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Weather Correlations to Calculate Infiltration Rates for U. S. Commercial Building Energy Models

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ABSTRACT

As building envelope performance improves, a greater percentage of building energy loss will occur through envelope leakage. Although the energy impacts of infiltration on building energy use can be significant, current energy simulation software have limited ability to accurately account for envelope infiltration and the impacts of improved airtightness.

This paper extends previous work by the National Institute of Standards and Technology that developed a set of EnergyPlus inputs for modeling infiltration in several commercial reference buildings using Chicago weather. The current work includes cities in seven additional climate zones and uses the updated versions of the prototype commercial building types developed by the Pacific Northwest National Laboratory for the U. S. Department of Energy.

Comparisons were made between the predicted infiltration rates using three representations of the commercial building types: PNNL EnergyPlus models, CONTAM models, and EnergyPlus models using the infiltration inputs developed in this paper. The newly developed infiltration inputs in EnergyPlus yielded average annual increases of 3 % and 8 % in the HVAC electrical and gas use, respectively, over the original infiltration inputs in the PNNL EnergyPlus models. When analyzing the benefits of building envelope airtightening, greater HVAC energy savings were predicted using the newly developed infiltration inputs in EnergyPlus compared with using the original infiltration inputs. These results indicate that the effects of infiltration on HVAC energy use can be significant and that infiltration can and should be better accounted for in whole-building energy models.

Keywords: airflow modeling, commercial buildings, CONTAM, energy modeling, EnergyPlus, infiltration, building envelope airtightness

1. INTRODUCTION

Heating, ventilating, and air-conditioning (HVAC) systems in buildings are designed to maintain acceptable thermal comfort and indoor air quality (IAQ). The operating cost of these HVAC systems is often a large percentage of the total energy cost of buildings, which constitutes 40 % of the primary energy consumed in the U.S. [1]. Given the current emphasis on reducing building energy consumption and associated greenhouse gas emissions, the use of energy simulation software has increased to investigate different design options. In order to comply with energy design standards, such as the California Code of Regulations, Title 24 [2] and ASHRAE Standard 90.1 [3], energy simulation is often performed, and in some cases required. One design option to reduce building energy use is the improvement of building envelope airtightness. Existing data show that unless efforts are made to design and build tight building envelopes, commercial buildings are actually much leakier than typically assumed [4, 5]. Thus, the energy impacts of uncontrolled infiltration are often greater than assumed.

Current energy simulation software and design methods generally do not accurately account for envelope infiltration, and therefore the impacts of improved airtightness on energy may not be fully captured. A review of the airflow analysis capabilities of energy simulation software tools found that many of the empirical infiltration models employed in these tools are based on calculation methods developed for low-rise, residential buildings [6]. These methods are not generally appropriate for other types of buildings, particularly mechanically ventilated commercial buildings as well as taller buildings. Also, these empirical infiltration models require the user to specify air leakage coefficients that are best obtained from building pressurization tests [7], which is challenging because only limited pressurization test results are available for commercial buildings [4]. While some energy simulation software tools can simulate airflow using multizone airflow models, the capabilities of the airflow calculations are often limited and can be difficult for users to employ. Examples of such capabilities include the AIRFLOW NETWORK model in EnergyPlus, coupling of CONTAM and TRNSYS [8], coupling of CONTAM and EnergyPlus [9] and IDA Indoor Climate and Energy [10, 11].

Empirical approaches for estimating infiltration rates have the advantage of ease of use relative to multizone building airflow models. These empirical approaches employ algebraic equations that relate simple building features, such as height and envelope leakage, as well as weather conditions to calculate infiltration rates. One of the earliest such approaches was developed by Shaw and Tamura [12], which provided equations to calculate total building infiltration rate due to stack induced pressure, wind pressure, and a combination of the two. Two widely used approaches for estimating infiltration rates in single-zones are the Lawrence Berkeley Laboratory (LBL) and Alberta Air Infiltration (AIM-2) models, which can be found in the ASHRAE Fundamentals Handbook [13]. Studies have shown that both models can overpredict infiltration rates and require inputs that may be difficult to obtain in the field, such as neutral pressure level and the leakage distribution [14, 15]. Pietrzyk and Hagentoft [16] estimated the probability of certain levels of infiltration based on factors such as wind speed, wind direction, sheltering and building characteristics in a low-rise building. Gowri et al. [17] proposed a method to estimate infiltration in commercial buildings using EnergyPlus that accounts for wind but not temperature effects, thereby ignoring stack effect and key building attributes, such as vertical shafts, on infiltration patterns. Overall, these methods tend to oversimplify the well-established interactions

of building envelope airtightness, weather, and HVAC system operation that affect infiltration rates [18].

Han et al. [19] compared the results of building energy simulations utilizing various calculation methods for estimating infiltration rates, and more specifically, the methods to determine wind pressure coefficients. The methods included rates from a coupled airflow-energy model, a database of coefficients from wind tunnel tests and published data, and the default settings in a building energy software. The authors found that using a coupled airflow-energy model increased the accuracy of the simulation results when compared to actual utility data [19]. However, detailed airflow models are not always available to be used in analyses.

The two simulation tools used in this study were CONTAM and EnergyPlus. CONTAM is a multizone indoor air quality and ventilation analysis program designed to simulate airflows and contaminant concentrations in buildings. It is developed by the National Institute of Standards and Technology (NIST). Airflows include infiltration, exfiltration, and room-to-room airflow rates and can be driven by mechanical means, wind pressures acting on the exterior of the building, and buoyancy effects induced by temperature differences between zones, including the outdoors [20]. The multizone airflow model CONTAM was selected for this study because it is one of the few models that captures the dynamic interaction of HVAC systems, weather and infiltration and because it does so relatively efficiently and quickly. CONTAM has been validated with data from both controlled experiments and real-world experiments [21-24]. EnergyPlus is a whole building energy simulation tool, developed by the U. S. Department of Energy (DOE), that can be used to model both energy consumption (HVAC, lighting and plug and process loads) and water use in buildings. EnergyPlus was selected for this study because it is widely used and publicly available. However, the infiltration correlations described in this paper can be applied to a variety of building energy simulation tools.

Sixteen commercial reference building types were developed by DOE [25], in part to support the development of ANSI/ASHRAE/IES Standard 90.1. The ASHRAE 90.1-2004 version of the EnergyPlus models of these buildings assumed that the infiltration was a constant value that varied only with HVAC operation. When the EnergyPlus models were updated to comply with ASHRAE 90.1-2013, the Gowri et al. [17] proposed method for accounting for infiltration was added. However, as stated above, both methods oversimplify the well-established interactions of building envelope airtightness, weather, and HVAC system operation that affect infiltration rates. Multizone airflow models account for these interactions by applying building airflow system physics. Previous work at NIST involved using results from CONTAM [20], a multizone airflow model, to develop EnergyPlus inputs for infiltration in the ASHRAE 90.1-2004 versions of the EnergyPlus commercial reference building models. The previous work was limited to Chicago Typical Meteorological Year 2 (TMY2) weather of ASHRAE climate zone 5A [26]. The new work described in this paper includes additional climate zones and the use of the ASHRAE Standard 90.1-2013 versions of the EnergyPlus commercial prototype building models. The buildings used in this study are: Hospital, Medium Office, Primary School, Small Hotel, and Stand Alone Retail.

2. METHODS

The following section presents the methods and models used in this study to account for infiltration in whole-building energy analysis. Section 2.1 describes how infiltration is currently

incorporated into EnergyPlus, though the approach is applicable to other energy simulation software. It also introduces the methodology proposed in this paper to develop EnergyPlus infiltration inputs using results from multizone airflow models. Section 2.2 describes the CONTAM models used in this study. Section 2.3 describes the process used to develop EnergyPlus infiltration inputs from the CONTAM analysis. In this study, infiltration refers to the outdoor air entering through unintentional building envelope leakage only and does not include outdoor air entering via the outdoor air intakes of the mechanical ventilation systems. While CONTAM simulates both infiltration and exfiltration rates based on the calculated indoor-outdoor pressure difference and building envelope leakage, this paper focuses on accounting for infiltration rates needed as an input for energy models.

2.1. Infiltration Modeling

This section first describes one of the methods to estimate infiltration in EnergyPlus. It requires the user to input a maximum infiltration rate, a schedule, and values for the temperature difference and wind coefficients. The second part of this section introduces the methodology proposed in this paper to determine the temperature difference and wind coefficients based on results from multizone airflow modeling.

The EnergyPlus object, ZoneInfiltration:DesignFlowRate, uses the following empirical equation to calculate infiltration:

$$\text{Infiltration} = I_{\text{design}} \cdot F_{\text{schedule}} [A + B|\Delta T| + C \cdot W_s + D \cdot W_s^2] \quad (1)$$

where I_{design} is defined by EnergyPlus as the airflow through the building envelope under design conditions. I_{design} is a user-specified value for each zone of the building that can be provided as either an air change rate (h^{-1}), a volume flow rate (m^3/s), or a volume flow rate per unit floor area or exterior surface area ($\text{m}^3/\text{s} \cdot \text{m}^2$). Zones may be assigned different I_{design} values. F_{schedule} is a factor between 0.0 and 1.0 that can change according to a user-defined schedule, for example, to account for the impacts of fan operation on infiltration. $|\Delta T|$ is the absolute indoor - outdoor temperature difference in $^{\circ}\text{C}$, and W_s is the local wind speed in m/s . In EnergyPlus, both the outdoor local temperature and local wind speed can be made to vary with zone height [27]. Both were varied in this manner in the current study.

