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Extending the Air and Moisture Leakage Calculator to add Residential Buildings and Additional Commercial Buildings

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Buildings and Transportation Science Division

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Niraj Kunwar

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February 2023

Prepared by

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ABSTRACT

The DOE Windows and Building Envelope Research and Development Roadmap for Emerging Technologies shows that in 2010, infiltration was responsible for 4 quads of space conditioning primary energy use in the residential and commercial sectors. The relative contribution of air leakage in building heating and cooling load is increasing with improvement in the thermal resistance of building envelopes. Advanced air barrier technologies and construction practices have been developed to reduce air leakage in buildings. However, limited information on the impact of air barrier technologies on energy consumption and the durability of buildings has hindered their adoption. In the past Oak Ridge National Laboratory (ORNL), the National Institute of Standards and Technology (NIST), Air Barrier Association of America (ABBA), and U.S.-China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE) collaborated to develop an online calculator that estimates the potential energy and cost savings in major U.S., Canadian and Chinese cities from improvement in air tightness in commercial buildings. In 2018–2019, the calculator was expanded to add moisture transfer calculations given that air leakage through the building envelope can have a significant impact on moisture transfer and associated impacts. In this study, the calculator is expanded further by adding data for two additional commercial buildings (strip mall and primary school) and a residential building. The team investigated the impact of airtightness on energy consumption and moisture transfer of the added buildings. The study includes the analysis of air tightness in 52 major cities in the U.S. and 5 cities in Canada.

ACKNOWLEDGMENTS

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1. BACKGROUND AND OBJECTIVE

The DOE Windows and Building Envelope Research and Development Roadmap for Emerging Technologies shows that in 2010, infiltration was responsible for 4 quads of space conditioning primary energy use in the residential and commercial sectors. In aggregate, infiltration accounted for higher energy losses than any other component of the building envelope, including fenestration. Improving airtightness is not always recognized by building owners, as they have been slow in acknowledging and diminishing the detrimental effects of air leakage on energy use and other aspects of building performance. The design and construction industries need a credible, easy-to-use tool that estimates potential energy and financial savings in a standardized manner so industry professionals can give building owners compelling reasons to invest in reducing air leakage.

In 2016-17, the Oak Ridge National Laboratory (ORNL), the National Institute of Standards and Technology (NIST), the Air Barrier Association of America (ABAA), and the US-China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE) collaborated and developed an online air leakage calculator that is free to the public, user-friendly, and uses the simulation results of the best-in-class building energy simulation tool EnergyPlus and the whole building airflow simulation tool CONTAM. The online calculator uses a database of EnergyPlus pre-run simulation results for the DOE commercial prototype buildings [1]. The database developed in 2016-17 contained three types of commercial buildings, out of 16 commercial prototype building models that were developed by DOE's Building Energy Codes Program. The 16 commercial prototype building models cover 80% of the commercial building floor area in the United States for new construction, including both commercial buildings and mid- to high-rise residential buildings, and across all U.S. climate zones.

In 2018 four more types of commercial buildings were added to the calculator. In addition to calculating the energy impact of air leakage, we also added moisture transfer associated with the air leakage in the calculator. The seven types of commercial buildings cover approximately 51% of the commercial building floor area in the United States for new construction. The existing calculator contains simulation data for 62 cities (52 in the U.S., 5 in Canada, and 5 in China) for seven commercial prototype building models.

The objective of this project co-funded by DOE BTRIC's Technical Collaborations Program is to add DOE's residential prototype building model for the single-family detached house [2] and two more types of commercial buildings in the web-based air leakage calculator. Adding residential buildings will significantly increase the building footprint covered by the calculator which will benefit designers and owners of residential buildings.

2. METHODOLOGY

The calculator uses pre-run simulations of DOE prototype buildings to calculate the energy consumption and cost for different levels of air-tightness. The pre-run simulation was performed for all the building types of interest, locations, and four levels of air-tightness. The procedure for the pre-run simulations is shown in Figure 1. Here, building type, location, and weather data based on the location and building air-tightness are chosen for each of the simulations. Then, first, an EnergyPlus simulation is run to get maximum HVAC/ventilation airflow rates. The HVAC/ventilation airflow rates are used as input into the CONTAM simulation along with other user inputs. Hourly air leakage rate for the whole building is calculated using the CONTAM simulation. This hourly air leakage rate is then used in EnergyPlus as input for infiltration as an annual schedule file and the results obtained from this EnergyPlus run are used as the final energy results from pre-run simulations.

The energy results from these simulations are then used for curve fitting with air leakage rate at different levels of air-tightness as an independent variable with HVAC-related electricity consumption as a dependent variable to obtain a quadratic regression coefficient between the two. Similarly, the regression coefficients are calculated between the air leakage rate and HVAC-related gas consumption. Then, these regression coefficients are fed into the online calculator to obtain energy consumption results at different leakage rates and also to show energy savings when the building envelope's air tightness is improved from one level to another. Further details on the calculator can be found in [3,4].

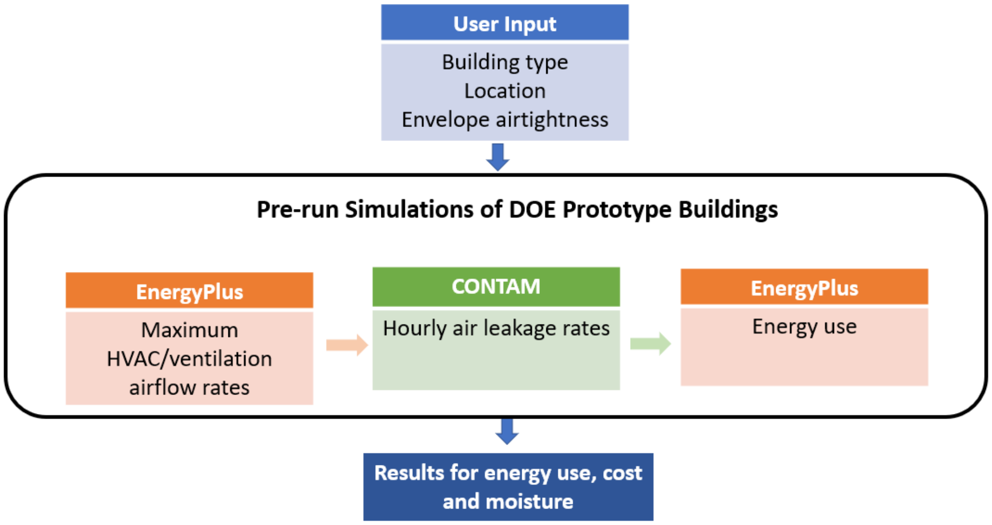

Figure 1 Procedure to get results for pre-run simulations

On the online calculator, the users can input building type, location, envelope airtightness, and cost for the fuels used for HVAC. The interface where users can provide such input is shown in Figure 2. The input could be provided for two scenarios "Base Case" and "Retrofitted Building" to evaluate the energy, cost, and moisture impact of the "Retrofitted Building" compared to the "Base Case". Figure 3 shows an example of the results obtained after the calculation is performed which includes energy savings, cost savings, and moisture transfer reduction results.

