

Simulation-based coefficients for adjusting climate impact on energy consumption of commercial buildings

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Abstract

This paper presents a new technique for and the results of normalizing building energy consumption to enable a fair comparison among various types of buildings located near different weather stations across the United States. The method was developed for the U.S. Building Energy Asset Score, a whole-building energy efficiency rating system focusing on building envelope, mechanical systems, and lighting systems. The Asset Score is based on simulated energy use under standard operating conditions. Existing weather normalization methods such as those based on heating and cooling degrees days are not robust enough to adjust all climatic factors such as humidity and solar radiation. In this work, over 1000 sets of climate coefficients were developed to separately adjust building heating, cooling, and fan energy use at each weather station in the United States. This paper also presents a robust, standardized weather station mapping based on climate similarity rather than choosing the closest weather station. This proposed simulated-based climate adjustment was validated through testing on several hundreds of thousands of modeled buildings. Results indicated the developed climate coefficients can adjust the climate variations to enable a fair comparison of building energy efficiency.

Keywords

commercial buildings, energy efficiency, asset rating, climate normalization, energy simulation

Article History

Received: 11 May 2016

Revised: 20 August 2016

Accepted: 19 October 2016

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1 Introduction

There has been growing effort in evaluating building energy efficiency in contexts of asset rating and operational rating. Examples include the Energy Performance Certificate, or EPC, (as-designed rating) and Display Energy Certificate (as-operated rating) in the U.K. (BPIE 2010), and the “theoretical” and “measured” ratings of Building Energy Efficiency Evaluation and Labelling in China (Chinese State Council 2008). In the U.S., the primary tool to compare building energy use against peers is ENERGY STAR Portfolio Manager® (U.S. Environmental Protection Agency 2014). Portfolio Manager evaluates a property’s total energy use based on its utility bills after weather normalization. Actual energy consumption is dependent of occupant behavior and the physical structure and electrical, mechanical equipment in a building. While occupants and their energy usage

patterns may change frequently, the building energy asset remains mostly constant until building retrofit. These assets, including building envelope (roof, walls, and windows), lighting, service hot water, and heating, cooling, and air-conditioning (HVAC) systems, significantly influence a building’s performance regardless of how the building is used and operated. The U.S. Department of Energy (DOE) developed the Building Energy Asset Score to enable a fair evaluation and comparison of these energy characteristics (EERE n.d.).

To enable a fair comparison of buildings, a rating system should use standardized energy modeling or calculating methodologies and normalization techniques to account for building use type and locate climate. Weather normalizations for operational rating and asset rating are different. The former deals with weather variation over time (temporal), the latter aims to correct climate impact across locations

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A portion of this paper was presented at 13th International IBPSA Building Simulation Conference, Chambéry, France, 2013.

(spatial). The U.S. Environmental Protection Agency defines temporal adjustment as weather normalization and geographic adjustment as climate normalization (U.S. Environmental Protection Agency 2015). These definitions are adopted in this paper. In some context, “weather” refers to local weather characteristics associated with climate normalization. The terms “weather station,” “weather site,” and “weather-sensitive variables” are also used in this paper to describe climate normalization.

The Asset Scoring tool built on EnergyPlus™ simulates building energy use under standard operating conditions and converts source energy use intensity (EUI; measured in kBtu/ft² [MJ/m²]) to an easy-to-understand 10-point score (with half-point increments) (Wang et al. 2016). Before a building is scored, energy loads that are sensitive to climate (i.e., heating, cooling, and ventilation) are adjusted by applying a series of climate coefficients to the modeled site energy use values. This paper presents the technical approach to selecting the most appropriate weather file for simulation and normalizing the climate impact to support fair comparisons of various types of commercial buildings at different locations. The paper first reviews commonly used weather and climate normalization techniques and discusses their limitations. Next, it proposes a new method to adjust heating, cooling, and fan energy consumption using a set of climate coefficients derived from analyses of nine typical building configurations and HVAC systems modeled with the Typical Meteorological Year 3 (TMY3) data set for 1020 locations, which is described in Section 3. The climate coefficients were tested on case studies and a large number of simulation runs. The results are included in this paper. To automate climate normalization in the Asset Scoring Tool, a mapping technique was developed to choose the most appropriate weather stations based on climate similarity to a building site, rather than using the nearest weather station. The mapping methodology is also presented in this paper.

2 Existing weather normalization methods

Weather or climate normalization is the process to adjust building energy use to a hypothetical “typical” weather condition. Traditionally, weather normalization is a curial task for utilities to regulate rates. It is also a challenge for energy efficiency benchmarking or estimating savings for building retrofit. In most of these applications, building utility bills over a period, typically 12 months, are normalized to a “typical” year to account for the variations and fluctuations in weather at a specific building site, i.e. they are normalized across time. Other applications such as asset rating require fair comparisons of building energy efficiency in different

climate regions; therefore, weather factors are normalized not in regard to time (i.e., seasonally or annually), but across different locations (Makhmalbaf et al. 2013). In this paper, the term “weather normalization” refers to the temporal adjustment, and “climate normalization” refers to the geographic or spatial adjustment. However, in some literature, the term “weather normalization” is used in general without specifying the type of adjustment.

A review of asset rating efforts in the U.S., such as the Massachusetts MPG Rating for Commercial Buildings (Massachusetts Department of Energy Resources 2010), ASHRAE Building Energy Quotient (ASHRAE n.d.), and California’s Commercial Building Energy Asset Rating System (Crowe et al. 2012), indicates no standard method for normalizing the impact of climate on building energy use. A baseline is often used to remove the climate variation. When a rated building is compared against its baseline, which is often modeled at the same weather location, the climate variable is automatically removed. This approach, however, only applies to ratings based on a ratio scale, i.e., percentage better than a building itself. The challenge is then shifted from climate normalization to how to define the right baseline.

Normalization and weather correction procedures were identified as critical areas in the Energy Performance of Buildings Directive (EPBD) (Concerted Action Energy Performance of Buildings 2013). The Concerted Action EPBD (Concerted Action Energy Performance of Buildings 2013) documents progress towards the implementation of EPBD in the European Union (EU), including the various EPC formats and their main contents. It is indicated that several EU member states use standardized or reference climate data in this evaluation. The need to correct heating and cooling energy use from real local weather conditions during a recorded period to standard conditions using officially provided climate correction factors is documented. Some EU states (e.g., Latvia) do not intend to run calculations for different climatic zones because the differences among local climates are small. Thomsen and Wittchen (2011) pointed out, “a correct and European-wide harmonized approach for the climate normalization for both heating and cooling would simplify the inter-comparison of national requirements, as well as the use of measured energy rating” (Concerted Action Energy Performance of Buildings 2013, p. II-105).