The terrain on which a building is situated affects how the wind speed measured at a weather station is modified to determine the local wind speed. The terrain type was “City” for all the building models except for the Small Hotel, for which the terrain type was “Suburb”. This method of modifying the wind speed measured at a weather station is applied in both EnergyPlus and CONTAM.

EnergyPlus further adjusts the local wind speed for each zone based on its height above ground. CONTAM does not make this adjustment because the physics of airflow at heights close to the ground and between buildings is complex and most accurately determined by wind tunnel experiments or computational fluid dynamics (CFD) simulations [28]. The user may also adjust the modifier for each opening in the model. Nevertheless, the height-varying local wind speed assumed in the EnergyPlus models must be accounted for when developing infiltration inputs for EnergyPlus. Thus, a “wind speed adjustment factor” was calculated by dividing the EnergyPlus

Output: Variable “Zone Outdoor Air Wind Speed” for each zone by the EnergyPlus
Output: Variable “Site Wind Speed” and taking the average over all of the levels of the building (Table 1).

CONTAM also accounts for wind speed and wind direction when determining infiltration rates on each face of the building. In contrast, EnergyPlus only accounts for wind speed, as demonstrated by Equation (1). Thus, CONTAM infiltration rates are averaged over the entire exterior surface area (walls, roof) before being used to develop the infiltration inputs to be used in EnergyPlus.

A , B , C , and D of Equation (1) are constants, for which values are suggested in the EnergyPlus user manual [29]. However, those values are based on studies in low-rise residential buildings. Given the challenges in determining valid coefficients for a given building, a common strategy used in EnergyPlus for incorporating infiltration is to assume fixed infiltration rates. In other words, $A=1$ and $B=C=D=0$. However, this strategy does not reflect known dependencies of infiltration on weather and HVAC system operation.

The commercial prototype building models upon which this study is based [30] were developed to meet ASHRAE 90.1-2013. In these models, the value for C in Equation (1) was set to 0.224 in order to account for wind speed [17], and all other coefficients were set to zero. Thus, Equation (1) simplifies to Equation (2):

$$\text{Infiltration} = I_{\text{design}} \cdot F_{\text{schedule}} \cdot 0.224 \cdot W_s \quad (2)$$

In the EnergyPlus models developed by DOE, the effective leakage area of the building envelopes was set to $2.2 \text{ cm}^2/\text{m}^2$ at 4 Pa (i.e., $I_{\text{design}} = 0.00057 \text{ m}^3/\text{s} \cdot \text{m}^2$ at 4 Pa in Equation (1)) when the system was off and, in many of the buildings, to 25 % of this value (i.e., $F_{\text{schedule}} = 0.25$) when the system was on. The EnergyPlus models with this I_{design} value reflect ASHRAE 90.1-2013 requirements and will be referred to in this paper as the “EnergyPlus (original)” models “without air barriers”.

Emmerich and Persily [4] found that inclusion of an air barrier led to a significant difference in building envelope leakage area. ASHRAE Standard 90.1-2016 defines a continuous air barrier as “the combination of interconnected materials, assemblies, and sealed joints and components of the building envelope that minimize air leakage into or out of the building envelope” [31]. While the buildings categorized with an air barrier by Emmerich and Persily may not all meet the literal definition of an air barrier in Standard 90.1, they all were built with significant attention to airtightness and the term “with an air barrier” is used herein as shorthand for them. Table 3 lists the two building envelope airtightness levels that were simulated.

The building envelope airtightness levels are given in units of $\text{m}^3/\text{s} \cdot \text{m}^2$ at 4 Pa because they can be directly entered into EnergyPlus as the I_{design} value (Equation (1)). The values for the building models without air barriers are the same for all the building types because they are 5-sided airtightness values, i.e., normalized by the exterior surface area except for those surfaces that are in contact with the ground (i.e., slab-on-grade floors or below-ground basement walls). The values for the building models with air barriers are different across the building types because

they are converted from the 6-sided airtightness value ($5 \text{ m}^3/\text{h}\cdot\text{m}^2 @ 75 \text{ Pa}$ or $0.27 \text{ ft}^3/\text{min}\cdot\text{ft}^2 @ 75 \text{ Pa}$) reported in Emmerich and Persily [4]. Thus, the values in the table are calculated using the ratio of each building's 5-sided to 6-sided exterior surface areas (Table 2) multiplied by the 6-sided airtightness value.

To improve upon the infiltration rates implemented in the EnergyPlus (original) models, correlations are developed to estimate the coefficients of Equation (1) (or “EnergyPlus infiltration inputs”) that account for both wind and indoor - outdoor temperature difference, and when the HVAC system is both on and off. The method by which CONTAM simulations were used to determine these coefficients are provided in Section 2.3. Wind pressure on a building surface is defined in ASHRAE Fundamentals as function of the square of the wind speed [32]. Therefore, C is set to zero in this study and Equation (1) simplifies to Equation (3):

$$\text{Infiltration} = I_{\text{design}} \cdot F_{\text{schedule}} [A + B|\Delta T| + D \cdot W_s^2] \quad (3)$$

The EnergyPlus models with the infiltration inputs developed using CONTAM results will be referred to herein as “EnergyPlus (correlations)” models. The I_{design} , or the assumed building envelope airtightness at an indoor-outdoor pressure difference of 4 Pa, will vary between what was originally in the EnergyPlus (original) models (“without air barrier”) and available data in the literature on measured building envelope airtightness (“with air barrier”). However, the way that infiltration is modeled will not change between the EnergyPlus (correlations) models. F_{schedule} will always be set to 1.0 in the EnergyPlus (correlations) models as the system on/off status will be accounted for with two separate sets of EnergyPlus infiltration inputs as outlined below.

2.2. CONTAM Prototype Building Models

The building geometry and layout of the EnergyPlus ASHRAE 90.1-2004 [33] and ASHRAE 90.1-2013 [30] versions of building types are essentially the same, with minor changes (such as the addition of zones that did not add to the total floor area of the building) described in Goel et al. [34]. The major changes included higher efficiency HVAC systems and ventilation requirements that changed in accordance with revisions in ASHRAE Standard 62.1 as incorporated by Standard 90.1-2013. There were also changes to occupant density and schedules that required modification of the CONTAM models used in the previous study [35]. HVAC design supply airflow rates and fan availability schedules, thermostat setpoints, and occupancy schedules were also updated in the CONTAM models, to match the EnergyPlus models.

Since CONTAM does not perform energy calculations, the thermostat setpoint schedules in the EnergyPlus models were converted to indoor temperature schedules and input into CONTAM. Also, CONTAM HVAC systems operated according to the fan availability schedules specified in the EnergyPlus models, i.e., they were not made to match those of the EnergyPlus models which varied during simulations according to thermal load requirements. The common design goal of pressurizing commercial buildings was accounted for in the CONTAM models by returning 90 % of the supply airflow rate to the HVAC system. In contrast, HVAC systems were modeled in EnergyPlus models with the supply airflow rate equal to the return airflow rate, reflecting no net pressurization or depressurization of the building.

Only five of the seven commercial building types used in the previous study were used in this study. The Full Service Restaurant was not used because the kitchen exhaust fan airflow rate was greater than 90 % of the design supply airflow rate, so that the amount of infiltration into the building was approximately equal to the exhaust airflow rate when the exhaust fan was on, which was 21 hours each day. Thus, infiltration in the Full Service Restaurant was not as dependent on weather as it would be in buildings with relatively smaller exhaust systems. The Large Office was not used in this study because the height of the EnergyPlus ASHRAE 90.1-2013 prototype building is 37.5 m, but was 47.5 m in the ASHRAE 90.1-2004 reference building [33]. When the EnergyPlus model is updated to reflect the correct height, infiltration inputs for the Large Office can be developed.

The five building types used in this study are: Hospital, Medium Office, Primary School, Small Hotel, and Stand Alone Retail. Physical and system characteristics of the buildings are listed in Table 2, specifically: building height (H in m), 5-sided exterior surface area to volume ratio (SV in m^2/m^3), and net system airflow rate normalized by exterior surface area (F_n in $\text{m}^3/\text{s}\cdot\text{m}^2$). F_n is defined as:

$$F_n = (F_{\text{sup}} - F_{\text{ret}} - F_{\text{exh}})/A_{\text{ext surface}} \quad (4)$$

where:

- $A_{\text{ext surface}}$ = exterior above-ground surface area (m^2)
- F_{sup} = design supply airflow rate (m^3/s)
- F_{ret} = design return airflow rate (m^3/s)
- F_{exh} = design exhaust airflow rate (m^3/s)

All the building types are designed to be pressurized ($F_n > 0$), i.e., $F_{\text{sup}} > (F_{\text{ret}} + F_{\text{exh}})$, but the Small Hotel has a fairly balanced HVAC system ($F_n \approx 0$). In the EnergyPlus models, all of the buildings have balanced airflow by definition, so that $F_{\text{sup}} = (F_{\text{ret}} + F_{\text{exh}})$. The system airflows were modeled in CONTAM to capture how buildings are designed to be operated. The HVAC systems of both the Hospital and Small Hotel operate 24 hours a day.

The EnergyPlus and CONTAM models of the prototype buildings in this paper are available on the NIST Multizone Modeling Website (<http://www.bfrl.nist.gov/IAQanalysis/CONTAM/>), under Case Studies.

2.3. Infiltration Correlation Process

The process used in this study to determine infiltration inputs for Equation (3) in EnergyPlus is outlined below and presented in Figure 1.

- Step 1: Perform annual CONTAM simulations using the design HVAC supply airflow rates, fan schedules, indoor temperature schedules based on thermostat setpoint schedules, occupancy schedules, and outdoor ventilation rates from EnergyPlus results as inputs to CONTAM. Use Typical Meteorological Year 3 (TMY3) weather data for each city [36].
- Step 2: Normalize CONTAM hourly whole-building infiltration results by 5-sided external surface area.