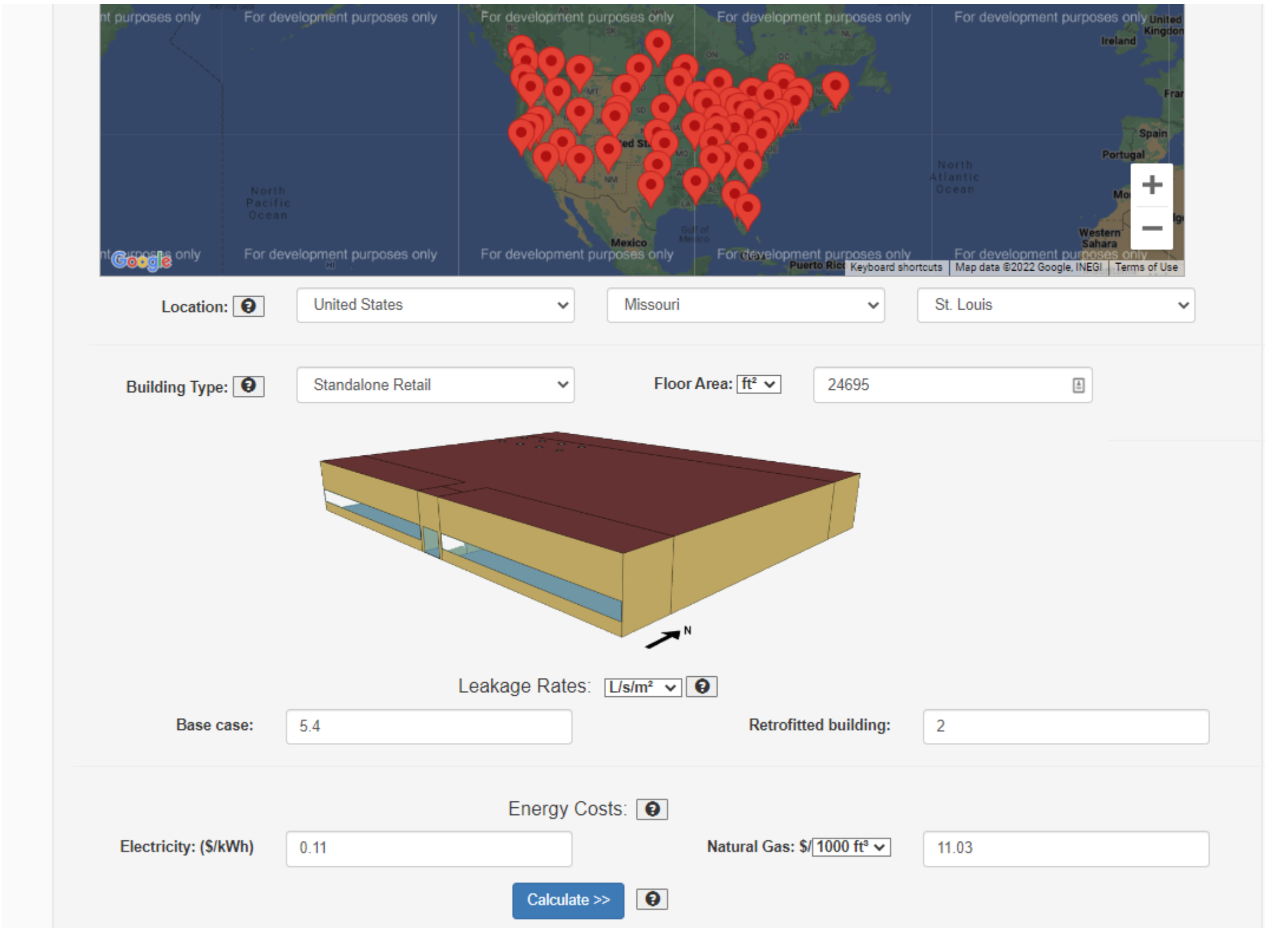

Figure 2 User interface of the online air-leakage calculator

The three building types whose data is added to the air-leakage calculator database and their basic geometrical properties are listed in Table 1. The commercial buildings had construction based on ASHRAE 90.1-13 and the residential building had the construction following International Energy Conservation Code (IECC) 2012.

Table 1 Three building types whose data is added to the air-leakage tool and their basic geometrical properties

Building type	Floor Area (ft^2)	5-sided envelope area (ft^2)	6-sided envelope area (ft^2)
Strip Mall	22497	57748	35241
Primary School	73959	174978	100998
Residential	2379	4747	3563