The literature implies that weather normalization methods for homes and single zone commercial buildings are better tested and documented; however, none has been adopted as a standardized approach (Akander et al. 2005). The following sections discuss the applications and limitations of three main normalization methods, including the degree-days methods, the modified utilization factor (MUF) method,

and the climate severity index (CSI) method (Makhmalbaf et al. 2013).

2.1 Degree-days methods

Heating and cooling degree-day¹ (HDD, CDD) are commonly used to isolate the effects of weather changes. A simple ratio of the average number of HDDs or CDDs over certain years and the specific number of HDDs or CDDs over the studied period is often calculated as the adjusting factor. For example, heating energy use of a particular year is adjusted by multiplying an HDD factor, which is obtained by dividing the average number of HDDs at a location by the specific number of HDDs in that year of the same location (U.S. Energy Information Administration 1995). This approach is often used for utility bill analysis. For example, the Bonneville Power Administration (2011) uses average HDD per day in each billing period to analyze monthly utility data. The Real Property Association of Canada (Real Property Association of Canada 2012) also appears to use lists of the HDDs and CDDs for each year and at various city center locations to account for temporal weather variations between years but within geographical areas. This approach is fast and easy; however, it requires disaggregating base-load energy consumption (non-weather-sensitive energy use such as lighting) from the total energy use. The reliability of the ratio method is discounted when heating and cooling loads cannot be easily separated from the base-load energy consumption, for example, when electricity is used for both heating and cooling or in cases where there is simultaneous heating and cooling (such as cooling a server room while the rest of the building is being heated).

A linear regression analysis method that correlates historical energy use data with degree-days is an improvement from the simple ratio-based normalization technique. The Princeton Scorekeeping Method is an example of least-squares linear regression-based techniques for analyses of energy efficiency measurements for residential buildings (Fels 1986).

Multiple regression is an extension of the linear regression method. The ENERGY STAR Portfolio Manager program uses a weighted ordinary least-squares regression to analyze how source EUI is associated with various independent characteristics (e.g., building size, operation, and weather) (U.S. Environmental Protection Agency 2014). Chung et al. (2006) developed a similar benchmark for the

energy efficiency of commercial buildings based on multiple regression analyses. The shortcoming of multiple regression analysis is the complexity of the regression model and the need for known variable inputs as predictors (e.g., building characteristics and disaggregated energy use data) (Chung et al. 2006).

Weather normalization using electric load as a dependent variable (such as change point method or the sliding Normalized Annual Consumption analysis) is often used by utilities to estimate the impact of weather variables and energy efficiency strategies (Lammers et al. 2011). For example, Hydro One's (2006) weather correction methodology uses 4 years of daily electrical energy and weather data to establish a statistical relationship of electrical load in the service territory and temperatures and other weather variables in the equation. Pepco Holdings, Inc. (2010) also derives estimated hourly electricity load based on current and historical weather data.

The degree-days-based techniques have several limitations. First, degree-days only address dry-bulb temperature, but exclude other climatic factors such as wind speed, humidity, insolation, and other forces that affect energy use in commercial buildings (Akander et al. 2005; Eto 1988). For locations where solar gains or wind significantly influence the heat balance of a building, the outdoor air temperature is less accurate. Second, degree-day methods assume the heat loss in buildings is linearly proportional to the indoor and outdoor temperature difference (Akander et al. 2005; Eto 1988). The steady-state equation cannot always represent commercial buildings that have multiple thermal zones with different temperature set points (Makhmalbaf et al. 2013). Third, a robust regression model requires a large quantity of building data. The low coefficient of determination of regression-based models based on a limited dataset often indicate that other variables than degree-days should be taken into consideration. Error made by simply correcting the heating and cooling energy use by degree-days increases in high performance buildings (Maldonado 2013, p. II-105).

2.2 Modified utilization factor method

The MUF method defined in European Standard prEN-ISO 13790 calculates the actual and normalized energy delivered for space heating by adjusting indoor temperature to the set-point temperature (Hogeling and Van Dijk 2008). This approach is used in northern Europe where little cooling is needed (Jokisalo and Kurnitski 2007).

The limitations of the MUF method are magnified when applying to commercial buildings. The calculations become complicated when space cooling is introduced in the equation. Currently, there is no European standard that uses MUF to normalize space cooling load (Akander et al.

¹ Degree-days represent the total positive or negative difference between a base temperature and the average daily outdoor dry-bulb temperature for a given period of time (ASHRAE 2009). In the U.S., the base temperature has been specified as 18.3 °C (65 °F).

2005). Indoor and outdoor temperature profiles need to be measured over the course of a year. Solar gains delivered to the space are estimated based on energy auditor's professional judgment and site experience. This introduces more uncertainty (Akander et al. 2005).

2.3 Climate severity index method

The CSI method normalizes energy consumption of buildings in different regions through an index that increases building energy use in more "severe" climate zones (Markus 1982). Separate CSIs are developed for heating and cooling seasons using computational simulations to estimate the energy use of a set of typical buildings (with different orientations, thermal properties, etc.) under different climates within the region (Akander et al. 2005). A building's energy use is normalized by multiplying the heating or cooling energy use by the ratio between the average CSI and the actual CSI. This method addresses the dynamic thermal condition in buildings and multiple climate variables, such as degree-days, monthly average global solar radiation, and solar insolation.

One limitation is that this method is highly dependent upon climate data available in the geographical region of interest. Only a limited number of CSIs have been developed and their accuracy needs further testing, especially for locations where CSIs were interpolated when simulations were not performed.

3 Study of energy use variations at 1020 climate locations

A simulation-based approach provides a controlled environment that allows to isolate the climate factors and investigate how their impacts on energy use are associated with building configurations. Many of variables related to building operations cannot be controlled in real buildings when analyzing their utility bills. Energy simulations for the Asset Score keep building operation and occupancy constant for each building use type. This allows the study to focus on climate and associated building characteristics (e.g., thermal properties, design features, and mechanical systems).

The proposed method for climate normalization is based on investigation of energy use patterns of various building configurations in different climate conditions. The hypothesis was that although buildings with different properties respond to weather differently, the relative difference between EUI modeled at a specific location and the mean EUI of all studied locations remains similar, if not exactly the same. The revealed patterns are expected to be useful not only for normalizing modeled energy use for

asset rating, but for other purposes, such as analyzing energy measures for buildings with similar characteristics but in different climate zones.

This analysis required a set of building models that represent typical building configurations and systems, suitable weather files for each climate region, and a simulation engine that can handle a large number of runs (Wang et al. 2016). The simulation procedure is described below.

