buildings	ASHRAE Standard 90.1-2004
Building operation inputs	Recommended values based on prototypical building energy models for existing buildings	

Based on the information in Table 2, the workflow of reconciling Building EQ As Design and ASHRAE Standard 90.1 modeled baseline EUIs can be drawn as Fig.3, which includes four steps:

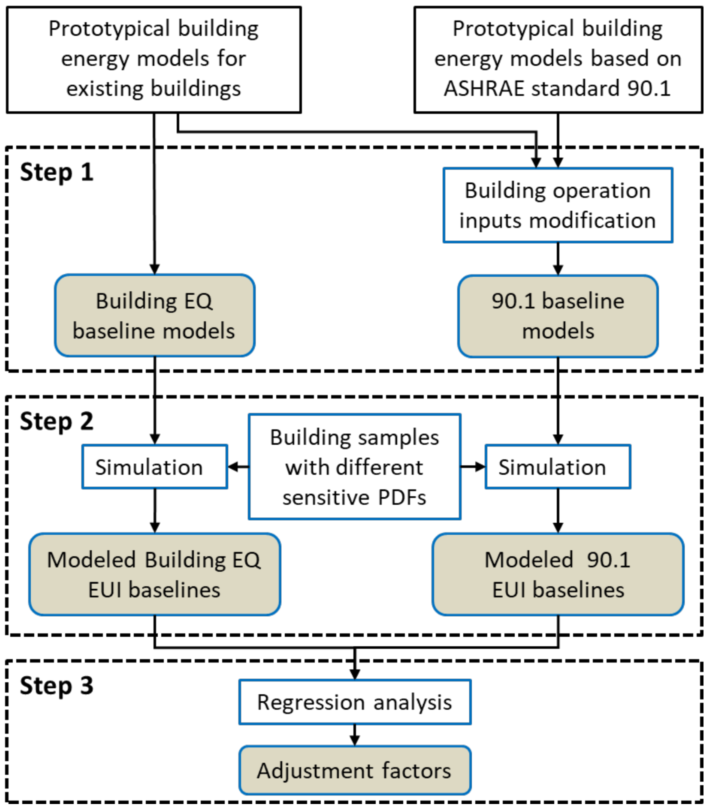

Fig.3. Methodology of reconciling Building EQ As Design and ASHRAE Standard 90.1 modeled baseline EUIs

Step 1: Develop Building EQ and 90.1 baseline models. Building EQ baseline models are developed by using the method illustrated in subsection 2.1. 90.1 baseline models are created based on ASHRAE standard 90.1-2014 by using OpenStudio Standards Gem (NREL 2018). In the building energy rating practice, the building operation inputs of baseline models should be the same as candidate buildings. Therefore, the building operation inputs of 90.1 baseline models are modified to keep consistent with the Building EQ baseline models.

Step 2: Generate modeled Building EQ and 90.1 baseline EUIs. In the building energy rating practice, the building program design features of baseline models should be the same as candidate buildings.

Therefore, we first generate building samples with different program design features. Then for each building sample, both Building EQ and 90.1 baseline models are created using the baseline models in Step 1 as a starting point. Finally modeled baseline EUIs are generated by running baseline models.

Step 3: Calculate adjustment factors. This step will calculate the adjustment factors that align the modeled 90.1 baseline EUI to the modeled Building EQ baseline EUI, as shown in following equation:

$$EUI_{bEQ\_cal} = k \times EUI_{90.1} + b, \tag{2}$$

where, EUI_{bEQ_cal} is the calculated Building EQ baseline EUI; $EUI_{90.1}$ is the modeled 90.1 baseline EUI; and k, b are code adjustment factors. Using equation (2)**Error! Reference source not found.**, the calculated Building EQ baseline EUI (EUI_{bEQ_cal}) will be consistent with modeled Building EQ baseline EUI (EUI_{bEQ}).

3. Results

3.1. Prototypical building energy models for existing buildings

3.1.1. Data preparation

We identified 18 commercial building types (Table 3), including 14 existing DOE's Commercial Prototype Buildings and 4 newly identified building types, which are supermarket, religious worship, college/university, and auto repair & service. These building types represent about 87.45% of buildings and 86.97% of total floor area in CBECS 2003 National Data.

Table 3. Reference commercial building types and information related to the criteria

No.	Building Type	Percentage of Number of Buildings in National Data (%)	Percentage of Total Floor Area of Buildings in National Data (%)	Number of Buildings in Microdata
1	Large Office	16.96	17.04	292
2	Medium Office			371
3	Small Office			313
4	Non-refrigerated Warehouse	12.29	14.06	389
5	Stand-alone Retail	9.12	6.02	349
6	Strip Mall	4.38	9.59	291
7	Primary School	7.95	13.78	330
8	Secondary School			126
9	College/University			88
10	Quick Service Restaurant	6.11	2.31	54
11	Full Service Restaurant			145
12	Hospital	0.16	2.66	217
13	Outpatient Health Care	2.49	1.76	144
14	Motel or Inn	2.92	7.11	109
15	Hotel			86
16	Religious Worship	7.62	5.24	311

No.	Building Type	Percentage of Number of Buildings in National Data (%)	Percentage of Total Floor Area of Buildings in National Data (%)	Number of Buildings in Microdata
17	Supermarket	4.65	1.75	63
18	Auto Repair & Service	12.80	5.65	268
Total		87.45	86.97	3,946

We investigated 15 climate locations in the U.S. In ASHRAE Standard Climate Zones, 15 typical cities are identified to represent 15 climate zones in U.S. However, a different climate zone system, which includes five climate zones in U.S., is defined by CBECS 2003 data, as shown in Fig.4. Fig.4 also shows the 15 typical cities representing each ASHRAE climate zone. The correlation between the climate zones in the U.S. from ASHRAE Standard and the climate zones in CBECS 2003 are shown in Table 4.