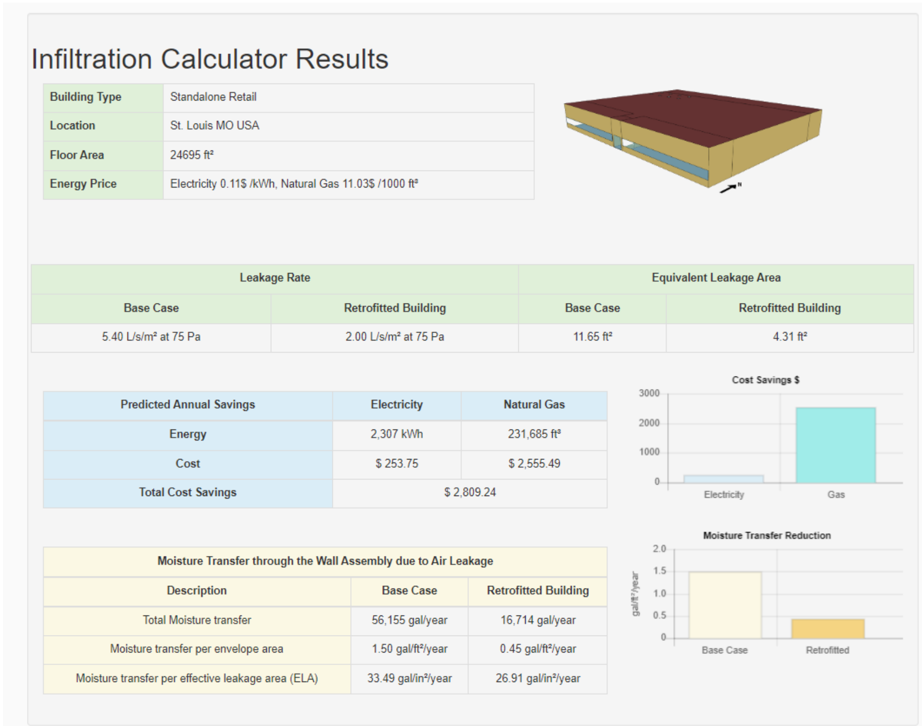

Figure 3 Results from the online air-leakage calculator

All the cities for which the energy simulations were performed were located in one of the 15 IECC climate zones which are listed in Table 2 [5].

Table 2 Climate zones for simulations and their descriptions

Climate Zone	Temperature	Humidity
1A	Very Hot	Humid
2A	Hot	Humid
2B	Hot	Dry
3A	Warm	Humid
3B	Warm	Dry
3C	Warm	Marine
4A	Mixed	Humid
4B	Mixed	Dry
4C	Mixed	Marine
5A	Cool	Humid
5B	Cool	Dry
6A	Cold	Humid
6B	Cold	Dry
7	Very Cold	-
8	Subarctic/Arctic	-

2.1 Residential Buildings:

The IECC 2012 prototype residential buildings [2] with a gas furnace heating system and crawlspace foundation were used for EnergyPlus simulations. A CONTAM airflow model of this building was also created, which consisted of four zones: crawlspace, first floor, second floor, and attic. Only the first and second floors were conditioned and occupied. The characteristics of the prototype residential building used for this study are provided in Table 1. The prototype buildings have different envelope thermal insulation and window properties in each climate zone following IECC 2012, and the heating and cooling systems are auto-sized for each of the locations. The coefficient of performance (COP) of the cooling coil and the efficiency of the supply air fan also vary by climate zone. All other inputs for building energy simulation are the same for the buildings in the different climate zones. The prototype buildings included an exhaust mechanical ventilation with a constant flow rate of 60 ft^3/min (CFM) per occupied zone. Note that the exhaust fans did not operate for the airflow simulations so the exhaust fan flow did not dominate the infiltration. Simulations were performed for 57 locations throughout climate zones 1A through 8. For each location, the prototype building model was selected according to its climate zone. A Typical Meteorological Year 3 (TMY3) file was used as the weather data input [6]. Four levels of air-tightness were used for airflow and energy simulation of the residential buildings.

Table 3 Four levels of air-tightness used for energy simulations of residential buildings

Case	Description	Airtightness $L/s\text{-}m^2$ at 75 Pa	Airtightness h^{-1} at 50 Pa
Base	Without air barrier	7.4	13
Case-1	Derived from IECC 2012 prototype building	4.9	8.5
Case-2	IECC 2012 maximum air leakage for climate zones 1 and 2	2.8	5
Case-3	Passive house [7]	0.4	0.6

We also observed the difference that can arise from using "ZoneInfiltration:EffectiveLeakageArea", further referred to as "EnergyPlus ELA" in this study, and the method using CONTAM-generated schedule of infiltration (EnergyPlus+CONTAM). For EnergyPlus ELA the leakage rate in Table 3 was first converted to ELA using Equation (1) [8].

$$ELA_{4\ Pa} = \sqrt{\frac{\rho}{2*\mathrm{P}}} * Q_{50\ Pa} * \left(\frac{4}{50}\right)^{0.65} \quad (1)$$

where,

$ELA_{4\ Pa}$ is the effective leakage area at 4 Pa

$Q_{50\ Pa}$ is the air leakage rate at 50 Pa calculated using the air leakage values in Table 3, the exterior surface area, and the volume of the conditioned space

ρ is the density of the air

P is the air pressure in Pa at which ELA should be calculated. In this study, P = 4 Pa

The $ELA_{4\ Pa}$ corresponding to the air leakage values in Table 3 were respectively 9.3 in^2, 78 in^2, 132.5 in^2, and 202.5 in^2. HVAC-related electricity and natural gas consumption for Baltimore, MD is shown in Figure 4. The results show that the EnergyPlus ELA method gives increasingly higher electricity consumption with an increase in air leakage compared to the CONTAM method. This trend was also found for commercial buildings [3]. As shown in Figure 4(b) EnergyPlus ELA approach underestimated HVAC-related heating use in the tighter cases and overestimated it in the leakier cases.

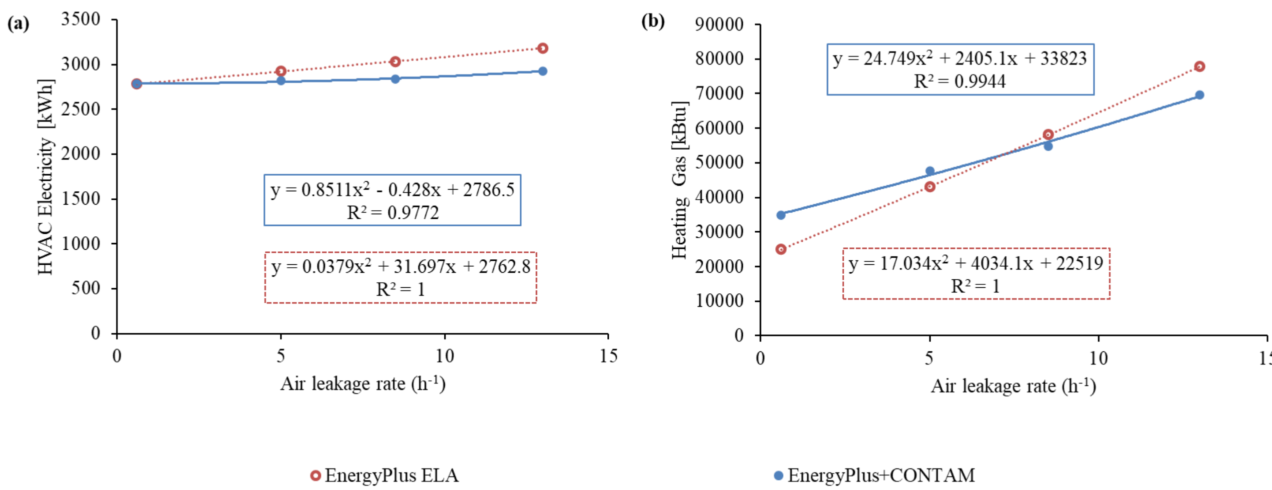

Figure 4 Comparison between energy consumption using EnergyPlus ELA and EnergyPlus+CONTAM approaches for incorporating infiltration at different air leakage rates in Baltimore, MD