3.1 Building models

The DOE commercial prototype building models were used to investigate how climate variability affects modeled energy use across all TMY3 weather stations for the United States (EERE 2014). The prototype models include 16 commercial building types in 17 climate locations (across all 8 U.S. climate zones) for recent editions of ASHRAE Standard 90.1. They represent 80% of the commercial building floor area in the United States (Thornton et al. 2011). In selecting the typical building models, the variation of building characteristics (i.e., gross floor area, building geometry, lighting types, HVAC system types, typical plug loads, and operating schedules) was a critical criterion in order to observe behavior of buildings with different properties in response to climate across and within different climate zones. Table 1 shows the chosen prototype buildings and their characteristics. These buildings represent a sample of typical building types exhibiting large variations in their designs and installed systems according to location and climate. The use of different building types was crucial in developing robust climate normalization that can be applied to a broad range of buildings. Note that Medium Office prototype was not selected because the system type appears to utilize the terminal electric reheat coil far greater than the central gas heat coil. This leads to significantly higher electric consumption for heating compared to gas consumption. An electric dominant heating system is an inefficient choice in a cold climate if gas for heating is available to the building.

The prototype building models compliant with ASHRAE Standard 90.1-2004 (ASHRAE 2004) were chosen for this study as they represent moderate energy efficiency requirements. The 2004 edition of Standard 90.1 is also used as a stable baseline for future energy code development because "after 2004 the prescriptive requirement in Standard 90.1 started becoming too complex to develop clear rules that result in consistent modeling of baseline" (Rosenberg et al. 2015, p. 3.4). The original models of all chosen prototype buildings were used except for the large office type. The datacenter in the original large office model was removed because of its extremely high internal loads would significantly affect the heating and cooling requirements. Thermal

Table 1 Key characteristics of chosen prototype buildings

Building type	Size (m ²)	Construction type	Window-wall ratio	Cooling system type	Heating system type	Ventilation system type
Small office	511	Mass wall	0.212	Unitary direct expansion (DX)	Gas furnace	Single zone constant volume
Large office	46 320	Mass wall	0.38	Multi-zone	Gas boiler	Variable volume and single zone constant volume
Primary school	6 871	Steel-frame	0.35	Packaged air-conditioning unit (PACU)	Gas boiler, gas furnace (gym, kitchen, and cafeteria)	Single zone constant volume and single zone variable volume
Secondary school	19 592	Steel-frame	0.34	Air cooled chiller, PACU (gym, aux gym, auditorium, kitchen, and cafeteria)	Boiler, gas heat (gym, aux gym, auditorium, kitchen, & cafeteria)	Variable volume and single zone constant volume
Small hotel	4 014	Steel-frame	0.11	DX	Gas furnace, unit heater, packaged terminal air-conditioner electric heat	Single zone constant volume
Strip mall	2 090	Steel-frame	0.105	Unitary DX	Gas furnace	Single zone constant volume
Stand-alone retail	2 294	Mass wall	0.071	Unitary DX	Gas furnace	Single zone constant volume
Midrise apartment	4 982	Steel-frame	0.33	PACU	Gas furnace and electric reheat	Single zone constant volume
Warehouse (non-refrigerated)	4 835	Metal building wall	0.0058	PACU in the office space	Gas furnace office, gas unit heaters storage	Single zone constant volume

properties of the walls, roofs, floors, and windows vary in these models depending on the climate zone, following the ASHRAE Standards (Deru et al. 2011). Specifications of HVAC equipment are also based on the corresponding requirements in the ASHRAE Standards (2004). All these buildings have constant volume fans except for large office and some zones in primary and secondary schools.

3.2 Weather data

The TMY3 data set, derived from the 1961–1990 and 1991–2005 National Solar Radiation Data Base archives, consists of hourly values of solar radiation and meteorological elements for a 1-year period (Renewable Resource Data Center n.d.). The TMY3 data set contains weather data files for 1020 locations in the U.S., including all 50 states and territories. Each prototype building was simulated using all available weather data files.

3.3 Simulation process

Fifteen cities are often used to represent eight climate zones (15 climate regions including the different moisture regimes) in the U.S. For each prototype building, 15 EnergyPlus models (IDF files) are available for these representative cities. 1020 EnergyPlus IDF files were then generated from the original 15 building models based on their climate zones. An energy

simulation infrastructure on several parallel servers by clustering (Rosenberg et al. 2015) was used to accomplish the 9180 runs (9 prototype buildings × 1020 TMY3 weather stations).

3.4 Simulation outputs

Site EUIs were calculated for all end uses of the above nine prototype buildings. The end uses calculated include heating (electricity), heating (gas), heating (district), cooling (electricity), interior lighting, exterior lighting, interior equipment (i.e., miscellaneous loads), exterior equipment, fans, pumps, heat rejection, hot water systems (electricity), and hot water systems (gas). Not all end uses are weather sensitive; therefore, there is no need to adjust all energy consumption for climate. As a result, only weather-sensitive end uses were examined. These end uses include space heating, space cooling, fans, and pumps.

3.5 Energy use patterns analysis

The simulations of multiple building types with 1020 TMY3 weather station files in the U.S. present a unique opportunity to add new knowledge to the building energy domain (Makhmalbaf et al. 2013). First of all, the simulations reveal that representative cities are inadequate for summarizing building performance in a specific climate zone. Figure 1

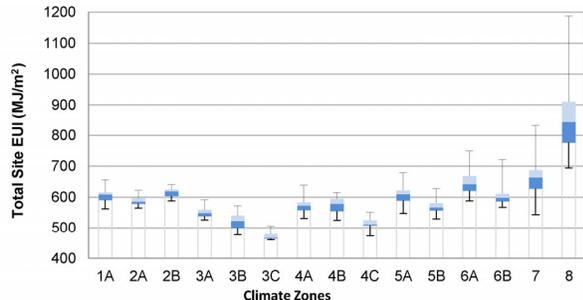


Fig. 1 Total EUI variation observed across different climate zones and within each climate zone for the small office building type

shows the EUIs of small office (compliant with ASHRAE Standard 90.1-2004) in the 8 climate zones. With identical internal loads and building operation schedules, climate is the sole cause of variation in the building EUIs. The difference in EUI between two climate regions within the same climate zones, e.g. 3A (warm-humid) and 3B (dry), highlights the effect of humidity. Larger differences in interquartile range are observed in the coldest climate zones (e.g., 7 and 8). It indicates larger variations between weather stations within the same climate zones. This suggests that it is critical to select the most appropriate weather station for the modeled building site. The methodology is discussed in Section 6.