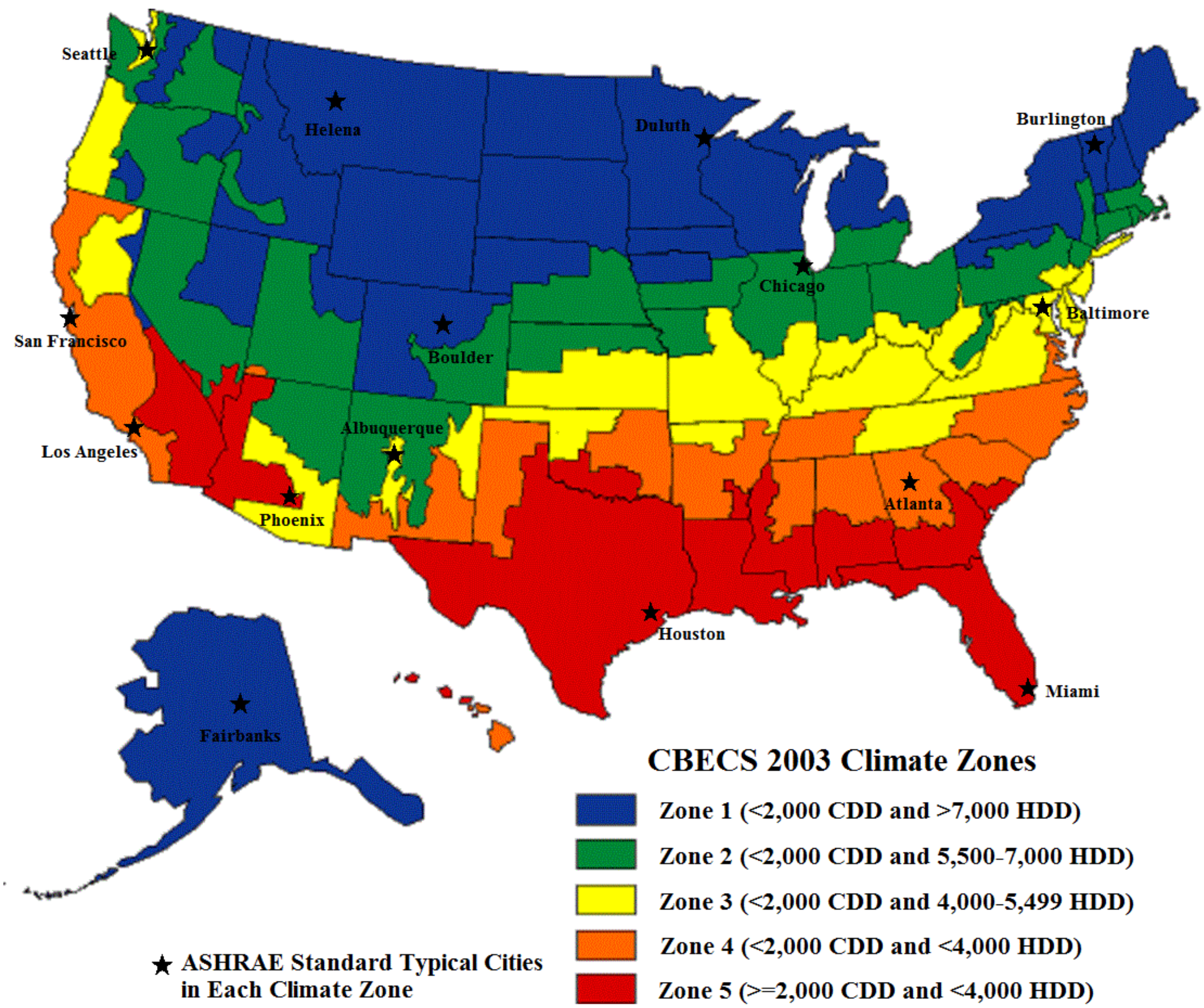

Fig.4. ASHRAE Standard typical cities in CBECS 2003 climate zone

Table 4. The climate zones of the models

No.	Typical City	ASHRAE Climate Zone	CBECS 2003 Climate Zone
1	Miami, USA	1A	Zone 5 ≥2,000 CDD and <4,000 HDD
2	Houston, USA	2A	
3	Phoenix, USA	2B	
4	Atlanta, USA	3A	Zone 4 <2,000 CDD and <4,000 HDD
5	Los Angeles, USA	3B	
6	San Francisco, USA	3C	
7	Baltimore, USA	4A	Zone 3 <2,000 CDD and 4,000~5,499 HDD
8	Albuquerque, USA	4B	
9	Seattle, USA	4C	
10	Chicago, USA	5A	Zone 2 <2,000 CDD and 5,500~7,000 HDD
11	Boulder, USA	5B	Zone 1 <2,000 CDD and >7,000 HDD
12	Burlington, USA	6A	
13	Helena, USA	6B	
14	Duluth, USA	7	
15	Fairbanks, USA	8	

Note: CDD is cooling degree day, HDD is heating degree day

3.1.2. Prototypical building energy models

We developed building energy models based on the 2003 CBECS data, which include 18 commercial building types in two vintages (pre-1980 and post-1980) in 15 climate locations in the U.S. This results in an overall set of 540 total building energy models, which are open released (SBS Lab 2022). The average relative error between modeled data and empirical data among 15 climate zones are presented in Table 5.