2.2 Commercial Buildings:

ASHRAE 90.1 2013 prototype building models [1] were used to create a database for "Strip Mall" and "Primary School". The whole building energy simulations were done for four levels of air-tightness of the building. The leakage rate for a baseline for a 5-sided envelope building was 9 L/s/m^2 at 75 Pa following average building envelope airtightness for commercial buildings reported by Emmerich et al. [9]. When converting this leakage to a six-sided envelope leakage area by multiplying by the ratio of the five-sided to six-sided envelope area. Following the stringent target level of air-tightness in IECC 2015, another air-leakage rate of 2 L/s/m^2 at 75 Pa was used for simulation. Also, an air-leakage rate of 1.25 L/s/m^2 was used for simulation following the air-tightness required by the US Army Corps of Engineers [10]. The leakage rate for four different cases for the two commercial buildings are shown in

Table 4 Six-sided building envelope air leakage rate for four different cases for Primary School and Strip Mall

Case	Description	Air leakage rate (L/s/m^2 at 75 Pa)	
		Primary School	Strip Mall
Base	Emmerich et al. [9]	5.2	5.49
Case-1	IECC 2015	2	2
Case-2	USACE	1.25	1.25
Case-3		0.25	0.25

3. RESULTS

3.1 Residential buildings

The impact of different levels of air leakage on energy consumption related to heating, ventilating, and air conditioning (HVAC) operation (including fan use) and moisture transfer rate through the building envelope were evaluated. The results were aggregated by averaging the results from all the simulations (e.g., cities) in a single climate zone. The correlations between energy consumption and moisture transfer at different airtightness levels are provided for three different climate zones.

3.1.1 Energy consumption and savings

Annual HVAC-related electricity consumption and savings for residential buildings compared to the base case at a different level of air leakage are shown in Figure 5. The negative number on top of each bar represents the reduction in electricity consumption for that particular case compared to the base case. In climate zones (1 and 2) both the electricity consumption and savings are higher compared to other climate zones. This can be attributed to the higher electricity needed for cooling in these climate zones. The highest reduction in electricity consumption was 1117 kWh in climate zone 1A, and the highest relative savings in HVAC-related electricity consumption was 20% in climate zone 8. Both of these savings were achieved for Case-3 with an air leakage rate of 0.6 h^{-1} at 50 Pa. In climate zone 3C, an increase in HVAC-related electricity was seen from reduced infiltration, which was a 43% increase in relative terms. This could be because, in the marine climate of 3C, the temperature of the ambient air can cool the building for a majority of the time rather than adding heat to the buildings as in other climate zones. Climate zones 3A to 6A are humid climate zones and have a higher respective reduction in electricity consumption compared to their drier counterparts (e.g., climate zones 3B to 6B). Climate zones 7 and 8, which are very cold and sub-arctic climate zones, have higher electricity savings compared to climate zones 4 to 6, mostly due to the reduction in energy consumed by fans to provide heating.

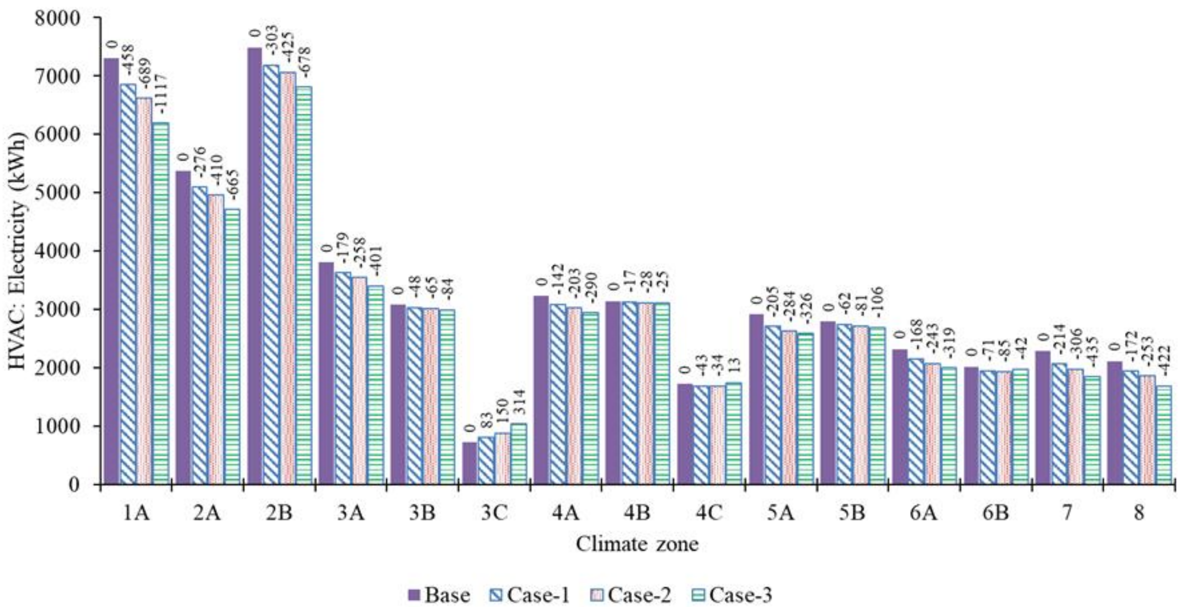

Figure 5 HVAC-related electricity consumption at four levels of air leakage for residential buildings (savings compared to the base case indicated by numbers above each bar).