Step 3: Combine the CONTAM simulation results, indoor and outdoor temperature, and wind speed into files for processing in Step 4. Correct the wind speed from the TMY3 file using the wind speed adjustment factors in Table 1.

Step 4: Perform least squares analysis to determine the EnergyPlus infiltration inputs A , B , and D in Equation (3).

Two sets of EnergyPlus infiltration inputs were calculated: HVAC system-on and HVAC system-off. It was assumed that $A = 0$ when the HVAC system was off, because when $|\Delta T|$ and W_s are zero, the system-off infiltration rate should be zero. Two EnergyPlus ZoneInfiltration:DesignFlowRate objects, “Infiltration_On” and “Infiltration_Off”, were created and populated with the calculated A , B , and D values in the format of Equations (5) and (6). Schedules were provided for each of the ZoneInfiltration:DesignFlowRate objects to activate them according to the HVAC system fan schedules, so that only one of the objects was active at a time. Note that system-on times may not correspond with the system operation simulated in EnergyPlus, but they do correspond with those of the EnergyPlus HVAC fan schedules.

$$\text{Infiltration_On} = I_{\text{design}} [A_{\text{on}} + B_{\text{on}}|\Delta T| + D_{\text{on}} \cdot W_s^2] \quad (5)$$

$$\text{Infiltration_Off} = I_{\text{design}} [0 + B_{\text{off}}|\Delta T| + D_{\text{off}} \cdot W_s^2] \quad (6)$$

TMY3 weather data for eight cities, representing eight of the nine climate zones defined by ASHRAE 90.1-2016 [31], were used in this study and are listed in Table 4. At this time, Climate Zone 0 has not been included, but can be added in the future.

3. RESULTS

This section contains the results of the correlation calculations and the simulations performed using these results, including comparisons between the simulation methods described earlier. Section 3.1 presents the infiltration inputs for each building type in each climate and for the two levels of building envelope airtightness (without and with air barrier). Section 3.2 contains comparisons between the infiltration rates calculated by the CONTAM, EnergyPlus (original) and EnergyPlus (correlations) models.

To evaluate the goodness-of-fit between the CONTAM and EnergyPlus model results, the coefficient of determination, R^2 , of the EnergyPlus (correlations) and EnergyPlus (original) infiltration rates was calculated, taking the CONTAM infiltration rates as the reference values. R^2 is defined as:

$$R^2 = 1 - \frac{\sum_i (y_i - x_i)^2}{\sum_i (\bar{y} - x_i)^2} \quad (7)$$

where:

$N = 8760$ time steps (hourly results for a whole year)

$x =$ EnergyPlus (“original” or “correlations”) infiltration rates (h^{-1})

$y =$ CONTAM infiltration rates (h^{-1})

$\bar{y} =$ annual mean of CONTAM infiltration rates (h^{-1})

For brevity, only the annual mean infiltration rates and R^2 values are discussed. Detailed tables of the mean and standard deviation of estimated infiltration rates, as well as the R^2 values between the CONTAM and EnergyPlus infiltration rates, are available on the NIST Multizone Modeling Website (<http://www.bfrl.nist.gov/IAQanalysis/CONTAM/>), under Case Studies.

The impacts on annual HVAC energy use for these different approaches are presented in Section 3.3. For each building in each climate zone, the annual energy use associated with HVAC operation (heating, cooling, and fan use) was calculated using EnergyPlus and compared between the EnergyPlus (original) and EnergyPlus (correlations) models (Figure 2). Section 3.4 presents differences in the new infiltration input values from those of the previous study for Chicago weather.

3.1. Building-specific Infiltration Correlations

Figure 3 and Figure 4 show the calculated system-on and system-off EnergyPlus infiltration inputs for the building models without and with air barriers. Detailed values are provided on the NIST Multizone Modeling Website (<http://www.bfrl.nist.gov/IAQanalysis/CONTAM/>), under Case Studies. The EnergyPlus infiltration inputs are presented by building type for each coefficient A , B and D .

Figure 3(a) shows the values of the EnergyPlus infiltration inputs A_{on} for the building types modeled without and with air barriers. Positive value for A_{on} may indicate that the HVAC airflows are not able to achieve the intended level of pressurization and that weather-induced infiltration still occurs (the terms $|\Delta T|$ and W_s in Equation (3)). This is especially apparent for the Hospital, which has the highest net imbalance between system flows, i.e., highest value of F_n (Table 2), of the buildings studied. Even in this building type, which otherwise would be expected to be highly pressurized, there is still weather-induced infiltration as exhibited by the highest A_{on} values in all but one climate zone (Figure 3(a)).

There is still weather-induced infiltration with the addition of an air barrier, even though the infiltration rates on average are less than those in the building models with no air barrier. About half of the A_{on} values increase when modeled with an air barrier compared with modeled without an air barrier across the five buildings in eight climate zones (Figure 3(b)). The largest increase in A_{on} values was for the Hospital. Increasing the building envelope airtightness reduces the relative impact of weather-induced pressure differences (accounted for by the terms $|\Delta T|$ and W_s in Equation (3)) to the imbalance in system flows so that the A_{on} values are higher in order to capture the infiltration into the building models.

Negative values for A_{on} , such as for the Medium Office and Primary School, indicate an opposite effect than that occurring in the Hospital. Specifically, the HVAC airflows are better able to achieve the intended level of pressurization and therefore there will be relatively less weather-induced infiltration (the terms $|\Delta T|$ and W_s in Equation (3)) in these building types compared with others.

The values for B_{on} (the constant associated with $|\Delta T|$ in Equation (3)) are similar across buildings, climate zones, and whether the building has an air barrier or not (Figure 4). The

difference between the maximum and minimum values for B_{on} and B_{off} are both only 0.012, while the difference for the A_{on} values is an order of magnitude more (0.15). It should be noted however, that the $|\Delta T|$ term is for absolute indoor - outdoor temperature difference. If EnergyPlus allowed negative values for this term, i.e., negative ΔT when the outdoor temperature was lower than indoor, the term may be more significant.

The values for D_{on} (the constant associated with W_s in Equation (3)) are not shown for brevity. The values can be found on the NIST Multizone Modeling Website (<http://www.bfrl.nist.gov/IAQanalysis/CONTAM/>), under Case Studies. They vary more than the B_{on} values, but not as much as the A_{on} coefficients. It was assumed that $A_{off} = 0$.

It is interesting to note that the system-off coefficients (B_{off} and D_{off}) are similar (Figure 5), regardless of whether the building model has or does not have an air barrier, even though the average annual system-off infiltration in the building models with air barriers is less than the infiltration in the building models without air barriers.

3.2. Infiltration Rates

Regardless of the simulation method, the average annual infiltration rates of the building models with air barriers were 74 % less than in the building models without an air barrier. The absolute differences between the infiltration rates predicted by the CONTAM and the EnergyPlus (correlations) models with air barriers was on average 0.0008 h^{-1} . This similarity resulted in relatively little difference in HVAC energy use predicted using the EnergyPlus (original) and EnergyPlus (correlations) airtight building models. The similarities in results indicates that a tighter building envelope can reduce the significance of the method used to estimate infiltration on building energy simulations. Therefore, only the results using the building models without air barriers are presented. However, the infiltration rates and HVAC energy use for each building (without and with an air barrier) in each climate zone can be found on the NIST Multizone Modeling Website (<http://www.bfrl.nist.gov/IAQanalysis/CONTAM/>), under Case Studies.

Figure 6 shows the annual mean infiltration rates calculated using the CONTAM models for the eight climate zones (bars, scale on left axis). The lines (scale on right axis) show the percentage difference of the mean infiltration rates calculated using the EnergyPlus (original) and EnergyPlus (correlations) models. A positive percentage difference means that the EnergyPlus model predicted a higher annual average infiltration rate than the CONTAM model. A black horizontal line is drawn across the graph to indicate a zero percentage difference between the CONTAM and EnergyPlus results. The Hospital and Small Hotel have HVAC systems that operate 24 hours a day, so there are only system-on plots for these buildings.

In general, the differences between the infiltration rates predicted using the CONTAM and EnergyPlus (correlations) models (black dots in Figure 6) were smaller than the differences between the CONTAM and EnergyPlus (original) model results (white triangles in Figure 6). Using the EnergyPlus (correlations) models, the differences between the EnergyPlus and CONTAM infiltration rates were 15 % when the system was on and 4 % when the system was off. In contrast, using the EnergyPlus (original) models, the differences between the EnergyPlus and CONTAM infiltration rates were 24 % when the system was on and 19 % when the system was off. Therefore, on average, for the five buildings in eight climate zones, the use of the

EnergyPlus (correlations) models reduced the error in the estimated infiltration rates by about 56 %, when compared to the CONTAM infiltration rates. Figure 6 also shows that in general the largest differences between the predicted CONTAM and EnergyPlus (original) infiltration rates were for the warmest and coldest climates (CZ1 and CZ8). The improvement of the infiltration rates estimated by the EnergyPlus (correlations) models, over the EnergyPlus (original) models, can also be described using the R^2 values, which are provided in detail on the NIST Multizone Modeling Website (<http://www.bfrl.nist.gov/IAQanalysis/CONTAM/>), under Case Studies. For all of the buildings in the eight climate zones, the R^2 values of the EnergyPlus (original) infiltration rates were on average $R^2 = -0.74$ (range -5.22 to 0.48). The R^2 values of the EnergyPlus (correlations) infiltration rates were on average $R^2 = 0.33$ (range -1.04 to 0.84). In general, the EnergyPlus (correlations) infiltration rates agree more with the CONTAM rates than the EnergyPlus (original) infiltration rates. Differences between the CONTAM and EnergyPlus (correlations) infiltration rates exist even though the EnergyPlus (correlations) models had infiltration inputs developed using the CONTAM rates. This is most likely due the treatment of local wind speed by EnergyPlus, resulting in differences in local wind speed with zone height. This phenomena was not fully captured when correlating CONTAM infiltration rates with weather. As discussed in Section 2.1, an average local wind speed modifier was used instead.