The variation of EUI across the climate locations is affected by a building's thermal properties and internal loads. For example, Fig. 2 shows the EUIs of the school and large office building types across all climate zones vary from one climate zone to another and even within each climate zone. This variation is much greater in climate zones 7 and 8. (Each dot represents the simulated EUI with a specific TMY3 weather file.) The graph also represents a similar pattern of variation between the school and office building types. However, the school building type has a larger step change to weather and climate changes, which is because the ratio of exterior envelop to floor area is larger for this building type. In addition to that, the school building type has lower insulation, longer hours of operation, and lower internal loads on average. Note that the number of available TMY3 weather files is not identical in all climate zones, resulting in different distances between vertical grid lines shown in Fig. 2.

3.6 Analysis of standardized EUI ratios

To further study the relative EUI variations, the average EUI modeled at all weather station locations was calculated

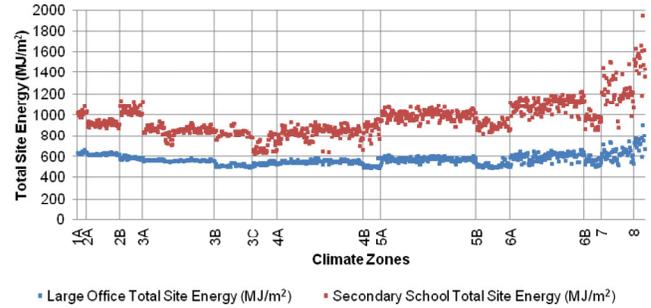


Fig. 2 Total EUI variations observed across different climate zones and within each climate zone for the large office and school building types

for each prototype. The variation of a specific EUI modeled at a specific TMY3 weather station (see Eq. (1)) is expressed as the ratio of location-specific EUI to the national average EUI. This standardized distance reflects how much the EUI needs to be adjusted for buildings at a specific location to obtain a "fair" Asset Score (i.e., one that can be compared to other buildings of that type regardless of their respective locations). It is assumed that the number of buildings in each climate zone is in proportion to the number of weather stations, which roughly resemble the population distribution.

Site EUI instead of source EUI is used to calculate this ratio because the purpose of this step is to investigate the relationship between a building's energy use and its weather site regardless of its fuel choice. Equation (1) presents how the EUI ratio is calculated.

$$\text{EUI ratio}_{\text{weather site } m} = \frac{\text{EUI}_{\text{site } m}}{\frac{1}{n} \sum_{i=1}^n \text{EUI}_{\text{site } i}} \quad (1)$$

where n is the number of weather sites and i represents the site number.

Rather than using the whole building EUI, the EUI ratios were separately calculated for weather-sensitive loads, i.e., space heating, space cooling, fans, and pumps. Four ratios were investigated for each weather station. The cooling EUI ratio was calculated by dividing the cooling EUI at a specific weather station site by the average cooling EUI calculated from modeling the prototype building across all TMY3 weather station sites (See Eq. (2)). A heating EUI ratio, a fan EUI ratio, and a pump EUI ratio were calculated in the same way.

$$\text{Cooling EUI ratio}_{\text{prototype building } j, \text{ weather site } m} = \frac{\text{EUI}_{\text{site } m}^{\text{cooling}}}{\frac{1}{n} \sum_{i=1}^n \text{EUI}_{\text{site } i}^{\text{cooling}}} \quad (2)$$

where n is the number of weather sites and i represents the site number.

Results of standardized EUI ratios calculated from all chosen prototype buildings indicated that except for the warehouse building, buildings with different characteristics respond similarly to variations in external heating and cooling loads (Fig. 3 and Fig. 4). This observation partially validates the original hypothesis that although buildings respond to climate conditions differently, the relative difference is similar. Therefore, these standardized variations can be used to adjust climate for the Asset Score, for the studied building types. Note that while most of the individual standardized EUI ratios cluster nicely, there is significant variability in some limited weather station locations (for example, within climate zone 8A for heating). These individual models with extremely high heating energy use will need to be further investigated.

Compared to heating and cooling EUI ratios, the variance of fan EUI ratios across the modeled buildings and weather stations is relatively small (Fig. 5). One reason is that most of the prototype models have single zone constant volume fans. Pump EUI ratios are unpredictable because the energy use for pumps varies by HVAC system type. For example, cooling systems that use direct expansion coils may not use any energy for pumps. Only three prototype buildings have pump energy use for space heating. On average, the pump energy use of the three prototype buildings accounts for less than 3% of the total HVAC energy use; therefore, pump energy use is excluded from its climate adjustment.

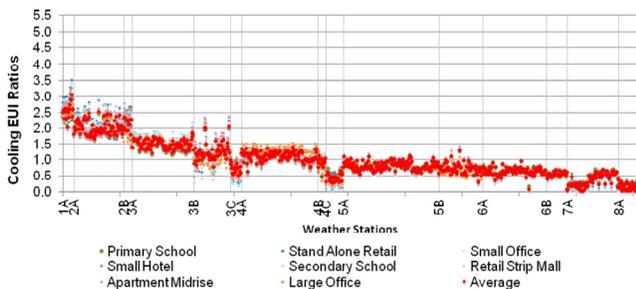


Fig. 3 Cooling EUI ratios of eight prototype buildings and their average

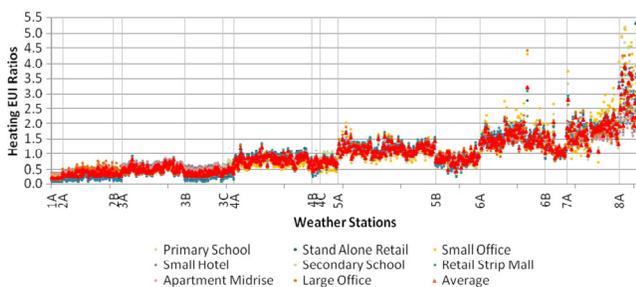


Fig. 4 Heating EUI ratios of eight prototype buildings and their average

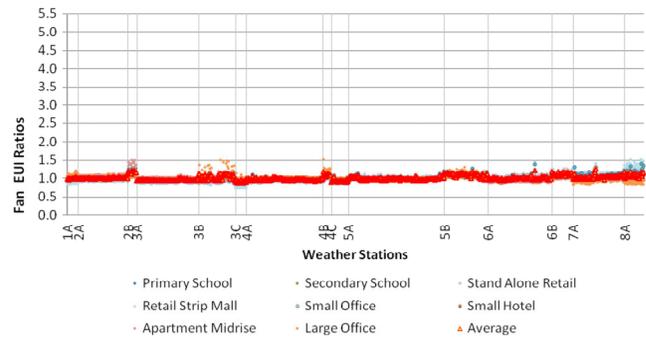


Fig. 5 Fan EUI ratios of eight prototype buildings and their average

4 Climate normalization using adjustment coefficients

4.1 Climate adjustment coefficients

This section describes the method of using the EUI ratios to develop a “coefficient” (inverse of the EUI) to adjust for the effect of climate in a specific weather station so that adjusted EUIs can be compared for buildings independent of location. To achieve this, 1020 sets of climate coefficients were calculated for each type of DOE commercial prototype building. Each set includes a coefficient for space heating, a coefficient for space cooling, and a coefficient for fans.

$$\text{Coefficient}_{\text{prototype building } j, \text{ weather site } m, \text{ end use } k} = \frac{1}{\text{EUI ratio}_{\text{prototype building } j, \text{ weather site } m, \text{ end use } k}} \quad (3)$$

where n is the number of weather sites and i represents the site number.