Annual HVAC-related gas consumption and gas savings compared to the base case are shown in Figure 6. Higher consumption and reduction of natural gas were observed in colder climate zones compared to hotter climate zones. Higher consumption and reduction in natural gas consumption were observed in humid climate zones (2A to 6A) compared to their dry counterparts (2B to 6B). The reduction of natural gas consumption from increasing the airtightness to Case-3 was more than 40% for most of the climate zones compared to the base case. The highest relative savings was 60% in climate zone 3C and the highest absolute savings was 86697 kBtu in climate zone 8.

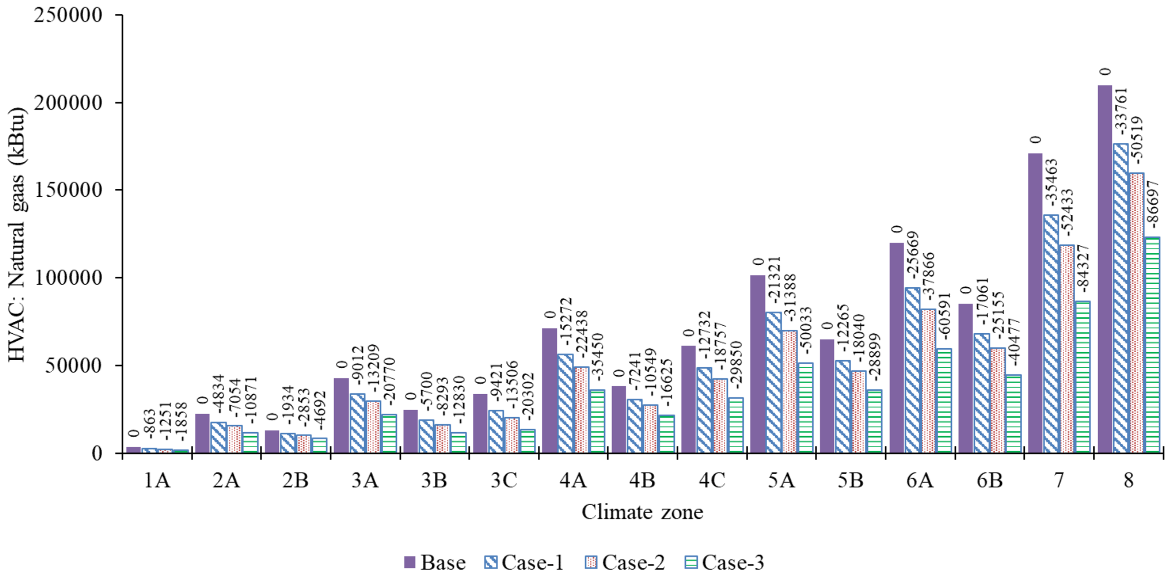

Figure 6 HVAC-related natural gas consumption at four levels of air leakage for residential buildings (savings compared to the Base case indicated by numbers above each bar).

3.1.2 Moisture transfer

Moisture transfer was calculated by multiplying the hourly infiltration by the outdoor air humidity ratio for each hour. Then, the hourly moisture transfer was summed up for a whole year to get the annual moisture transfer through the building envelope. The amount of moisture transfer for residential buildings at different leakage rates along with the reduction compared to the base case (denoted by a negative number) is shown in Figure 7. This represents the moisture transfer per unit of the 6-sided surface area of the building's conditioned space. The moisture transfer was generally higher in warmer climates compared to colder climates and in humid climate zones (2A to 6A) compared to their dry counterparts (2B to 6B). The reduction in moisture transfer was in the range of 5.1 lb/ft^2/year to 24.3 lb/ft^2/year by increasing air-tightness from Base to Case-3. In relative terms, Case-3 resulted in the moisture transfer from infiltration being reduced by 70% or more in every climate zone compared to the Base case.

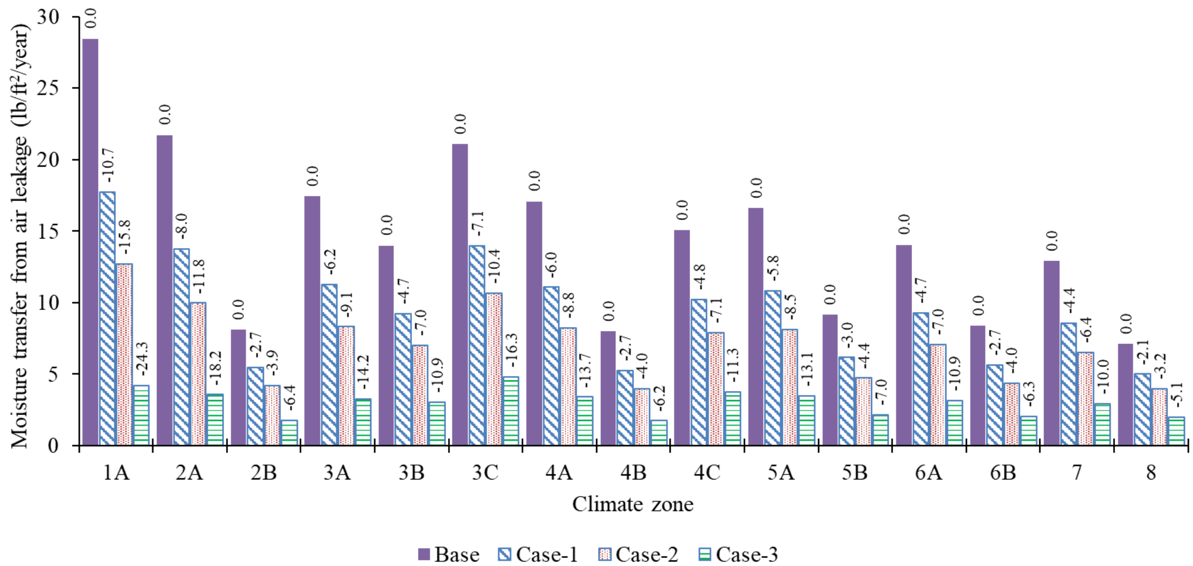

Figure 7 Moisture transfer from building envelope at four levels of air leakage for residential building (reduction compared to the Base case indicated by numbers above each bar).