3.3. Energy Usage

To evaluate the relative impact of the infiltration rates using the EnergyPlus (original) models to those using the EnergyPlus (correlations) models, the annual heating, cooling, and fan energy use from the EnergyPlus simulations were compared. All of the buildings had electrical energy associated with cooling and fan use. Electricity is also used for a portion of heating in the Hospital (variable air volume (VAV) systems), Medium Office (VAV systems), and Small Hotel (guestrooms and common areas). All the buildings utilized gas for heating. Table 5 summarizes the percentage increase in annual HVAC electrical and gas use using the EnergyPlus (correlations) models compared to using the EnergyPlus (original) models.

The change in predicted annual HVAC electrical use of the EnergyPlus (correlations) models, compared with using the EnergyPlus (original) models, was minimal for the Hospital and Primary School (except in CZ 8 for the school). However, for all the building types in all eight climate zones, the annual average HVAC electrical increase was 3 %. The highest increase in HVAC electrical use of 27 % was for the Medium Office in CZ 8, which was due to the reheat coils in the VAV boxes. There was also a high increase in HVAC electrical use of 18 % in the Small Hotel in CZ 8, which was due to heating coils in the guestrooms and in the systems serving the common areas. In general, the predicted increase in HVAC electrical use, when using the EnergyPlus (correlations) models over the EnergyPlus (original) models, for the building types was largest in the colder climates, CZ 5 to CZ 8.

The predicted increase in annual HVAC gas use of the EnergyPlus (correlations) models, compared with using the EnergyPlus (original) models, was an average of 8 % across the five building types in the eight climate zones. The lowest average increase across eight climate zones was 2 % for the Hospital and the highest average increase was 17 % for the Stand Alone Retail. In some building types and in some climate zones, using the EnergyPlus (correlations) models resulted in a decrease in HVAC energy use (negative values in Table 5), but those tended to be small (around 1 %). The largest predicted decrease of 7 % in gas heating energy was for the

Stand Alone Retail in CZ 1 (Miami, Florida). The absolute heating use in the Stand Alone Retail was the smallest of all the building types. In general, when using the EnergyPlus (correlations) models compared with using the EnergyPlus (original) models, the climate zones with less severe heating seasons (CZ 1 and CZ 2) saw a decrease or no change in heating use while the climate zones with larger heating seasons (CZ 5 to CZ 8) saw an increase in heating use. The exception was the Small Hotel, which had an increase in heating use for all climate zones.

As mentioned in the Introduction, current energy simulation software and design methods generally do not accurately account for envelope infiltration, and therefore they may not fully capture the impacts of improved airtightness on energy. Figure 7 shows the additional HVAC energy use savings predicted by the EnergyPlus (correlations) models relative to using the EnergyPlus (original) models after building envelope airtightening. In other words, using the EnergyPlus (correlations) models, the impact of envelope airtightening (e.g., reducing the annual average infiltration rate by 74 %) showed a greater impact on HVAC energy savings than using the EnergyPlus (original) models.

On average, for the five building types in eight climate zones, the average additional savings in annual HVAC electrical energy use was 2 % when using the EnergyPlus (correlations) models, with a range of savings of -3 % to 16 %. A negative savings means a relative increase in HVAC use after building envelope airtightening using the EnergyPlus (correlations) models relative to using EnergyPlus (original) models. On average, for the five building types in eight climate zones, the average additional savings in annual HVAC gas use was 5 % when using the EnergyPlus (correlations) models, with a range savings of -3 % to 17 %.

The higher estimated savings in HVAC energy use, using EnergyPlus (correlations) models over using EnergyPlus (original) models, are greatest in the colder climates, CZ 5 to CZ 8, for all the building types except the Hospital. For the Hospital, the infiltration was relatively small and therefore not as impacted by building envelope airtightening. There were only a few instances when using the EnergyPlus (correlations) models estimated an increase in HVAC energy after building envelope airtightening (negative values in Figure 7).

3.4. Differences from Previous Study

In the previous study, infiltration inputs were developed for commercial reference buildings for only the Chicago weather (CZ 5) with a building envelope leakage value of $I_{\text{design}} = 14 \times 10^{-4} \text{ m}^3/\text{s}\cdot\text{m}^2$ at 4 Pa [37, 38]. This is more than double the value used in this study for the models without air barriers ($5.7 \times 10^{-4} \text{ m}^3/\text{s}\cdot\text{m}^2$ at 4 Pa), leading to significant differences in the infiltration inputs described in this paper. The reason the building models were not as airtight in the previous study was due to the data on airtightness of commercial buildings that was available at the time [39].

The EnergyPlus models of the commercial reference building types developed by DOE in 2011 had infiltration inputs that were constant values. The infiltration varied only with HVAC system operation. During system-off hours, the I_{design} value was used directly. During system-on hours, the I_{design} value was multiplied by 0.5 or 0.75. While the EnergyPlus models of the commercial prototype buildings, developed by DOE in 2014, included an infiltration model that accounted for wind effects, the effects of temperature, wind direction, HVAC operation, and building

layout are not accounted for. Nevertheless, neither method of infiltration input (constant or wind-driven only) could predict infiltration rates as well as using the infiltration inputs developed by NIST, when compared with CONTAM results.

4. SUMMARY AND DISCUSSION

Current approaches to account for infiltration and improved envelope airtightness in energy models either ignore or simplify the effects of weather, system operation, and envelope leakage. Oftentimes, zero or constant infiltration rates are input into energy simulation software due to a lack of understanding of how to more accurately account for infiltration or the level of effort involved in doing so. While multizone airflow modeling is a widely accepted approach to calculate infiltration and other airflows in buildings, current implementations in energy simulation programs are limited and can be cumbersome to use.

In this paper, infiltration inputs were developed that incorporate the effects of weather, system operation, and building characteristics for a subset of the ASHRAE 90.1-2013 prototype buildings – Hospital, Medium Office, Primary School, Small Hotel, and Stand Alone Retail – for eight U. S. climate zones. The use of the infiltration inputs (or “EnergyPlus (correlations) models”) improved the predicted annual average infiltration rate, compared with using the EnergyPlus (original) models, by 50 % when compared with CONTAM infiltration rates. The use of the EnergyPlus (correlations) models resulted in an average 3 % increase in the estimated annual HVAC electrical use, and an average 8 % increase in the HVAC annual gas use, compared with using the EnergyPlus (original) models. Thus, using the EnergyPlus (correlations) models had a greater impact on heating use than on cooling use.

In some buildings, there would be no significant difference in estimated infiltration or HVAC energy use using the EnergyPlus (correlations) or EnergyPlus (original) models, such as for the Hospital. It had an average increase in annual HVAC electrical use of 0.1 % and an average increase in annual gas electrical use of 0.4 %. This is due to the Hospital being highly pressurized, operated 24 hours, and having a very low infiltration rate (0.03 h^{-1} on average), so any improvement in the estimated infiltration is relatively small. In other buildings, using the EnergyPlus (correlations) models instead of the EnergyPlus (original) models had a significant impact on HVAC energy use, particularly HVAC gas use.

When analyzing the benefits of building envelope airtightening, greater HVAC energy savings can be predicted using the EnergyPlus (correlations) models than using the EnergyPlus (original) models. It was predicted that the EnergyPlus (correlations) models yielded on average 2 % more savings in annual HVAC electrical use and 5 % more savings in annual HVAC gas use compared with using the EnergyPlus (original) models. The greatest savings were in the colder climates, CZ 5 to CZ 8.

5. FUTURE WORK

Infiltration correlations based on weather, system operation, and building characteristics were developed using hourly infiltration rates from CONTAM for five prototype commercial building models in eight climate zones. There are prototype commercial buildings that were not included in this study, such as additional offices, schools, hotels, and multi-family residences, for which infiltration inputs could be developed. There are also more cities in the eight climate zones that

could be studied. To make the infiltration inputs developed in this paper easily accessible, the infiltration correlations developed in this study could be incorporated into an existing OpenStudio Measure developed by NIST (<https://bcl.nrel.gov/node/83101>). Lastly, the impact of the infiltration rates estimated by the EnergyPlus (correlations) models on system sizing and system operating efficiency should be investigated. These effects may have implications related to equipment cost and operating efficiency, which can be even more significant in terms of cost increases or savings than the effects of infiltration on HVAC energy use alone.

6. CONCLUSIONS

Given the increased emphasis on energy consumption and greenhouse gas emissions, the potential savings from energy efficiency measures are often analyzed using energy simulation software. To comply with energy design standards, energy simulation is often required. However, the impact of implementing improved building envelope airtightness is oftentimes inadequate because building envelope infiltration is not accounted for properly. Multizone airflow modeling is a widely accepted approach to calculating infiltration that accounts for building geometry, system operation, building envelope airtightness, and weather. Multizone CONTAM models of five prototype commercial buildings were developed and used to determine infiltration inputs for eight climate zones. The infiltration inputs were then implemented in the EnergyPlus models of the prototype buildings. It was found that infiltration inputs developed in this paper resulted in EnergyPlus models that predicted infiltration rates closer to CONTAM rates when compared with using the inputs originally in the prototype building models. The improvements in the estimates of the infiltration rates led to increases in the predicted annual HVAC energy use, particularly in annual HVAC gas use in colder climates. This was the case in most buildings, but for buildings like the Hospital which are continuously highly pressurized, the change in predicted annual HVAC energy use were less significant. Nevertheless, the use of the EnergyPlus (correlations) models, in general, increased the predicted annual HVAC energy savings due to building envelope airtightening compared with using the EnergyPlus (original) models. Thus, accounting for infiltration more accurately in energy modeling will allow for more accurate estimates of energy savings when evaluating the benefits of building envelope airtightening.