Table 5. Average relative error between modeled energy consumption data and empirical data among 15 climate zones

Unit: %

No.	Building Type	Reference Models		Prototypical Building Energy Models		
		Pre-1980	Post-1980	Pre-1980	Post-1980	All
1	Large Office	27.75	26.10	7.11	6.91	7.01
2	Medium Office	33.27	22.49	9.26	8.97	9.12
3	Small Office	28.41	21.23	3.31	6.02	4.67
4	Non-refrigerated Warehouse	18.89	11.60	13.50	12.20	12.85
5	Standalone Retail	53.69	55.91	10.79	9.14	9.96
6	Strip Mall	19.03	17.45	2.73	2.97	2.85
7	Primary School	20.14	34.81	5.90	6.28	6.09
8	Secondary School	6.53	14.59	5.68	4.08	4.88
9	College/University	15.59	15.38	12.81	8.10	10.45
10	Quick Service Restaurant	30.48	10.34	10.48	2.27	6.38
11	Full Service Restaurant	30.81	30.46	14.98	14.32	14.65
12	Hospital	12.35	17.63	3.98	4.61	4.30

No.	Building Type	Reference Models		Prototypical Building Energy Models		
		Pre-1980	Post-1980	Pre-1980	Post-1980	All
13	Outpatient Health Care	32.13	26.28	6.85	7.14	6.99
14	Motel or Inn	18.50	22.29	6.04	4.36	5.20
15	Hotel	56.01	34.75	4.47	8.95	6.71
16	Religious Worship	11.01	5.55	7.80	4.49	6.15
17	Supermarket	5.73	4.91	4.53	3.10	3.82
18	Auto Repair Service	8.01	10.80	5.53	2.64	4.01

Note: pre-1980 are buildings constructed before 1980; post-1980 are buildings constructed after 1980

3.2. Reconciliation of Building EQ's empirical and modeled baseline EUIs

Following the methodology introduced in subsection 2.2, this section adopts pre-1980 medium office buildings as an example to present the results of sensitive PDFs (subsection 3.2.1), the empirical baselines by climates (subsection 3.2.2), and the modeled baselines by climates of individual buildings (subsection 3.2.3). Finally, the adjustment factors of sensitive PDFs to reconcile the difference between empirical baseline and modeled baseline EUIs are shown in subsection 3.2.4. The sensitive PDFs, empirical baselines, and adjustment factors of sensitive PDFs of 18 commercial building types are provided in Appendix. The application of adjustment factors to building energy rating practices will be introduced in Section 4.

3.2.1. Sensitive PDFs

There are three possible sensitive PDFs for the medium office building models: Climate zone, floor-to-floor height, and plug load density. Since the prototypical models (created in section 3.1) have already considered the impact of climates on the buildings, we will focus on the sensitive analysis for the remaining two PDFs (listed in Table 6). The maximum and minimum values were identified based on literature review (Deru et al. 2011; Griffith et al. 2008; Huang and Franconi 1999; NREL 2022; Sharp 1996; N Wang et al. 2015; Na Wang and Gorrissen 2013; Winiarski et al. 2006, 2007). Then we used the sampling method to select values for each possible sensitive PDF.

Table 6. Possible sensitive PDFs of medium office buildings

No.	Possible Sensitive Model Inputs	Unit	Minimum Value	Maximum Value
1	Climate	-	-	-
2	Floor-to-floor height	ft	8.00	14.00
3	Plug load density	W/ft^2	0.32	3.03

Table 7 shows the selection of sensitive model inputs for medium office buildings. If total credits are larger than 1.25, the possible sensitive model input is the sensitive one. Based on the results shown in Table 2 4, plug load density and climate zone are the two sensitive model inputs of medium office buildings.

Table 7. Selection of sensitive PDFs for medium office buildings

	Possible Sensitive Model Inputs	PCC^2 or $\widehat{T}_j$	Credit
LIN_REG: $R^2 = 0.947$	Climate zone	0.032	0.24

	Possible Sensitive Model Inputs	PCC^2 or $\hat{T}_j$	Credit
	Floor-to-floor height	0.065	0.72
	Plug load density	0.946	1.00
RS_REG: $R^2 = 0.985$	Climate zone	0.037	0.31
	Floor-to-floor height	0.009	0.02
	Plug load density	0.961	1.00
GAM: $R^2 = 0.983$	Climate zone	0.033	0.25
	Floor-to-floor height	0.004	0.00
	Plug load density	0.961	1.00
RP_REG: $R^2 = 0.985$	Climate zone	0.047	0.46
	Floor-to-floor height	0.000	0.00
	Plug load density	0.970	1.00
$\boldsymbol{Total\ Credits} \times \frac{\mathbf{4}}{\boldsymbol{N_{R^2 \geq 0.9}}}$	Climate zone	-	1.26
	Floor-to-floor height	-	0.74
	Plug load density	-	4.00
Sensitive program design features: Plug load density, climate zone			

3.2.2. Empirical baselines

Table 8 shows the empirical baseline (site EUI) of pre-1980 medium offices. The median site EUI of the pre-1980 medium office in the 2003 CBECS is 79.37 kBtu/ft2-yr. The empirical baselines (site EUIs) are calculated by multiplying the median site EUI and climate adjustment factors defined in ASHRAE Standard 100 (ASHRAE 2015).

Table 8. Empirical baseline site EUI by climate for pre-1980 medium office buildings

Unit: kBtu/ft^2-yr

Climate Zone	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Empirical baseline site EUI	78	77	78	77	74	61	83	72	74	88	76	98	87	106	148

3.2.3. Modeled baselines

Sensitive model inputs have been identified in subsection 3.2.1, which are plug load density and climate zone. But we only need to determine the value of plug load density since the building energy models have already considered the impact of climate. Modeled baselines are generated by running baseline models. First, values of sensitive model inputs are sampled randomly. For pre-1980 medium office buildings, we only need to sample the value of plug load density within the range defined in Table 6. Each value represents one candidate building. Then, baseline models for candidate buildings are created based on the prototypical building energy models in subsection 3.1 and values of sensitive model inputs.

Fig.5 shows the modeled baselines for pre-1980 medium office buildings. Climate zone 8A has the highest modeled baseline in most climate zones and climate zone 3C has the lowest modeled baseline in most climate zones. The modeled baselines increase with the increase of the plug load density and the relation between plug load density and modeled baseline in each climate zone is almost linear.