Based on results observed, to simplify implementation of climate adjustment, EUI ratios derived from eight prototype buildings (except warehouse) were combined into a single EUI ratio, the inverse of which was used as a single coefficient for each weather-sensitive end use (heating, cooling, and fans) and weather station location. The average coefficient for the eight prototype buildings (excluding warehouse) was calculated and the final climate coefficients for these use types that are included in the current Asset Score were collapsed into three sets of coefficients (heating, cooling, and fans) for each of the 1020 available weather stations (see (Wang et al. 2015) for the calculated coefficients).

The much greater discrepancy observed in behavior of the warehouse building type in response to climate was caused by its low requirements for ventilation and space conditioning due to its nearly zero occupancy. Also, lower levels of required envelope insulation for the set of buildings grouped into this category lead to more variation based on climate. Therefore, the Asset Score uses a separate set of coefficients derived from the warehouse prototype building for buildings such as non-refrigerated warehouses and heated parking garage.

4.2 Calculation of normalized EUI

For the Asset Score, climate normalization was achieved by adjusting the EUI of a building to a national average EUI of the same building type. In other words, the “average” EUI across all weather stations for a specific building type is taken as the target value for normalization. For a candidate building in a particular location (i.e., a weather station site), a normalized heating EUI is calculated by multiplying the modeled heating EUI by the corresponding climate coefficient:

$$\check{N}EUI_{site\ m}^{heating} = EUI_{site\ m}^{heating} \times Coefficient_{site\ m}^{heating} \quad (4)$$

where \check{N} represents normalized. Normalized cooling and fan EUIs are found similarly:

$$\check{N}EUI_{site\ m}^{cooling} = EUI_{site\ m}^{cooling} \times Coefficient_{site\ m}^{cooling} \quad (5)$$

$$\check{N}EUI_{site\ m}^{fan} = EUI_{site\ m}^{fan} \times Coefficient_{site\ m}^{fan} \quad (6)$$

Total normalized EUI is then calculated by adding normalized heating and cooling EUIs in addition to all non-weather-sensitive loads that were not normalized:

$$\check{N}EUI_{site\ m}^{total} = \check{N}EUI_{site\ m}^{heating} + \check{N}EUI_{site\ m}^{cooling} + \check{N}EUI_{site\ m}^{fan} + EUI_{site\ m}^{plug\ loads} + EUI_{site\ m}^{lighting} + EUI_{site\ m}^{load\ n} \quad (7)$$

After climate adjustment, the adjusted site EUIs are converted into source EUIs, the total of which is then used for scoring. National average site-to-source conversion factors (Table 2) are used because they allow national-level

Table 2 Source-site ratios

Source	Ratio
Electricity (grid purchase)	3.14
Electricity (onsite solar or wind installation)	1.00
Natural gas	1.05
Fuel oil (1, 2, 4, 5, 6, diesel, kerosene)	1.01
Propane and liquid propane	1.01
Steam ^(a)	1.20
Hot water	1.20
Chilled water ^(b)	1.00
Wood	1.00
Coal/coke	1.00
Other (e.g., waste biomass)	1.00

(a) The weighted average of two source-site factors: 1.35 for conventional steam generation and 1.01 for steam produced by CHP (combined heat and power).

(b) The weighted average of two source-site factors: 0.98 for electric chiller and 1.11 for steam-driven chiller.

Source: U.S. Environmental Protection Agency 2013.

or low rating for the relative efficiency of its regional power comparisons and ensure that a building does not receive a high grid and generation source mix. The Asset Score uses an EUI-based 1- to 10-point scale with 0.5-point intervals (Wang et al. 2016). The adjusted EUI does not represent the building energy use. Rather, it is used only to calculate a building’s Asset Score as a comparison to the performance of similar buildings in other climate locations.

5 Test of climate coefficients

5.1 Test Case 1: Test on prototype buildings

To verify the adequacy of quantified climate normalization coefficients they were applied to a sample of simulated building EUIs. The climate normalized EUIs for the same set of small office buildings across all climate zones are shown in Fig. 6. The observation is that the impact of climate on EUIs is better isolated and adjusted in milder climate zones (e.g., 4A and 5A) when compared to those with more extreme climate conditions. For instance, in climate zones 7 and 8, buildings in some weather locations have very low cooling load. This results in a cooling EUI that is very small compared to other climate zones. Therefore, the quantified cooling coefficients for these regions are very large. This causes the normalized cooling EUI curve to appear over-adjusted (i.e., skewed).

Figure 7 depicts a box-plot of climate normalized EUIs for the same set of small office buildings. The box-plot shows that EUI deviation from average EUI across different climate zones is minimized and the difference between EUIs within a given climate zone is reduced. This test verifies adequacy of coefficients quantified in this work by showing their effectiveness in adjusting for the impact of climate on building energy consumption of the studied building use types.