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Table 1. Average local wind speed adjustment for each building

Building	Average Local Wind Speed Adjustment
Hospital	0.44
Medium Office	0.37
Primary School	0.26
Stand Alone Retail	0.30
Small Hotel	0.62

Table 2. Summary of building types simulated

	Hospital	Medium Office	Primary School	Small Hotel	Stand Alone Retail
<i>H</i> (m)	21	12	4	12	6
Exterior surface area, 5-sided (m²)	8937	3638	9383	2698	3471
Exterior surface area, 6-sided (m²)	13107	5299	16254	3702	5765
Volume (m³)	79802	19741	27484	11622	13984
<i>SV</i> (m²/m³)	0.11	0.18	0.34	0.23	0.24
<i>F_n</i> (m³/s•m²) × 10⁻⁴	5.1	3.2	1.8	0.18	2.5
General HVAC operation					
Weekdays	24 h	6 a.m. to 10 p.m.	7 a.m. to 9 p.m.	24 h	7 a.m. to 9 p.m.
Saturdays	24 h	6 a.m. to 10 p.m.	Off	24 h	7 a.m. to 10 p.m.
Sundays & Holidays	24 h	Off	Off	24 h	9 a.m. to 7 p.m.

Table 3. Airtightness values used in this study

Airtightness level (m³/s•m² @ 4 Pa)	Hospital	Medium Office	Primary School	Small Hotel	Stand Alone Retail
Without air barrier	5.7E-4				
With air barrier	3.0E-04	3.0E-04	3.6E-04	2.8E-04	3.4E-04

Table 4. Climate zones and associated city

Climate zone (CZ)	City, State (USA)
1	Miami, Florida
2	Phoenix, Arizona
3	Memphis, Tennessee
4	Baltimore, Maryland
5	Chicago, Illinois
6	Helena, Montana
7	Duluth, Minnesota
8	Fairbanks, Alaska

Table 5. Annual predicted percentage increase in HVAC electrical and gas use for each building model and climate zone using EnergyPlus (correlations) model over using EnergyPlus (original) models (without air barriers)

CZ	Hospital	Medium Office	Primary School	Small Hotel	Stand Alone Retail
Increase in annual HVAC electrical use (%)					
1	0	-1	-1	-1	0
2	0	-1	-1	-1	1
3	0	1	-1	0	1
4	0	3	-1	1	0
5	0	13	0	2	1
6	0	8	1	4	2
7	0	11	0	4	3
8	0	27	4	18	12
All	0	8	0	3	3
Increase in annual HVAC gas use (%)					
1	0	0	0	3	-7
2	0	-1	-2	8	-4
3	1	6	1	8	18
4	1	6	2	9	24
5	2	18	5	9	26
6	2	11	2	10	23
7	3	16	5	9	27
8	6	17	10	14	32
All	2	9	3	9	17