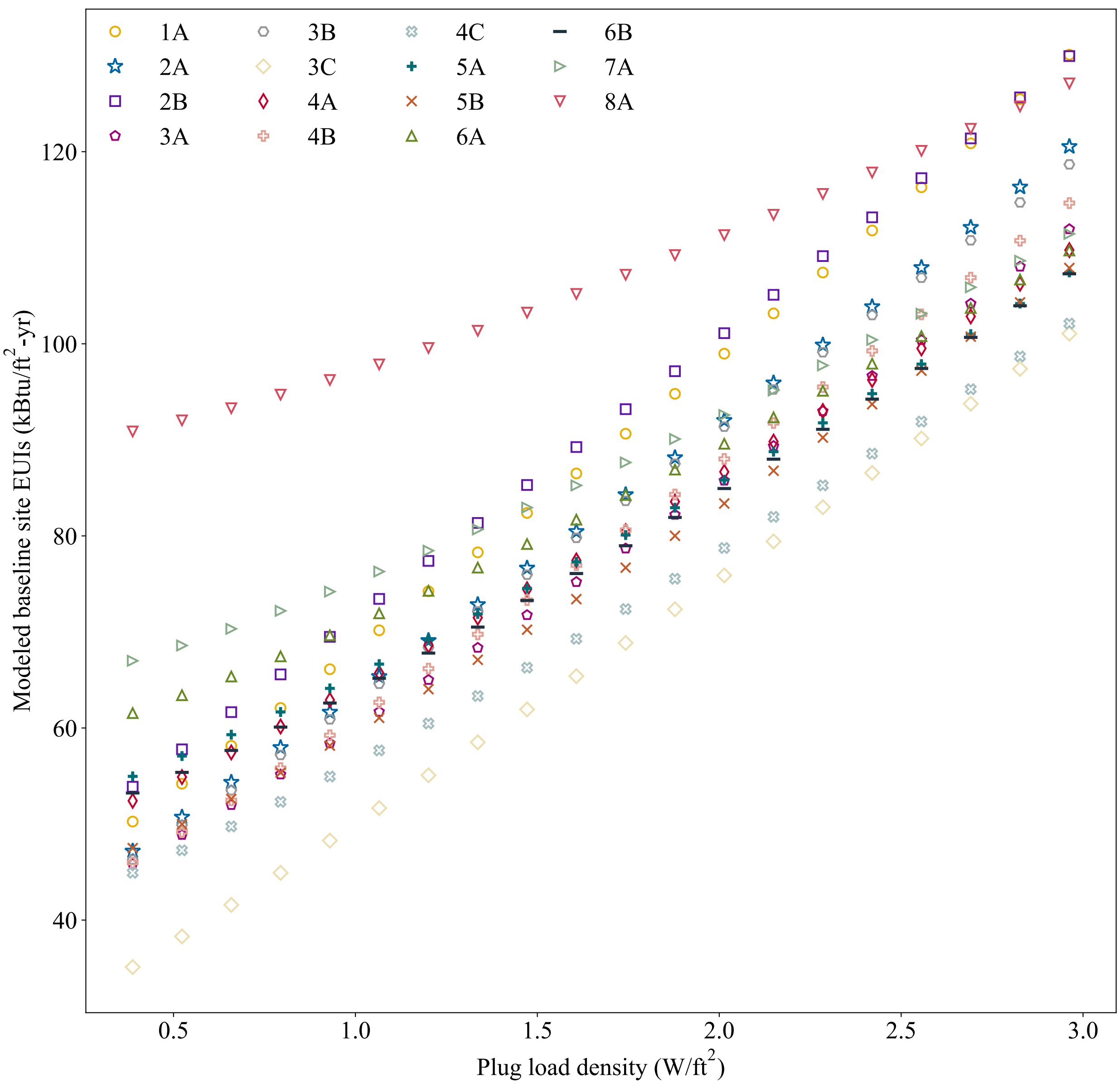

Fig.5. Modeled baselines for pre-1980 medium office buildings

3.2.4. Adjustment factors of sensitive PDFs

Plug load density and climate zone are the two sensitive model inputs of medium office buildings. But we only need to calculate the adjustment factor for plug load density since the building energy models have already considered the impact of climate. The adjustment factors of plug load density for pre-1980 medium office buildings are shown in Table 9. Subsection 4.1 will introduce the application of these adjustment factors for the calculation of modeled baseline EUIs. Fig.6 shows the modeled and calculated modeled baseline EUIs for the pre-1980 medium office buildings. The relative errors between these two types of baseline EUIs are all within 5%.

Table 9. Adjustment factors of sensitive PDFs (a_i) for pre-1980 medium office buildings

Unit: $kBtu$/W-yr

Sensitive Model Inputs	**1A**	**2A**	**2B**	**3A**	**3B**	**3C**	**4A**	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**	**8**
Plug load density	31	28	29	26	28	26	22	27	22	20	24	19	21	17	14

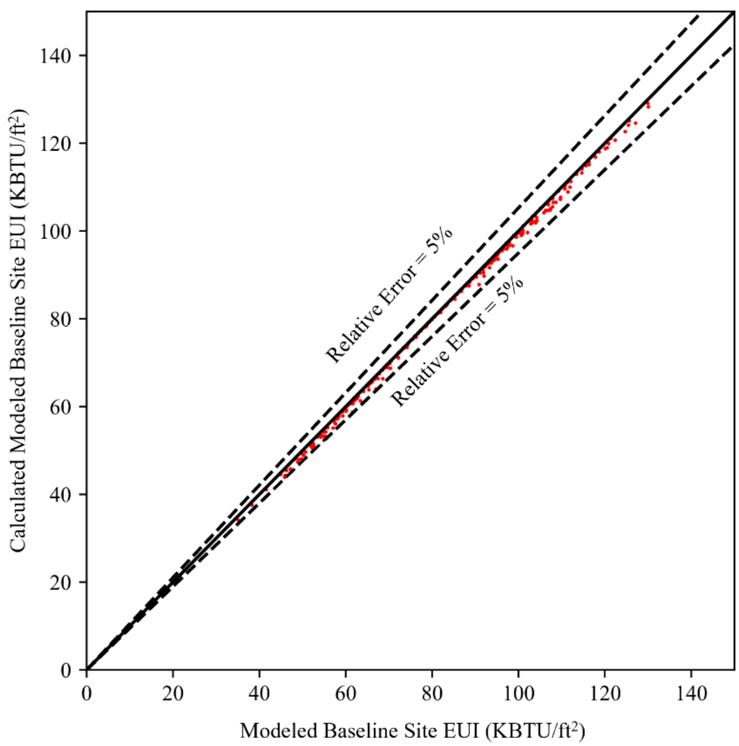

Fig.6. Comparison of the modeled and calculated baseline EUIs for the pre-1980 medium office buildings