3.1.3 Correlation of HVAC-related energy use and moisture transfer with infiltration

The results for the energy consumption and moisture transfer were used to obtain quadratic regression coefficients using least squares estimation in the form $y = C_2x^2+C_1x+C_0$, where, C_2 is the quadratic coefficient, C_1 is the linear coefficient and C_0 is the constant term. Although the relationship between the leakage rate and dependent variables could potentially be captured using linear regression, a quadratic regression was used to be consistent with the methods used for commercial buildings [3,4]. The leakage rate was the independent variable and electricity consumption, natural gas consumption and moisture transfer rate respectively were the dependent variables. Figure 8 shows an example of the relationship between the dependent and independent variables for three locations: Miami (FL), Baltimore (MD), and Minneapolis (MN) located in climate zones 1A, 4A, and 6A, respectively. The figure shows that the coefficient of determination (R2) is greater than 0.97 for all the cases tested.

Figure 8 shows that a higher impact on electricity consumption is seen in Miami compared to Baltimore and Minneapolis from the same change in air leakage rate. In case of natural gas consumption, the impact of airtightness was highest in Minneapolis and lowest in Miami. The reduction in infiltration from 13 h^{-1} to 0.6 h^{-1} at 50 Pa resulted in a reduction in electricity consumption by 1117 kWh in Miami, 144 kWh in Baltimore, and 539 kWh in Minnesota. Similarly, a reduction in infiltration from 13 h^{-1} to 0.6 h^{-1} at 50 Pa resulted in a reduction of HVAC-related natural consumption by 1857 kBtu in Miami, 34718 kBtu in Baltimore, and 60650 kBtu in Minneapolis.

Miami had the highest change in moisture transfer, for the same change in the air leakage rate in all three cities. The reduction in infiltration from 13 h^{-1} to 0.6 h^{-1} at 50 Pa resulted in a reduction of related moisture transfer rate by 24.2 lb/ft^2/year in Miami, 11.9 lb/ft^2/year in Baltimore, and 12.3 lb/ft^2/year in Minnesota. The regression equations for the 57 locations are used in the online calculator to estimate the energy consumption and moisture transfer for a building at a user-specified airtightness level that is not any of the values used for the simulation.

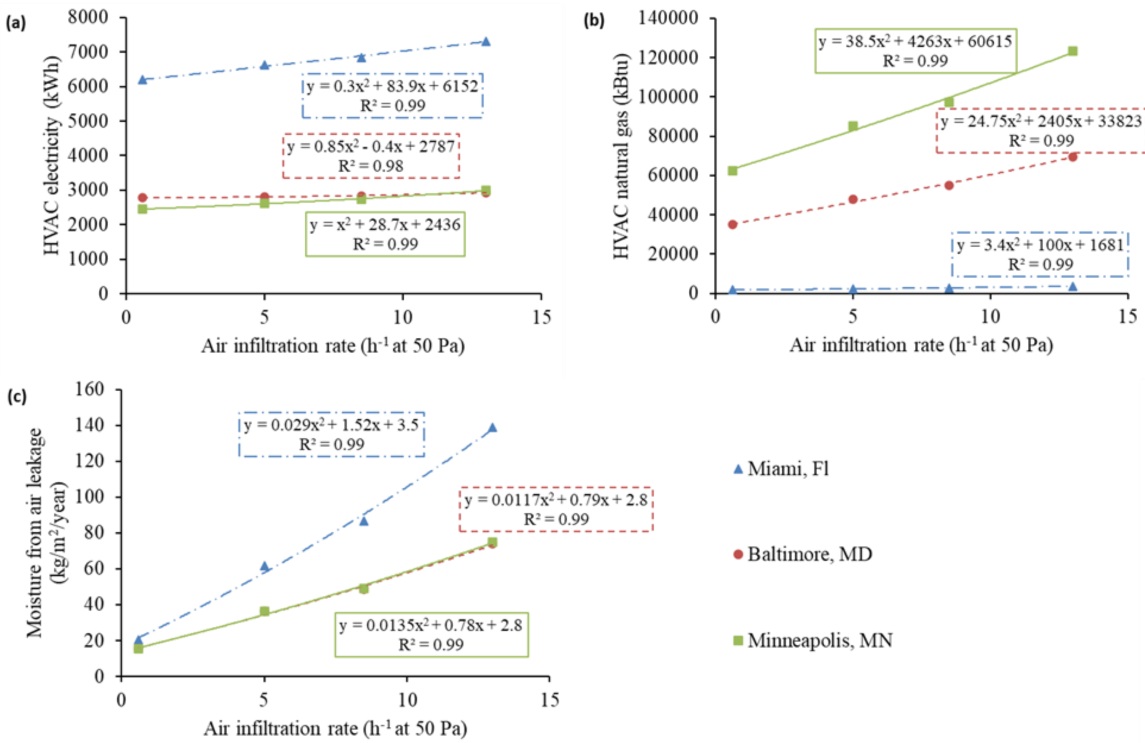

Figure 8 Quadratic regression with infiltration rate as dependent variable (a) HVAC electricity consumption (b) HVAC natural gas consumption (c) Moisture transfer from air leakage

3.2 Commercial Buildings

In commercial buildings, similar to residential buildings, the results for energy consumption/savings and moisture transfer/reduction were presented by aggregating the results in climate zone level i.e. averaging results for all the cities in that climate zone.

3.2.1 Energy consumption/savings

3.2.1.1 <u>Primary School</u>

HVAC-related electricity consumption and savings for primary school from increasing the air-tightness compared to the Base case are shown in Figure 9. In primary school, the highest absolute HVAC electricity savings of 74251 kWh was obtained in climate zone 6A for Case-3 compared to Base. In climate zone 4B and 4C, there was an increase in the HVAC electricity consumption from increasing air tightness. In relative terms, the highest energy savings was 27.5 % at climate zone 6A. The electricity savings was higher in some of the cold climate zones like 5A, 6A, 7, and 8 compared to other locations unlike in residential buildings where higher electricity reduction was achieved in climate zone 1A, 2A, and 2B compared to other locations.