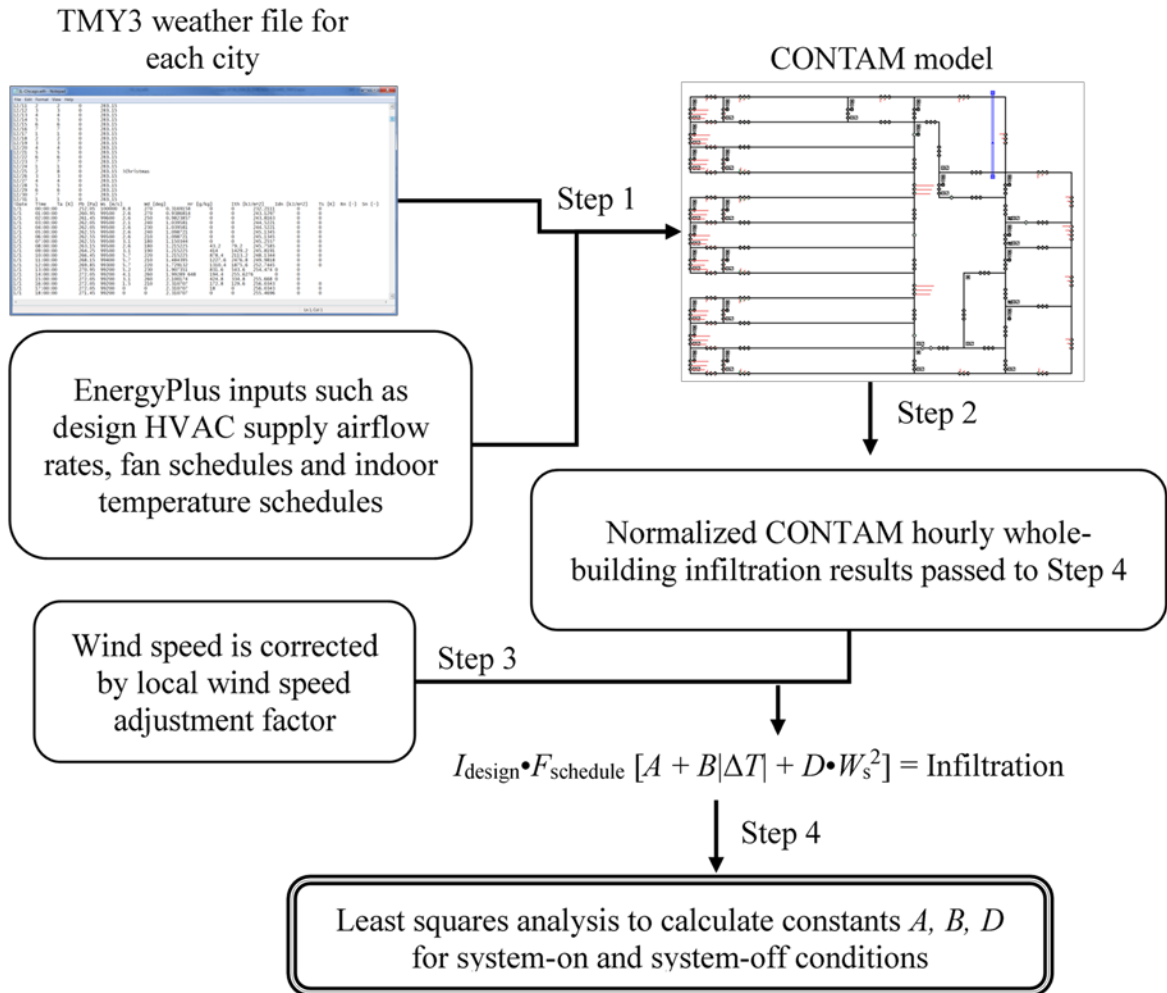


Figure 1. Infiltration Correlation Process

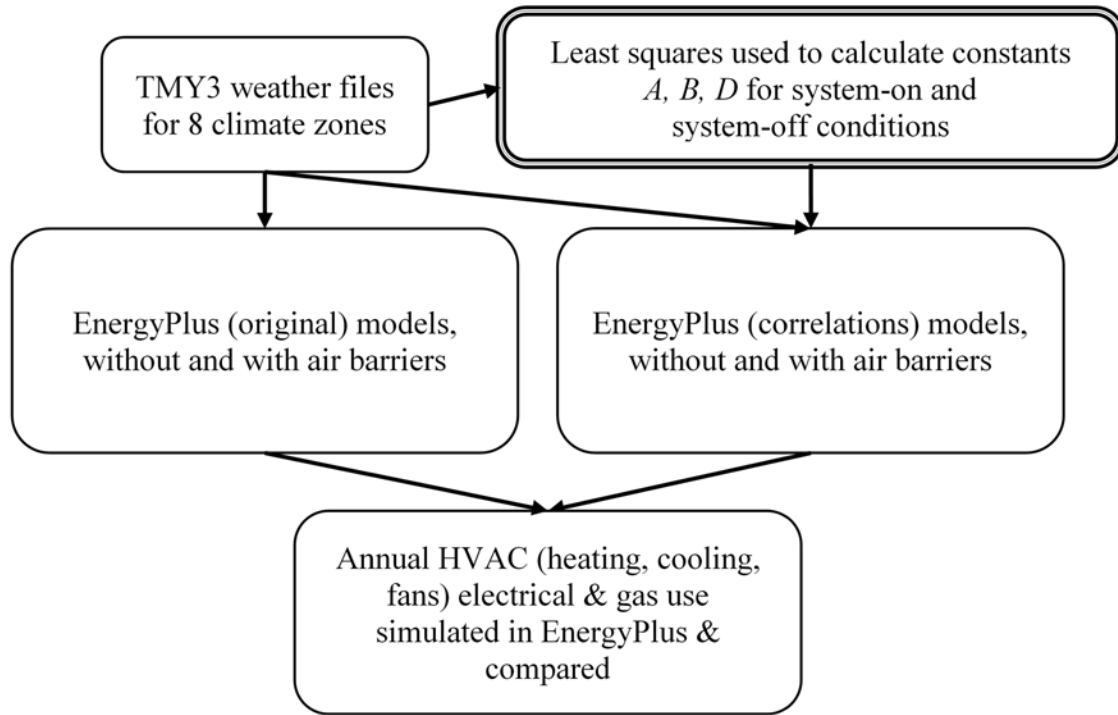
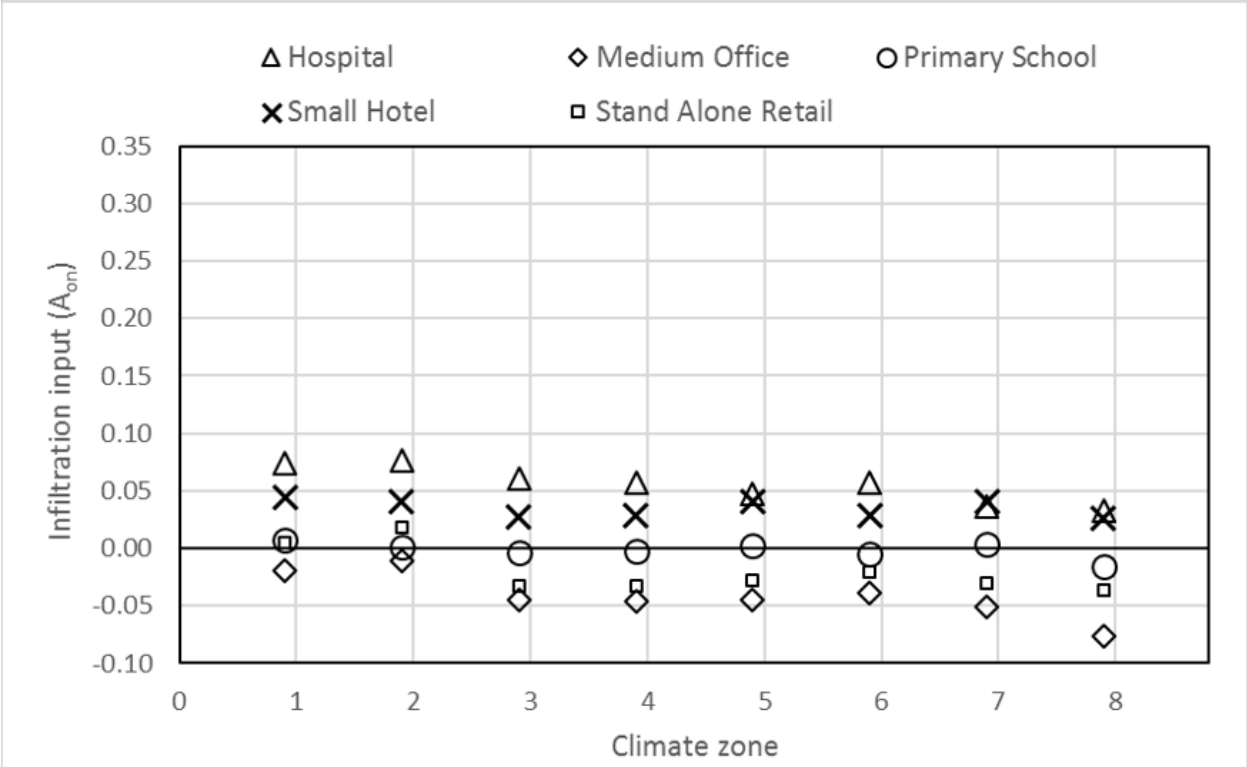
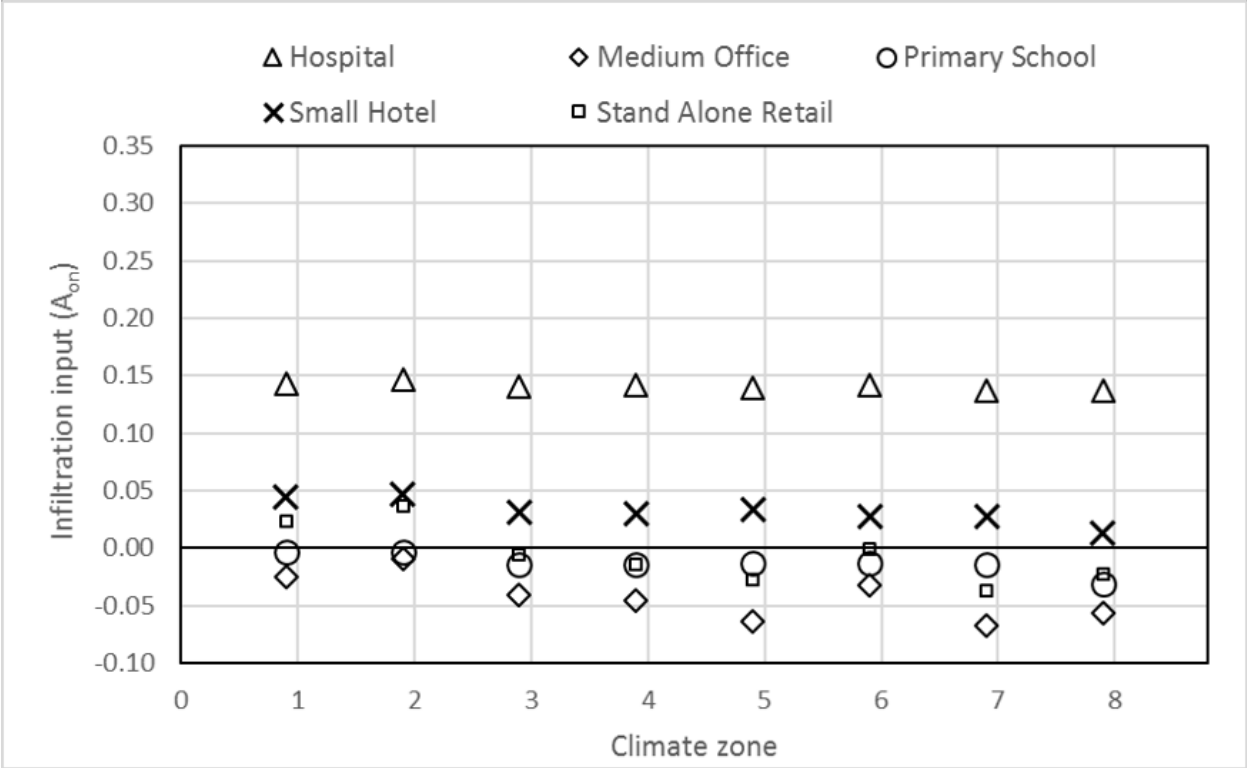


Figure 2. Comparing annual HVAC energy costs of EnergyPlus (original) and EnergyPlus (correlations) models