3.3. Reconciliation of Building EQ As Design with ASHRAE Standard 90.1 modeled baseline EUIs

Following the methodology introduced in subsection 2.3, this section adopts pre-1980 medium office building as an example to present the baseline models of Building EQ and ASHRAE 90.1 (subsection 3.3.1), the modeled baselines (subsection 3.3.2), and adjustment factors of EUI (subsection 3.3.3). The adjustment factors for 18 commercial building types are provided in the Appendix. The application of adjustment factors to building energy rating practices will be introduced in Section 4.

3.3.1. Baseline models

The Building EQ baseline models based on CBECS 2003 for pre-1980 medium office buildings in 15 climate zones have been developed in subsection 3.1. The key model inputs of Building EQ baseline models for pre-1980 medium office buildings are shown in Table 10. Using the baseline models of ASHRAE standard 90.1-2014 (NREL 2018) as a starting point, 90.1 baseline models will be developed by modifying to the value as same as the building operation inputs in Table 10. The key model inputs of 90.1 baseline models for pre-1980 medium office buildings are shown in Table 11.

Table 10. Key model inputs of Building EQ baseline models for pre-1980 medium office

Input	Unit	Climate Zone														
		1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Program design features																
Plug load density	W/ft^2	1.67														
Building assets																
Lighting power density	W/ft^2	1.14														
Gas burner efficiency	-	0.78														
DX cooling coil COP	-	3.08														
Heating size factor	-	1.24														
Cooling size factor	-	1.10														
Water heater efficiency	-	0.79														
Outdoor airflow	ft^3/min-person	25.68														
Window-to-wall ratio	-	0.39														
Projection factor of overhang	-	0.29	0.28	0.28	0.22	0.22	0.22	0.13	0.13	0.13	0.07	0.07	0.03	0.03	0.03	0.02
R-value of insulation of exterior walls	ft^2-h-F/Btu	1.96	1.96	1.96	2.06	1.96	2.08	3.23	3.05	3.32	4.02	3.82	4.51	4.51	4.97	5.61
R-value of insulation of roof	ft^2-h-F/Btu	8.88	8.88	8.88	8.88	8.88	8.88	10.52	10.13	10.64	12.77	12.03	15.53	15.53	15.53	15.53
U-value of window	Btu/ft^2-h-F	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	0.62	0.62	0.62	0.62	0.62	0.62
SHGC of window	-	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.41	0.41	0.41	0.41	0.41	0.41
Building operation inputs																
Occupancy schedule max value	Fraction	0.87 (Workday); 0.28 (Saturday); 0.05 (Sunday)														
Equipment (plug load) schedule max value	Fraction	0.88 (Workday); 0.49 (Saturday); 0.29 (Sunday)														
Service water usage schedule max value	Fraction	0.52 (Workday); 0.21 (Saturday); 0.08 (Sunday)														
Lighting schedule max value	Fraction	0.92 (Workday); 0.31 (Saturday); 0.05 (Sunday)														
Heating setpoint	°F	72														
Cooling setpoint	°F	75														
Occupancy operation hour	Hours/week	31.25														
Equipment operation hour	Hours/week	40.25														
Service water heating operation hour	Hours/week	31.25														
Lighting operation hour	Hours/week	36.25														
HVAC system operation hour	Hours/week	78.25														

Table 11. Key model inputs of 90.1 baseline models for pre-1980 medium office

Input	Unit	Climate Zone														
		1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Program design features																
Plug load density	W/ft^2	0.75														
Building assets																
Lighting power density	W/ft^2	1.00														
Gas burner efficiency	-	0.80														
DX cooling coil COP	-	3.39														
Heating size factor	-	1.00														
Cooling size factor	-	1.00														
Water heater efficiency	-	0.80														
Outdoor airflow	ft^3/s-ft^2	0.0017														
Window-to-wall ratio	-	0.30														
Projection factor of overhang	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
R-value of insulation of exterior walls	ft^2-h-F/Btu	14.76	14.76	14.76	4.23	4.23	4.23	4.23	4.23	4.23	5.74	5.74	7.21	7.21	8.72	10.11
R-value of insulation of roof	ft^2-h-F/Btu	14.76	14.76	14.76	14.76	14.76	14.76	14.76	14.76	14.76	14.76	14.76	14.76	14.76	14.76	19.70
U-value of window	Btu/ft^2-h-F	1.02	1.02	1.02	0.54	0.54	1.02	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
SHGC of window	-	0.31	0.31	0.31	0.43	0.43	0.62	0.43	0.43	0.43	0.50	0.50	0.50	0.50	0.50	0.50

Input	Unit	Climate Zone														
		1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Building operation inputs																
Occupancy schedule max value	Fraction	0.87 (Workday); 0.28 (Saturday); 0.05 (Sunday)														
Equipment (plug load) schedule max value	Fraction	0.88 (Workday); 0.49 (Saturday); 0.29 (Sunday)														
Service water usage schedule max value	Fraction	0.52 (Workday); 0.21 (Saturday); 0.08 (Sunday)														
Lighting schedule max value	Fraction	0.92 (Workday); 0.31 (Saturday); 0.05 (Sunday)														
Heating setpoint	°F	72														
Cooling setpoint	°F	75														
Occupancy operation hour	Hours/week	31.25														
Equipment operation hour	Hours/week	40.25														
Service water heating operation hour	Hours/week	31.25														
Lighting operation hour	Hours/week	36.25														
HVAC system operation hour	Hours/week	78.25														

3.3.2. Modeled baseline EUIs

This subsection generates modeled Building EQ baseline EUIs and modeled 90.1 baseline EUIs based on two kinds of baseline models described in subsection 3.3.1.