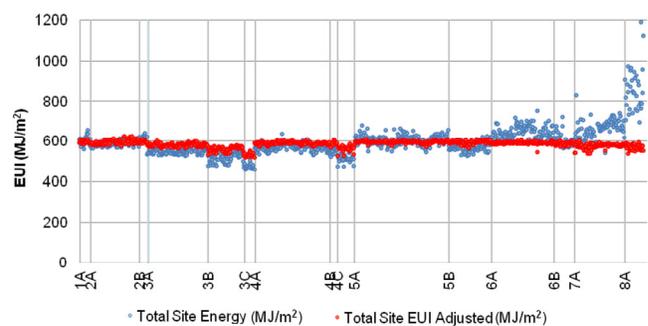


Fig. 6 Results of applying climate adjustment coefficients to the same set of buildings shown in Fig. 1

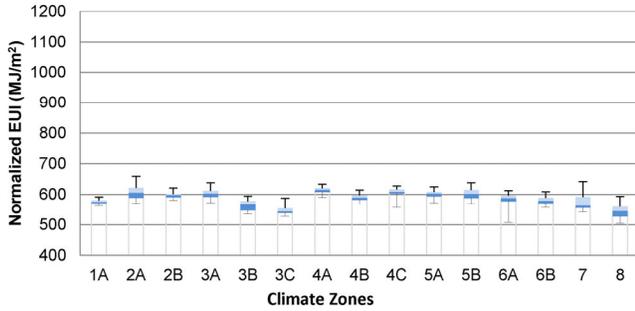


Fig. 7 Results of applying climate adjustment coefficients to the same set of buildings shown in Fig. 1

5.2 Test Case 2: Test on real buildings

The second test case involved applying climate coefficients on the pilot buildings, which are more varied in their design, size, thermal properties, and mechanical systems compared to prototype buildings. Three pilot buildings of different sizes and with HVAC systems were selected for this test (Table 3). To examine if climate coefficients are more effective on building configurations and thermal properties or on their mechanical systems, each building was also modeled with the other two buildings’ mechanical systems. Nine buildings models were created.

Figure 8 shows that the climate coefficients are equally effective if applied to the three buildings when they have the same mechanical systems. Note that a flatter line indicates a better climate adjustment result within and across climate zones. Adjusted source EUI is shown for comparison because scores are given to source EUIs after being converted from adjusted site EUIs. Therefore, this is a better indicator of how buildings’ EUI adjustments really compare.

The comparisons were also made between mechanical systems within each of the three buildings. Figure 9 shows that different mechanical system types introduced some level of discrepancy. For example, system 1 (chiller and boiler) has the best results across the three buildings: the EUI standard deviations of the three buildings were reduced to 6.5, 7.6, and 7.4 (Table 4). The heat pump in building 2 has abnormal system behavior in the coldest climate zones.

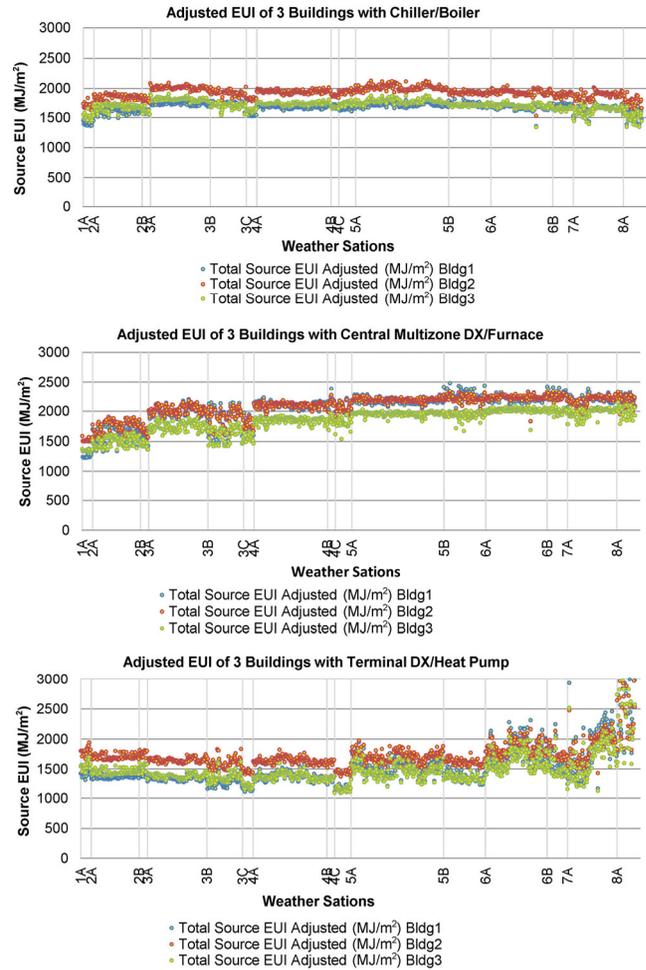


Fig. 8 Testing coefficients on various system types

This caused an even higher standard deviation after climate adjustment. However, using a heat pump in very cold climate zones is not an efficient choice and is often not recommended. Therefore, abnormal behavior observed is not only because of limitations of climate adjustment coefficients, but also because of inherently poor performance of heat pumps in very cold climate zones.

This test by no means represents a complete sensitivity analysis; it is intended to investigate whether any building property can cause a larger discrepancy between weather

Table 3 Building and system properties of pilot buildings selected for testing

Building number	Area (m ²)	Year of construction	Total envelope U-value (UA)	Window-wall ratio	Cooling system type	Cooling system efficiency (COP)	Heating system type	Heating system efficiency
1	21 510	1977	0.105	16.3%	Chiller	3.5	Boiler	80%
2	103 914	1975	0.071	44%	Terminal DX	5.57	Heat pump	5.57 (COP)
3	4 448	1904	0.191	16%	Central DX multi-zone	3.5	Multi-zone central furnace	80%

COP is coefficient of performance.

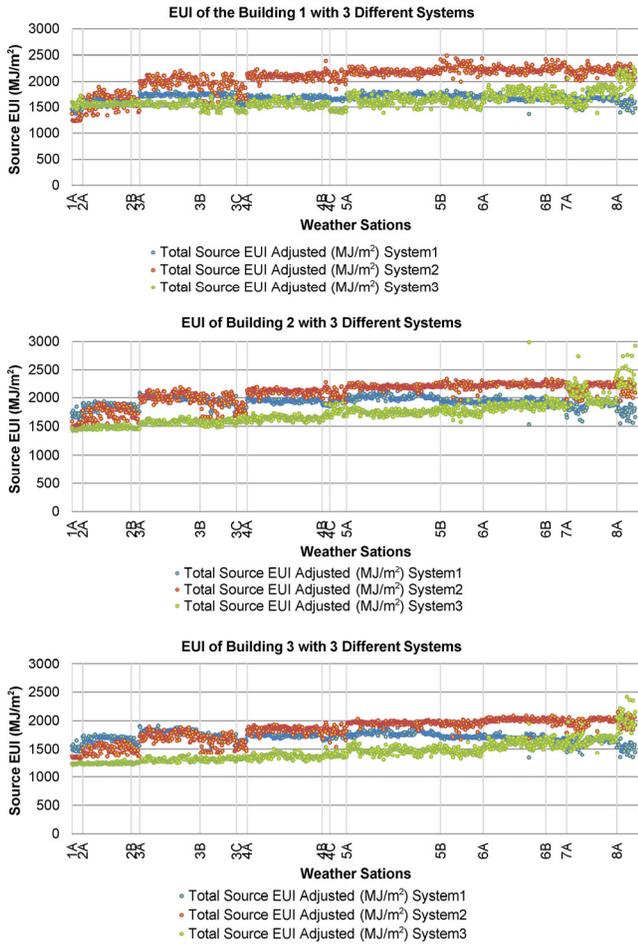


Fig. 9 Testing of coefficients on building configurations

locations after climate normalization. Overall, the results show that the climate coefficients can reduce the EUI standard deviation by 50%, which is consistent with the finding in Test Case 1.