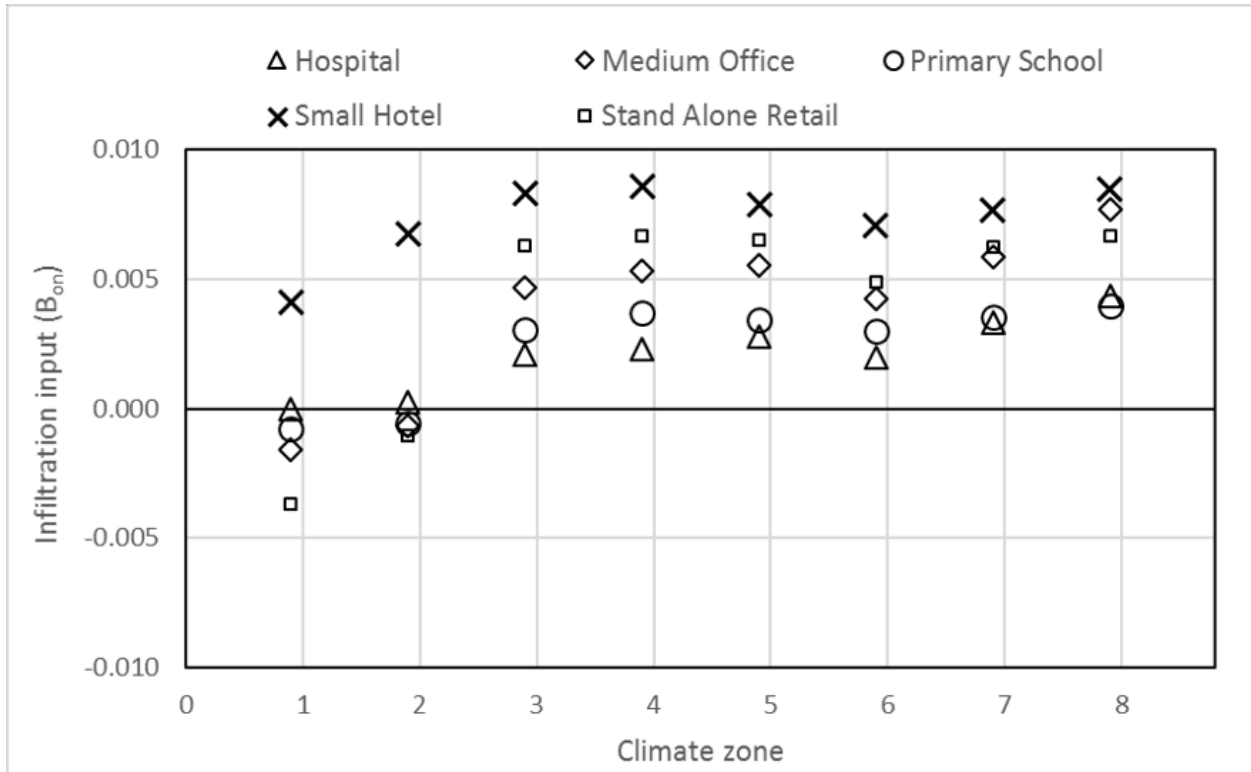


(a) Without air barrier

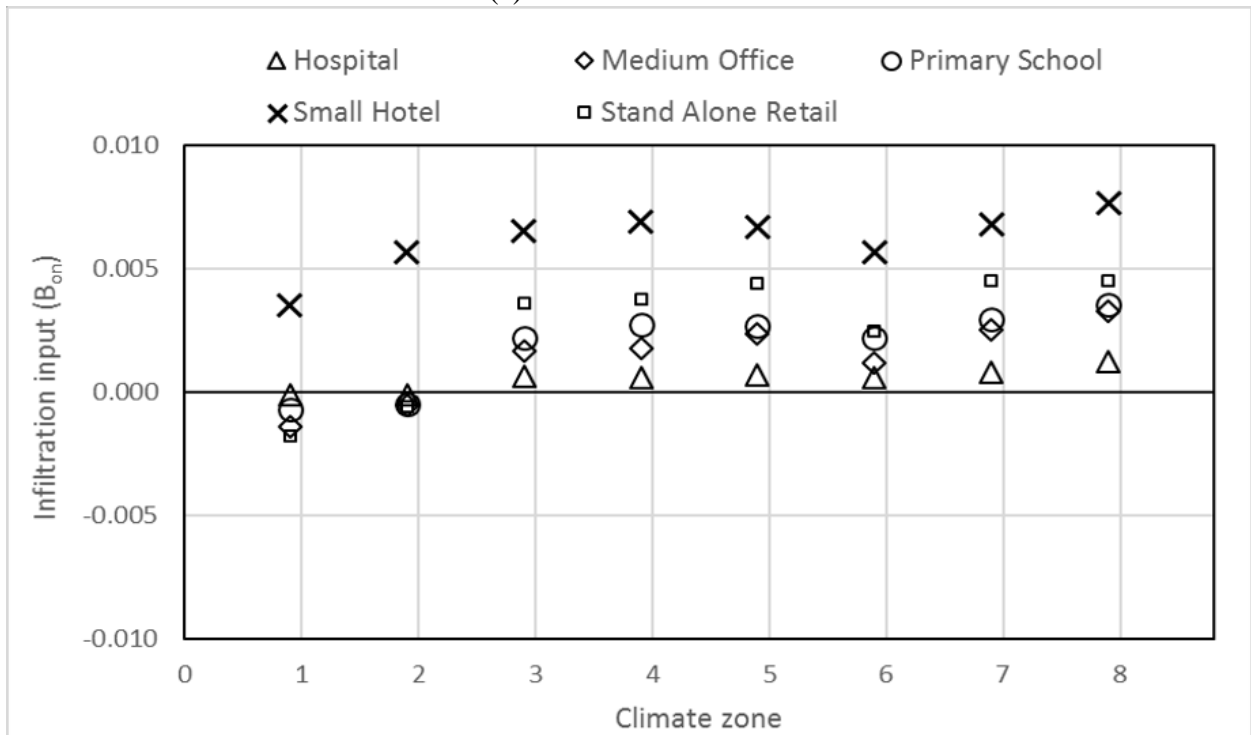


(a) With air barrier

Figure 3. Infiltration input A_{on} grouped by building type for 8 climate zones (a) Without air barrier (b) With air barrier

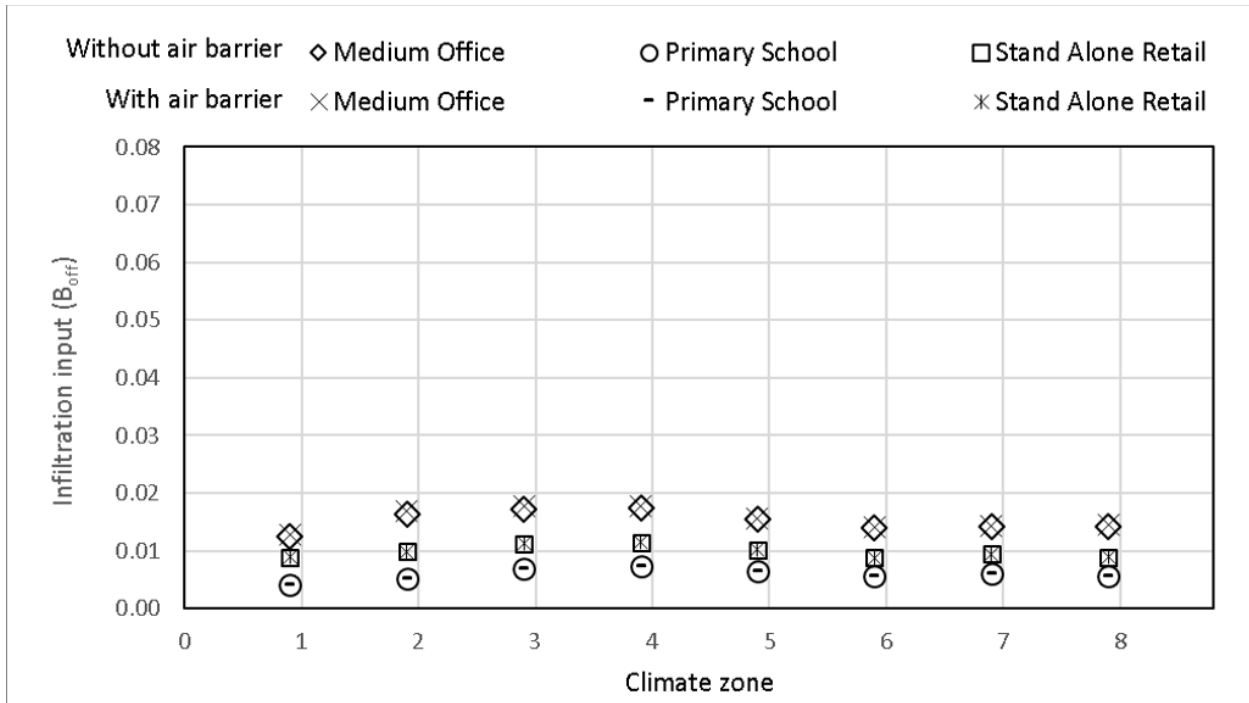


(a) Without air barrier

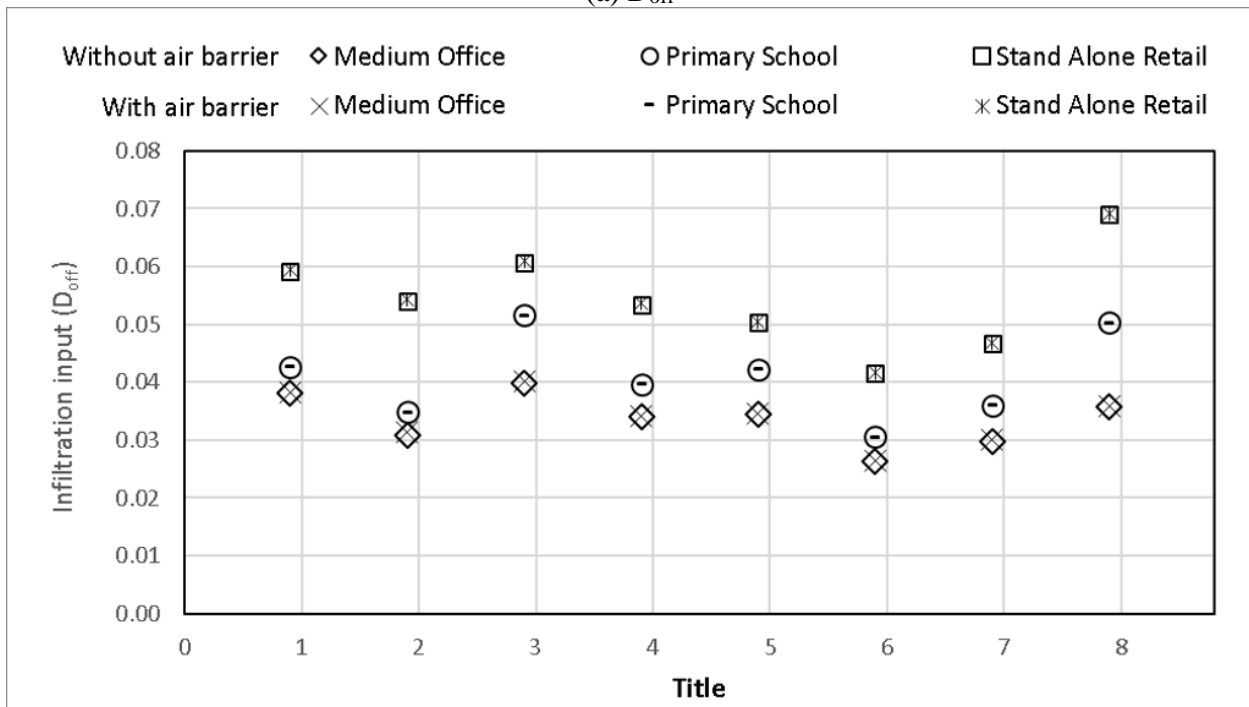


(b) With air barrier

Figure 4. Infiltration input B_{on} grouped by building type for 8 climate zones (a) Without air barrier (b) With air barrier



(a) B_{off}



(b) D_{off}

Figure 5. Infiltration inputs B_{off} and D_{off} grouped by building type for 8 climate zones