As identified in subsection 3.2.1, the sensitive program design features for pre-1980 medium office is only the plug load density. Therefore, the values of plug load density will be sampled in the range determined in Table 6. This research samples 50 buildings for each climate zone for pre-1980 medium office.

Then, the values of plug load density will be modified in these two kinds of baseline models: Building EQ baseline models and 90.1 baseline models. Finally, for each building sample, modeled Building EQ Baseline EUI and modeled 90.1 baseline EUI will be generated by running these two kinds of baseline models. The modeled bEQ baseline EUIs and modeled 90.1 baseline EUIs of 50 building samples for pre-1980 medium office in 15 climate zones are shown in Fig.7. It can be seen modeled Building EQ baseline EUI and modeled 90.1 baseline EUI for pre-1980 medium office is a linear relationship.

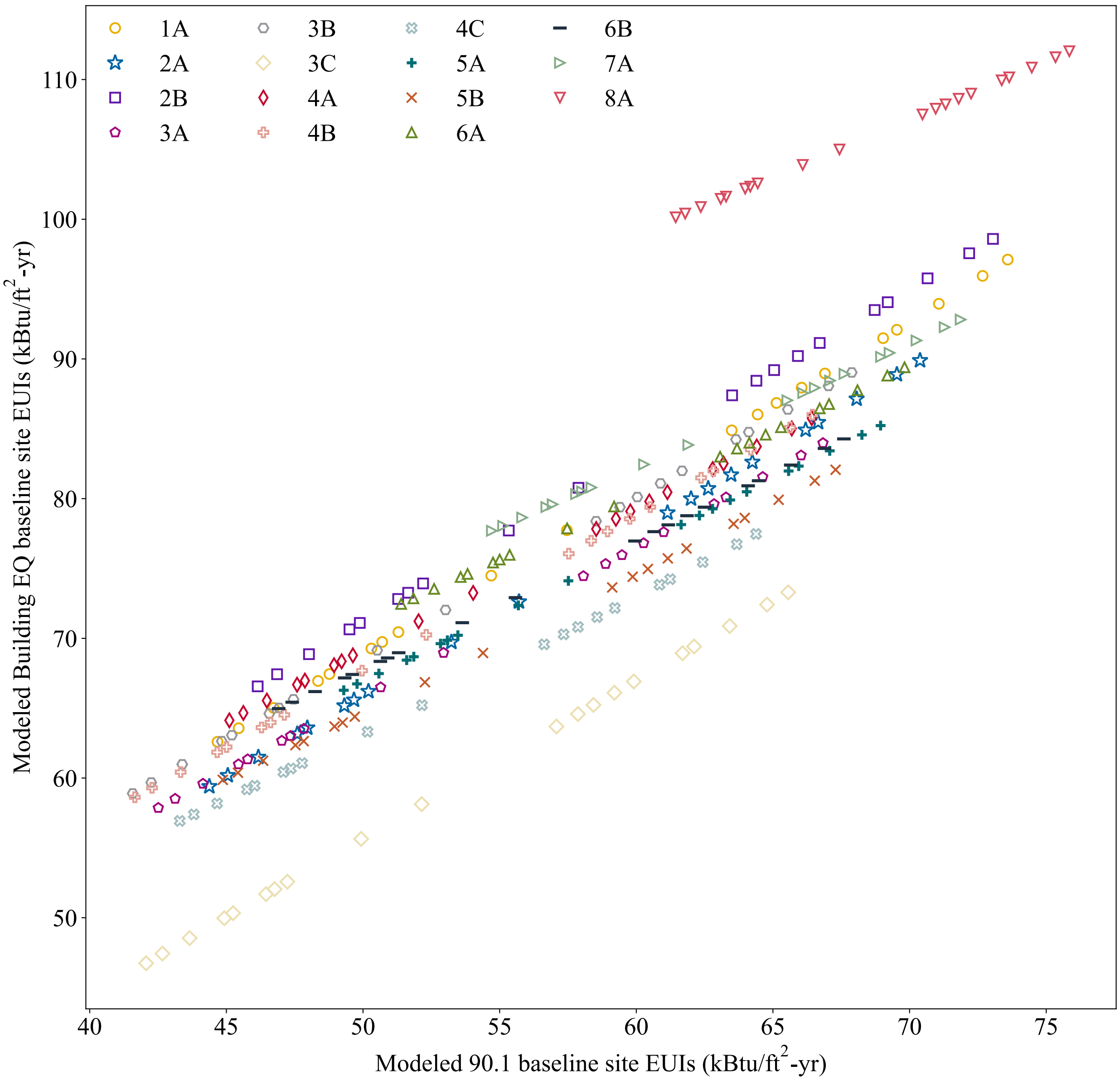

Fig.7. Modeled Building EQ and 90.1 baseline site EUIs for pre-1980 medium office buildings

3.3.3. Adjustment factors of EUIs

This subsection calculates the code adjustment factors that align the modeled 90.1 baseline EUI to the modeled Building EQ baseline EUI for pre-1980 medium office in each climate zone. For each climate zone, using the 50 buildings prepared in subsection 3.3.2 as a training sample, we obtained the best k and b in equation (2), which can minimize the sum of the absolute difference between calculated Building EQ baseline EUIs (obtained in equation (2)) and modeled Building EQ baseline EUIs. The values of k and b for each climate zone are listed in Table 12. The modeled Building EQ baseline EUIs and the calculated Building EQ baseline EUIs are compared, as shown in Fig.8. It can be seen that the calculated Building EQ baseline EUIs are consistent with the modeled Building EQ baseline EUIs, and the relative errors are all lower than 5%.