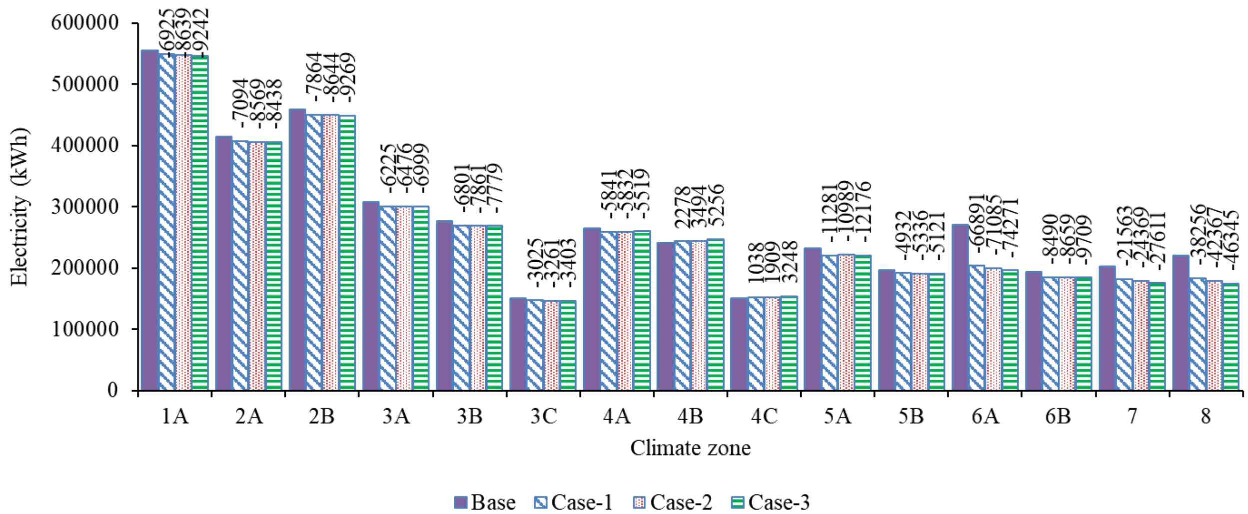

Figure 9 HVAC-related electricity consumption at four levels of air leakage for primary school (savings compared to the Base case indicated by numbers above each bar).

HVAC-related natural gas consumption and savings for primary school from increasing the air-tightness compared to the Base case are shown in Figure 10. The natural gas savings was in the range of 3 MMBtu to 2019 MMBtu with higher savings in colder climates. In all the climate zones, the increase in air-tightness increased the natural gas consumption. In relative terms, energy savings were in the range of 42% in climate zone 3C up to 73% in climate zone 6A for Case-3 compared to Base.

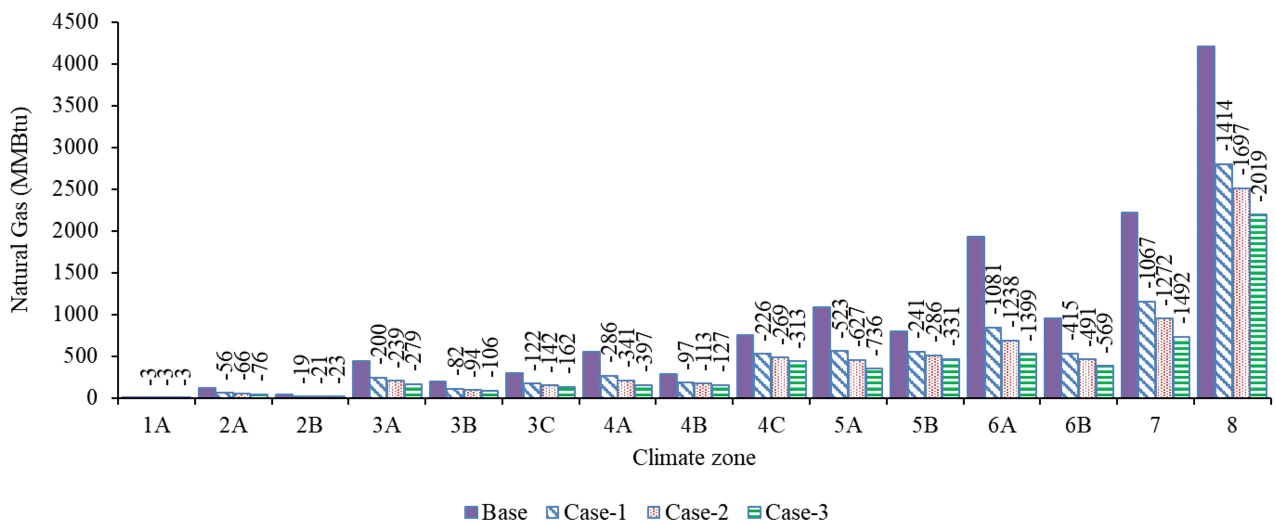

Figure 10 HVAC-related natural gas consumption at four levels of air leakage for primary school (savings compared to the Base case indicated by numbers above each bar).

3.2.1.2 Strip Mall

HVAC-related electricity consumption and savings for strip mall from increasing the air-tightness compared to the Base case is shown in Figure 11. In strip highest energy savings were achieved at climate zone 1A followed by 6A. In climate zones, 3B, 3C, 4B, 4C, 5B, and 6B increase in energy savings was present instead of energy savings.

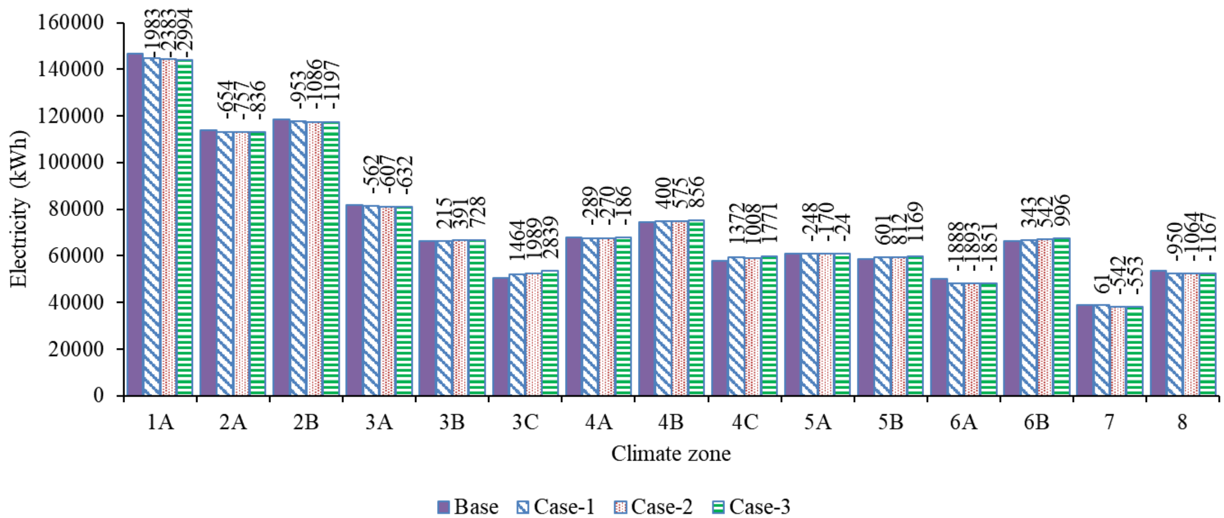

Figure 11 HVAC-related electricity consumption at four levels of air leakage for strip mall (savings compared to the Base case indicated by numbers above each bar).