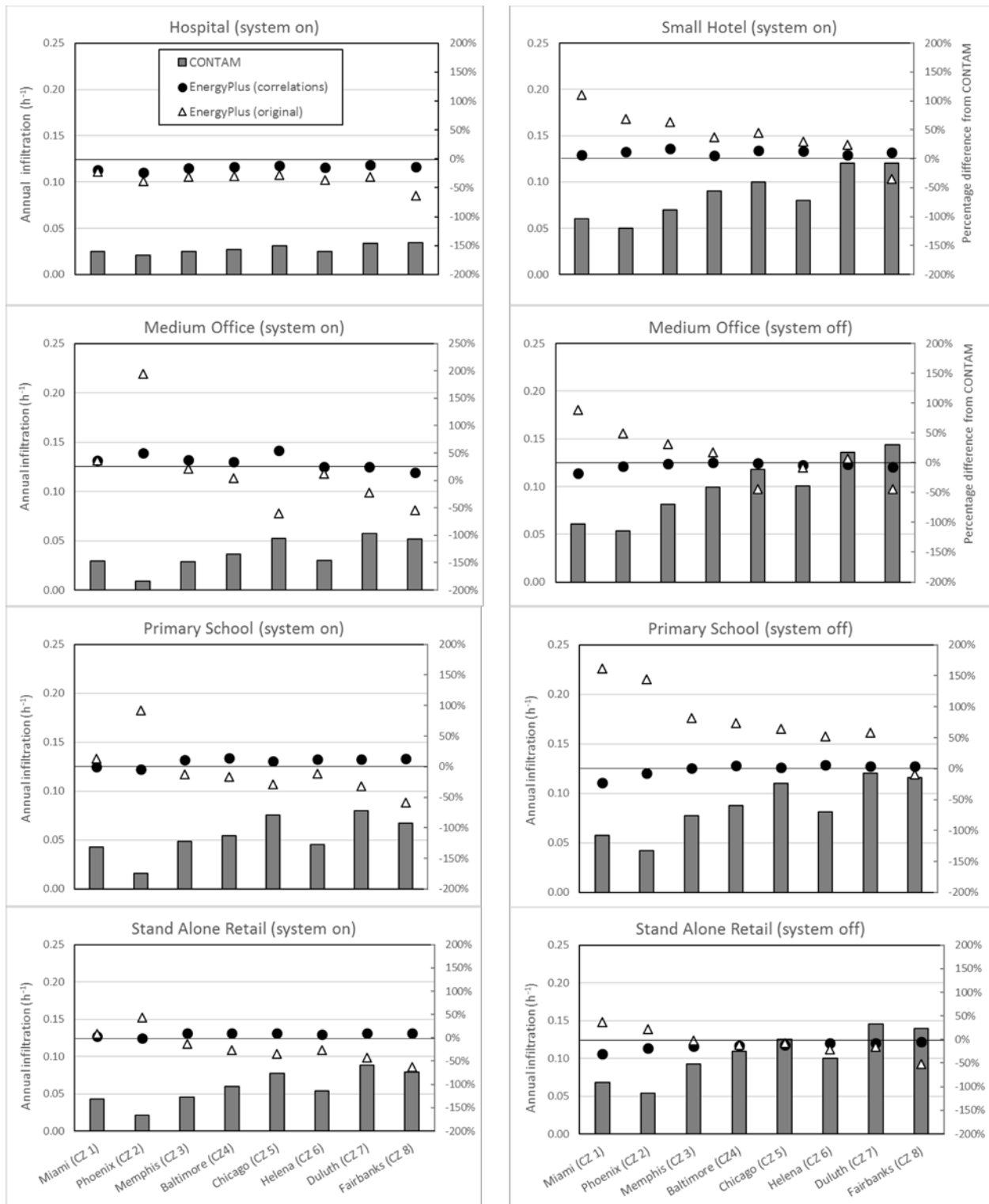
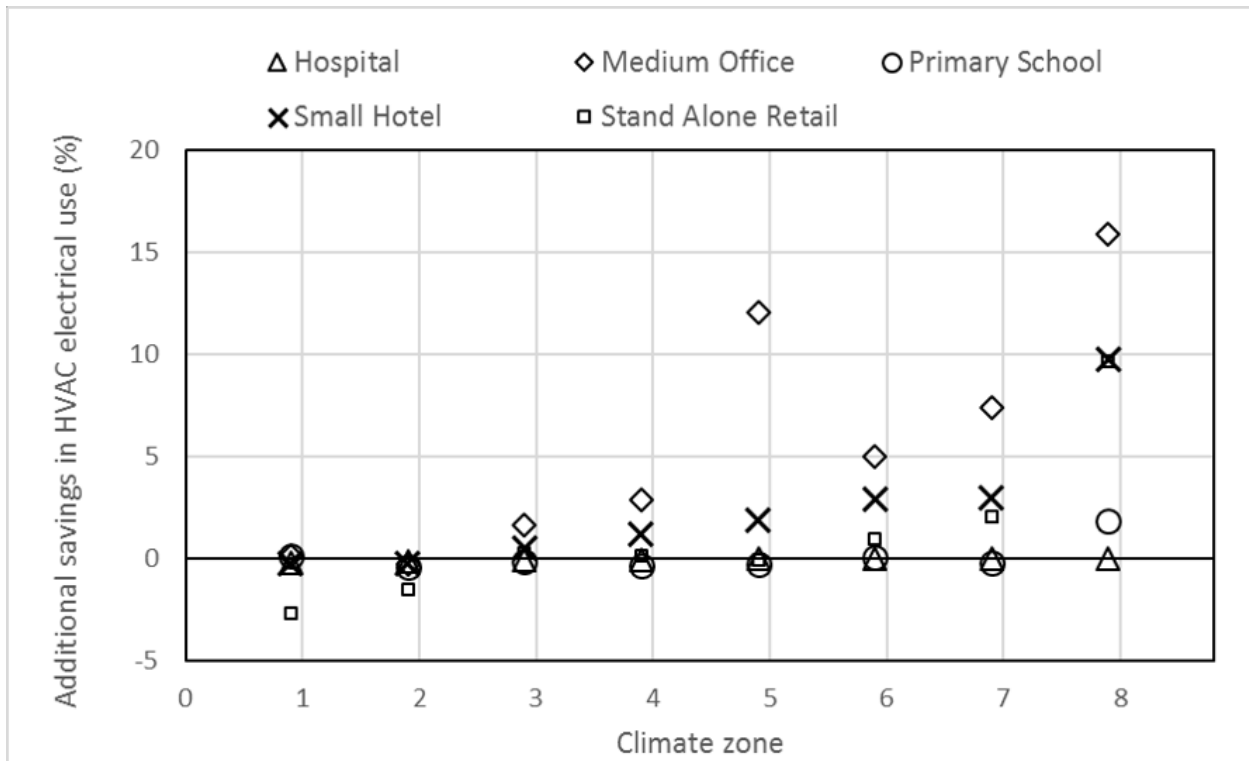
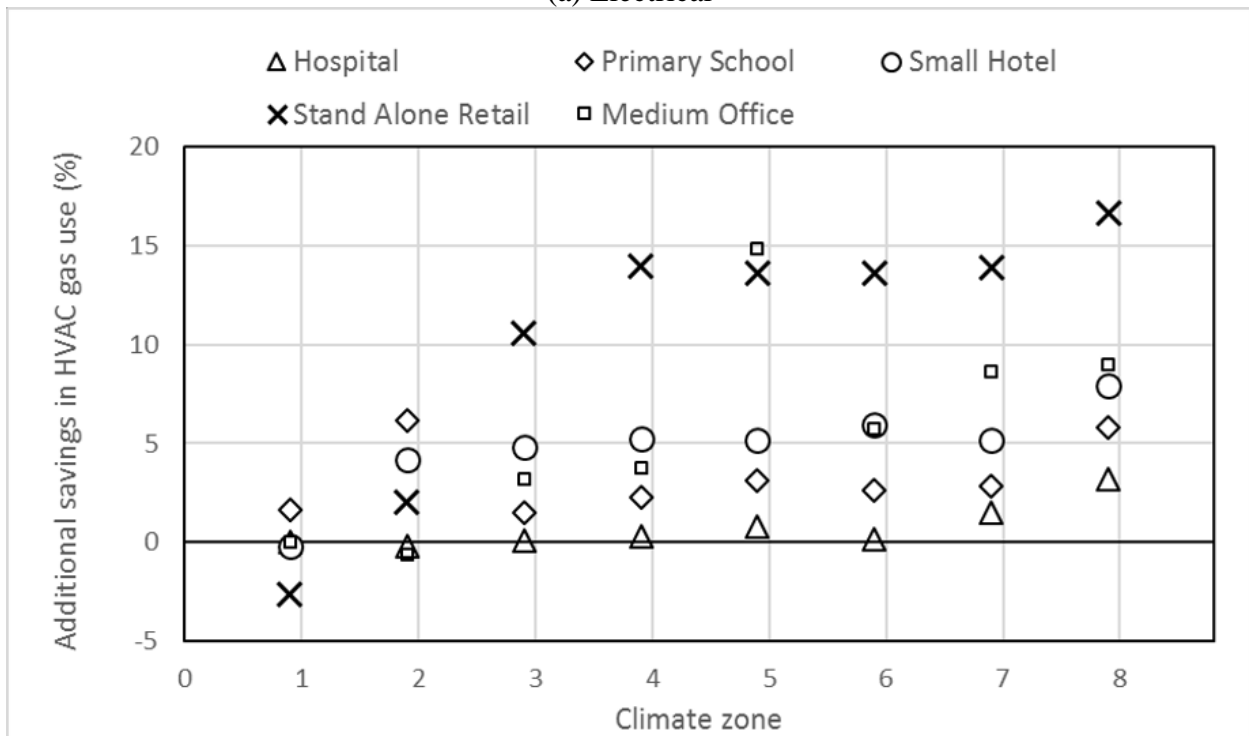


Figure 6. Comparison of annual average infiltration rates for each building model and climate zone (without air barrier)



(a) Electrical



(b) Gas

Figure 7. Additional percentage savings in annual HVAC (a) electrical and (b) gas use for each building types and climate zone using EnergyPlus (correlations) models over using EnergyPlus (original) models after building envelope airtightening *Note: Negative values mean a relative*

decrease in HVAC energy use after building envelope airtightening using EnergyPlus (correlations) models over using EnergyPlus (original) models