Table 12. Code adjustment factors for pre-1980 medium office

Adjustment Factors	Unit	Climate Zone														
		1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
k for site EUI	-	1.20	1.18	1.19	1.08	1.14	1.13	1.01	1.11	0.98	0.97	1.00	0.93	0.94	0.89	0.83
b for site EUI	kBtu/ft^2-yr	9	7	12	12	11	-1	18	12	14	18	15	25	21	29	49

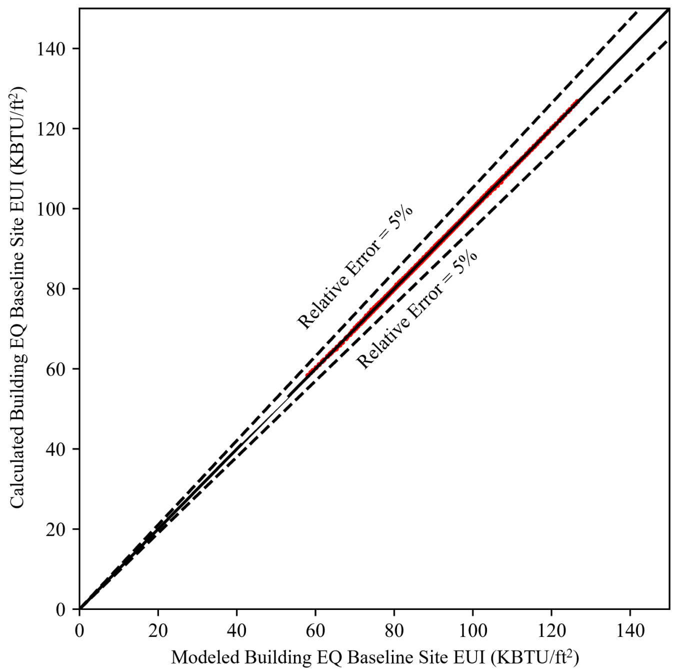

Fig.8. Comparison of the modeled Building EQ baseline EUIs and calculated Building EQ baseline EUIs for pre-1980 medium office

4. Application

4.1. The application of this research on Building EQ In Operation rating for existing buildings.

There are five steps of using adjustment factors to calculate the modeled baseline, as shown in Table 13.

Table 13. Calculate the modeled baseline based on the empirical baseline for *In Operation* rating

Step	Action	Data Source
1	Find empirical baseline (EUI_{emp}) for corresponding building type in corresponding vintage and climate zone.	Appendix Table X-A in this research

2	Find default values of sensitive PDFs ($PDF_{i,def}$) for corresponding building type in corresponding vintage.	Appendix Table X-B in this research
3	Find adjustment factors (a_i) of sensitive PDFs for corresponding building type in corresponding vintage and climate zone.	Appendix Table X-C in this research
4	Give the values of sensitive PDFs of a candidate building ($PDF_{i,can}$).	Given by the user
5	Apply the data in Steps 1-4 to equation (1) to calculate modeled baseline (EUI_{mod_cal}).	-

For example, a medium office building located in Denver (climate zone 5B) is constructed in the year 1950. The plug load density of this building is 2.00 W/ft^2. What is the modeled baseline (site EUI) of this medium office building using the developed adjustment factors?

Step 1: Find empirical baseline (EUI_{emp}) for medium office buildings in vintage pre-1980 and climate zone 5B in Appendix Table 2-A, which is 76.19 kBtu/ft^2-yr.

Step 2: Find default values of sensitive PDFs ($PDF_{i,def}$) for medium office buildings in vintage pre-1980 and climate zone 5B in Appendix Table 2-B. Beside the climate, the sensitive program design feature for medium office is plug load density, and the default value of plug load density for pre-1980 medium office in climate zone 5B is 1.67 W/ft^2.

Step 3: Find adjustment factors (a_i) of site EUI for medium office buildings in vintage pre-1980 and climate zone 5B in Appendix Table 2-C, which is 24 kBtu/W-yr.

Step 4: Give the values of sensitive PDFs of a candidate building ($PDF_{i,can}$), which is 2.00 W/ft^2.

Step 5: Apply the data in Steps 1-4 to equation (1) to calculate modeled baseline.

$$EUI_{mod\_cal} = 76.19\ kBtu/ft^2\text{-}yr + 24\ kBtu/W\text{-}yr \times (2.00W/ft^2 - 1.67W/ft^2)$$

$$= 84.11\ kBtu/ft^2\text{-y}$$

4.2. The application of this research on Building EQ As Design rating for new buildings.

There are three steps of using adjustment factors to translate the Building EQ and ASHARE 90.1 modeled baselines, as shown in

Table 14. Translate the Building EQ and ASHARE 90.1 modeled baselines for *As Design* rating

Step	Action	Data Source
1	Generate the 90.1 modeled baseline ($EUI_{90.1}$) or generate the Building EQ modeled baseline (EUI_{bEQ}).	Baseline models
2	Find adjustment factor (k and b) for corresponding building type in corresponding vintage and climate.	Appendix Table X-D in this research
3	Apply the data in Steps 1-2 to equation (2) to calculate Building EQ modeled baseline (EUI_{bEQ}) or 90.1 modeled baseline ($EUI_{90.1}$).	-

For example, a medium office building located in Denver (climate zone 5B) is constructed in the year 1950. The baseline model of this building based on ASHRAE 90.1-2004 has been created and the 90.1 modeled baseline (site EUI) of this building is 80 kBtu/ft^2-yr. What is the Building EQ modeled baseline of this medium office building using the developed adjustment factors?

Step 1: Generate the 90.1 modeled baseline ($EUI_{90.1}$), which is 80 kBtu/ft^2-yr.

Step 2: Find adjustment factor (k and b) for medium office buildings in vintage pre-1980 and climate zone 5B in Appendix Table 2-D, which is 1.17 and 36 kBtu/ft^2-yr respectively.