5.3 Test Case 3: Test on randomly sampled buildings

In this test, climate coefficients were applied to a large number of buildings (over 10 000 models for each use type) sampled by computer. The base models were prototype buildings. The building characteristics were randomly modified; therefore, variations of prototype buildings with various envelope, lighting, and mechanical system characteristics were generated. These buildings were modeled at the representative cities (as shown in Fig. 1) of each climate zone; the source EUIs before and after climate adjustments are plotted in Fig. 10. The figure shows that after climate normalization, the EUI distribution curves across the 16 climate zones are closer to each other (if not overlapping), which means that their Asset Scores will become more comparable after the climate impact is minimized by the coefficients.

6 Postal code to weather file mapping

To automate climate normalization in the Asset Scoring Tool, an important step is choosing the most appropriate weather file for the building site. Energy modelers who are familiar with the building location often choose the weather

Table 4 Statistics of three buildings before and after climate adjustment

	System 1 (Chiller, Boiler)		System 2 (Central DX, Furnace)		System 3 (Terminal DX, Heap Pump)	
	Before normalization	After normalization	Before normalization	After normalization	Before normalization	After normalization
Building 1 (21 510 m ²)						
Min EUI (MJ/m ²)	1235.5	1361.3	1312.6	1227.2	1094.1	1372.9
Max EUI (MJ/m ²)	3019.3	1835.9	6025.3	2483.4	4881.9	2280.1
Mean EUI (MJ/m ²)	1696.1	1682.6	2144.6	2061.2	1521.9	1623.6
Std. Dev.	16.7	6.5	50.5	20.9	33.0	12.5
Building 2 (103 914 m ²)						
Min EUI (MJ/m ²)	1461	1532.9	1465.7	1501.4	1362.8	1426.3
Max EUI (MJ/m ²)	3077.6	2130.3	5141.8	2343.0	3635.3	5290.4
Mean EUI (MJ/m ²)	1955.6	1929.1	2159.5	2075.7	1726.0	1752.5
Std. Dev.	15.5	7.6	35.0	16.8	18.7	27.8
Building 3 (4 448 m ²)						
Min EUI (MJ/m ²)	1284.33	1340.6	1295.5	1323.5	1085.3	1203.9
Max EUI (MJ/m ²)	2771.411	1913.7	4917.4	2150.9	4028.1	2416.4
Mean EUI (MJ/m ²)	1739.388	1712.4	1929.6	1835.4	1483.0	1446.3
Std. Dev.	14.3	7.4	34.6	16.9	24.3	16.0

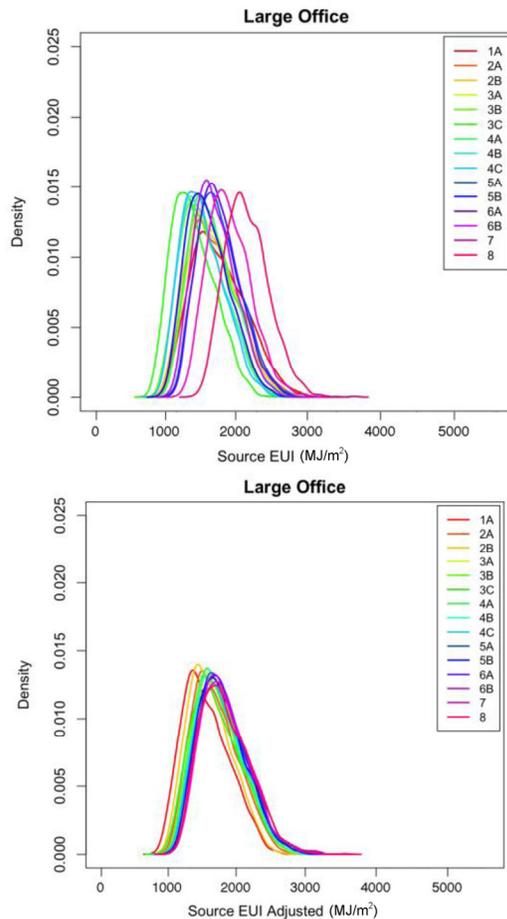


Fig. 10 Variations of prototype buildings before and after climate adjustment

station nearest to the site. Computer programs usually use building postal code to locate the closest weather station. For the Asset Scoring Tool, a previously developed method was adopted that matches weather stations to spatial regions based on climate similarity as opposed to distance (Hathaway et al. 2013).

To identify representative weather stations for specified spatial regions (e.g., postal codes), this process depends on 1/8-degree grid data over the United States from NASA's Land Data Assimilation System (NLDAS-2) for the period 1979–2005, together with the locations of known weather stations across the U.S. (NASA 2016). The method reduces the computational overhead associated with representing small-scale spatial climate variability of buildings while still maintaining an operating procedure that can accurately model sub-state level building energy demand with appropriate weather stations (Dirks et al. 2015).

In this process, the NLDAS 1/8-degree grid cells that contained known Class I–III weather stations were used to define the reference cells, i.e., weather station locations. Then, the 53 746 grid cells within the U.S. were compared

to each weather station location using a goodness-of-fit procedure developed by Finkelstein and Schafer (1971) across nine different climate variables similar to the methods used to generate TMY data (Wilcox and Marion 2008). Table 5 shows the comparisons of Sandia method variable weightings used for this study, the TMY weightings, and the International Weather Files for Energy Calculations (IWEC). This procedure provides a climate similarity score (CSS) of each weather station to each of the 53 746 grid cells (Dirks et al. 2015). These CSSs are then used to find the weather station location that is most representative of a region (e.g., which weather station location is most representative climatically for county A while accounting for population?).

In this application the spatial partitioning is fixed by the five-digit postal code users enter for their building. Some postal code regions are smaller than the 1/8-degree resolution of the previous work's CSS data. At a scale smaller than the 1/8-degree grid, the nearest station is assumed to be the optimal station.

In Fig. 11, as an example, the five-digit postal code centroids for California are depicted to show whether an optimal station is the same as the nearest station. The postal code centroids are colored to identify if the nearest station is the optimal station (blue triangles have optimal weather stations that are also the nearest station, and the red triangles are not optimally represented by the nearest station). California is selected to highlight the shortcomings of previous methods that simply used the nearest station. The complex topography and weather coincides with the populous regions of the state. Additionally, there are far fewer candidate weather stations for California compared to east coast states. Having fewer stations increases the distances from the stations to postal code regions, which exacerbates the poor performance of using the nearest station.