Step 3: Apply the data in Steps 1-2 to equation (2) to calculate Building EQ modeled baseline (EUI_{bEQ})

$$EUI_{bEQ} = 1.17 \times 80 kBtu/ft^2\text{-}yr + 36\ kBtu/ft^2\text{-}yr = 129.6\ kBtu/ft^2\text{-}yr$$

5. Conclusion

This research developed a methodology to make the baselines in both Building EQ *In Operation* and *As Designed* consistent and reconcile the Building EQ As Design with ASHRAE Standard 90.1 modeled baselines. By developing adjustment factors of sensitive PDFs, we could adjust the empirical baseline EUI of Building EQ's *In Operation* to match the modeled baseline EUI of Building EQ's *As Designed*, with relative errors of less than 5%. By developing adjustment factors of EUI, we could reconcile the modeled baseline EUIs of Building EQ and ASHRAE Standard 90.1, with the relative errors of less than 5%. We have developed adjustment factors for 18 commercial building types in the U.S., which are provided in the

Appendix. The application of these adjustment factors in the practice of building energy rating is illustrated step by step.

The contribution of this research mainly lies in the following two aspects. First, we created building energy models based on 2003 CBECS survey data, which include 18 commercial building types in two vintages (constructed before 1980 and after 1980) and 15 climate zones in the U.S. These models can be used to study the impact of energy and carbon policy on existing commercial buildings in the U.S. Second, we developed adjustment factors that allow seamless translation of building energy performance metrics among Building EQ *In Operation* ratings, Building EQ *As Design* rating, and ASHRAE standard 90.1.

Acknowledgment

This paper is the outcome of the research project TRP-1771 sponsored by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). This research was supported by the National Science Foundation under Awards No. CBET- 2217410.

Reference

ASHRAE. 2013. ANSI/ASHRAE/IESNA standard 90.1-2013: Energy standard for buildings except low-rise residential buildings.

ASHRAE. 2014. *ANSI/ASHRAE/IES/USGBC Standard 189.1-2013: Standard for the Design of High-Performance Green Buildings*. ASHRAE: Atlanta, GA.

ASHRAE. 2015. *Standard 100-2015 -- Energy Efficiency in Existing Buildings*.

ASHRAE. 2023. Building EQ.

Deru, M., K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, B. Liu, M. Halverson, D. Winiarski, and M. Rosenberg. 2011. US Department of Energy commercial reference building models of the national building stock.

EIA. 2006. 2003 commercial buildings energy consumption survey.

EPA. 2023. ENERGY STAR Certification and Other Recognition.

Griffith, B., N. Long, P. Torcellini, R. Judkoff, D. Crawley, and J. Ryan. 2008. *Methodology for modeling building energy performance across the commercial sector*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

Helton, J. C., J. D. Johnson, C. J. Sallaberry, and C. B. Storlie. 2006. Survey of sampling-based methods for uncertainty and sensitivity analysis. *Reliability Engineering & System Safety*, *91*(10–11):1175–1209.

Huang, J., and E. Franconi. 1999. Commercial heating and cooling loads component analysis. *LBL-37208, Lawrence Berkeley National Laboratory, Berkeley, CA*.

Lou, Y., Y. Ye, Y. Yang, W. Zuo, G. Wang, M. Strong, S. Upadhyaya, and C. Payne. 2023. Individualized empirical baselines for evaluating the energy performance of existing buildings. *Science and Technology for the Built Environment*, *29*(1):19–33.

NREL. 2018. openstudio-standards.

NREL. 2022. Building component library.

SBS Lab. 2022. Building energy models for commercial buildings based on CBECS data.

Sharp, T. 1996. Energy benchmarking in commercial office buildings. In *Proceedings of the ACEEE* (Vol. 7996, pp. 321–329).

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

Storlie, C. B., and J. C. Helton. 2008b. Multiple predictor smoothing methods for sensitivity analysis: example results. *Reliability Engineering & System Safety*, *93*(1):55–77.

Storlie, C. B., L. P. Swiler, J. C. Helton, and C. J. Sallaberry. 2009. Implementation and evaluation of nonparametric regression procedures for sensitivity analysis of computationally demanding models. *Reliability Engineering & System Safety*, *94*(11):1735–1763.

Tian, W. 2013. A review of sensitivity analysis methods in building energy analysis. *Renewable and Sustainable Energy Reviews*, *20*:411–419.

Turner, C., M. Frankel, and U. G. B. Council. 2008. Energy performance of LEED for new construction buildings. *New Buildings Institute*, *4*(4):1–42.

USGBC. 2023. Leadership in Energy and Environmental Design (LEED) Rating System.

Wang, N, S. Goel, V. Srivastava, and A. Makhmalbaf. 2015. Building energy asset score program overview and technical protocol (version 1.2). *PNNL-22045. Richland, WA, USA: Pacific Northwest National Laboratory*.

Wang, Na, and W. J. Gorrissen. 2013. *Commercial building energy asset score system: program overview and technical protocol (Version 1.1)*. Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Winiarski, D. W., M. A. Halverson, and W. Jiang. 2007. *Analysis of building envelope construction in 2003 CBECS*. Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Winiarski, D. W., W. Jiang, and M. A. Halverson. 2006. *Review of pre-and post-1980 buildings in Cbecs-Hvac equipment*. Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Ye, Y., K. Hinkelman, J. Zhang, W. Zuo, and G. 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*:351–365.

Ye, Y., Y. Lou, M. Strong, S. Upadhyaya, W. Zuo, and G. Wang. 2020. Development of New Baseline Models for US Medium Office Buildings Based on Commercial Buildings Energy Consumption Survey Data. *Science and Technology for the Built Environment*, (9):1–19.

Ye, Y., W. Zuo, and G. Wang. 2019. A comprehensive review of energy-related data for US commercial buildings. *Energy and Buildings*, *186*:126–137.