Table 5 Comparisons of Sandia method variable weights, the TMY weightings, and the IWEC

Variable	IWEC	Sandia method	TMY3
Maximum dry-bulb temperature (K)	0.050	0.0417	0.05
Minimum dry-bulb temperature (K)	0.050	0.0417	0.05
Mean dry-bulb temperature (K)	0.300	0.0833	0.10
Maximum dew point temperature (K)	0.025	0.0417	0.05
Minimum dew point temperature (K)	0.025	0.0417	0.05
Mean dew point temperature (K)	0.050	0.0833	0.10
Maximum wind speed (m/s)	0.050	0.0833	0.05
Mean wind speed (m/s)	0.050	0.0833	0.05
Total solar (or global horizontal) radiation (W/m^2)	0.400	0.5000	0.25
Direct radiation (W/m^2)	0	0	0.25

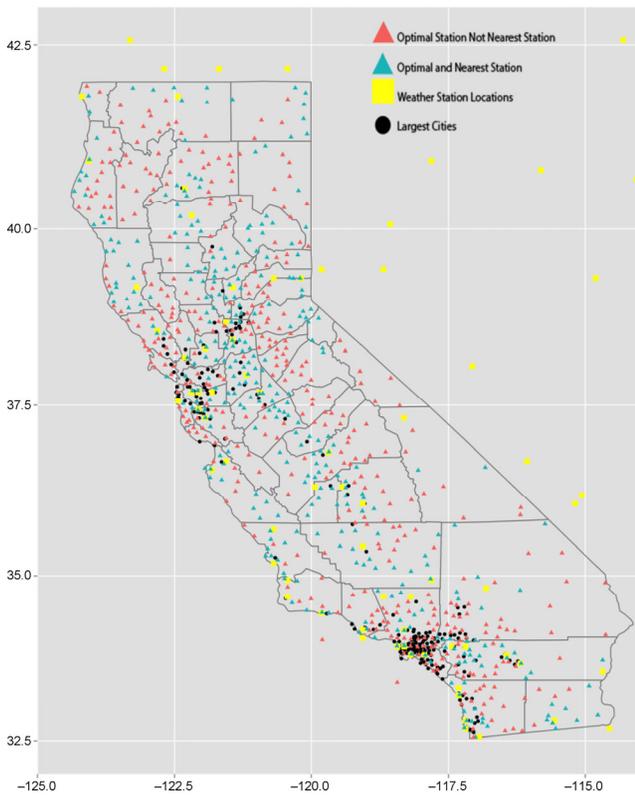


Fig. 11 Map of the postal code centroids (triangles), candidate weather stations (yellow squares), and largest cities (black dots) to demonstrate CSS zip code selection results

7 Conclusions

This paper presents a new, simulation-based climate normalization method developed for the Asset Score. The study investigated the EUI variations across all climate locations. The correlations between climate and energy use were converted to a set of climate adjustment coefficients to normalize heating and cooling energy consumption. The climate coefficients were integrated into the Asset Scoring Tool. After the simulation engine generates the breakdown of energy use for each end-use of a building, heating EUI, cooling EUI, and fan EUI are calculated as the first step of the data post-processing. Corresponding coefficients are then applied to the modeled heating, cooling, and fan EUIs to adjust them for differences in climate.

The purpose of climate adjustment is to enable a fair comparison between buildings in different locations. Due to the complex climate variables (temperature, humidity, solar radiation, and wind) even within one climate zone, it is inaccurate to normalize climate impact on building energy use using analysis of the representative city of each climate location. Therefore, a unique set of climate adjustment coefficients were derived for each available weather station

location based on eight prototype buildings compliant with ASHRAE Standard 90.1-2004. Given the fact that thermal properties of buildings affect their unique ways of responding to their immediate exterior environment, it is almost impossible to equally diminish the effect of climate on all buildings of different vintages across all of the climate zones. Using the coefficients derived from the 2004 prototype buildings, buildings with less efficient thermal properties will be adjusted less because they are more affected by their exterior environment. This effect will be even more pronounced for buildings in extremely hot or cold climates, where the relative difference between a location-specific EUI and the mean EUI of all weather stations is larger. This is acceptable from an energy-efficiency perspective because the Asset Score is intended to encourage and give credit to good envelope thermal performance, which is particularly more important for buildings in hot or cold climates.

The effectiveness of the proposed methodology was tested using various cases. The test results indicated that the climate coefficients developed can isolate and adjust for the impacts of local climate for asset rating. However, their level of success varies among different climate zones. There are uneven numbers and distributions of weather stations in different climate zones. There are fewer weather stations in climate zones with more severe climates, for example, 19 weather stations in climate zone 1 (hot and humid, e.g., Florida), 34 in climate zone 8 (very cold, e.g., Alaska), and 134 in climate zone 4 (mild, e.g. Maryland). The average EUI from all weather stations is skewed by regions with more weather stations. Ideally we would use a grid of weather stations evenly spaced over the entire country. However, this is not the real case and the weather stations appear to follow population densities (see Fig. 12). Therefore, using the number of weather stations in each climate zone to approximate to the number of buildings is a reasonable assumption.



Fig. 12 The TMY3 weather stations marked on a map of the U.S. (created using Google Maps)

8 Future work

Future research can compare other normalization methods such as degree-days methods with the results presented in this paper. To improve the coefficients, additional study should be carried out to investigate the outliers in the extremely hot and cold climate zones. Testing the coefficients on different HVAC systems also revealed various degrees of effectiveness of the coefficients. Future work should further investigate this relationship and develop sets of climate coefficients for different HVAC system types. Grouping coefficients by HVAC types may further improve their accuracy by including systems types that are not well addressed in this study such as heat recovery ventilation, electric reheat system, and variable air volume system. This research only investigated eight prototype buildings; the study should also be expanded to more building types, such as food services, in the future. Last, this research is based on the assumption that building distribution is associated with locations of weather stations. Further study can investigate if any weighing factor based on actual number of buildings in each climate zone would yield more accurate normalization results.

Acknowledgements

This project is funded by the U.S. Department of Energy, Building Technologies Office. The authors would like to thank Joan Glickman and Andrew Burr at the U.S. Department of Energy for their support and guidance throughout this effort. In addition, the authors would like to thank the Building Energy Asset Score team members at Pacific Northwest National Laboratory and our collaborators at the National Renewable Energy Laboratory.

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