HVAC-related natural gas consumption and savings for strip mall from increasing the air-tightness compared to the Base case is shown in Figure 12. Natural gas savings was in the range of 1 MMBtu up to 656 MMBtu. The natural gas savings were higher in colder climate zones compared to hotter climate zones. Also, higher natural gas savings were obtained in humid regions (A's) compared to dry climate zones (B's).

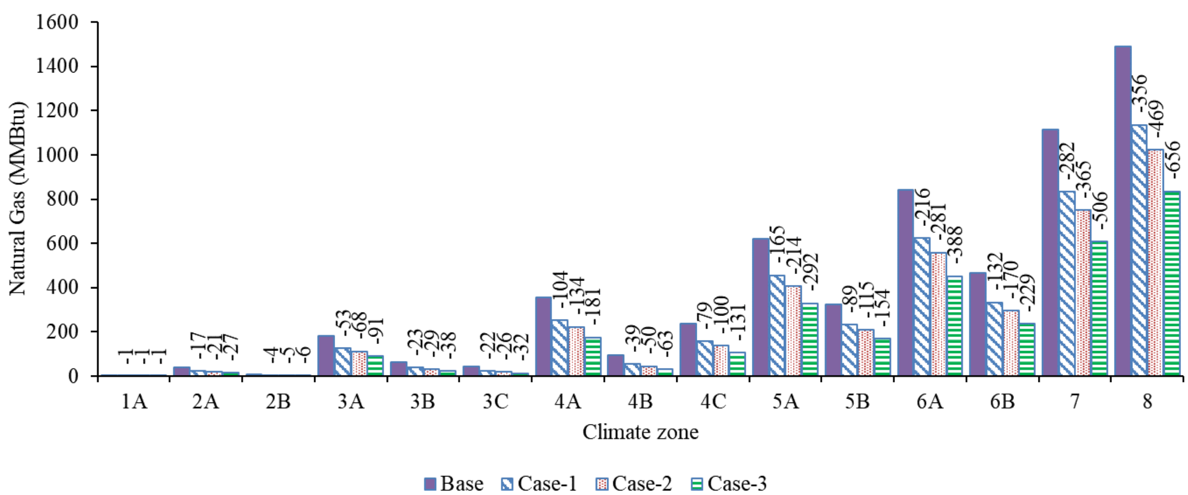

Figure 12 HVAC-related natural gas consumption at four levels of air leakage for strip mall (savings compared to the Base case indicated by numbers above each bar).

3.2.2 Moisture transfer/reduction

The amount of moisture transfer for primary school and strip mall at different leakage rates along with the reduction compared to the base case (denoted by a negative number) is shown in Figure 13 and Figure 14 respectively. The moisture transfer reduction is generally higher in hotter climate zones compared to colder climate zones for both primary school and strip mall. Similarly, moisture transfer in humid climate zones is higher compared to dry climate zones. From Case-3 in primary school, the moisture transfer per envelope area was reduced from 2.9 $lb/ft^2/year$ to 11.1 $lb/ft^2/year$ compared to the Base case. This result was similar for the strip mall where the moisture reduction for Case-3 was in the range of 2.7 $lb/ft^2/year$ to 11.3 $lb/ft^2/year$ compared to the Base case.

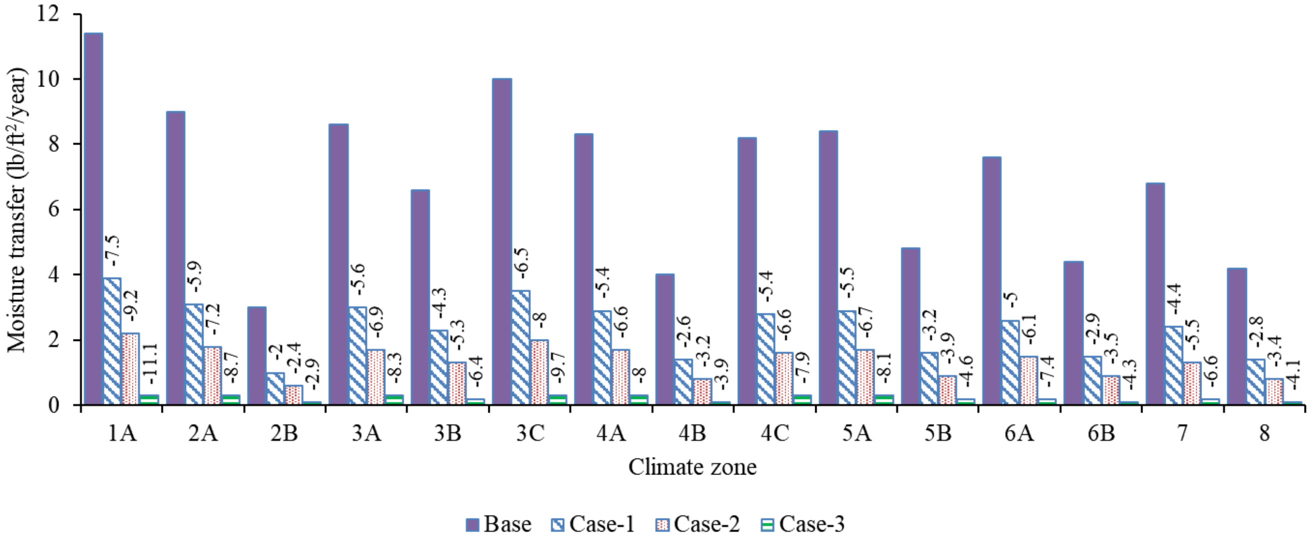

Figure 13 Moisture transfer from building envelope at four levels of air leakage for primary school (reduction compared to the Base case indicated by numbers above each bar).

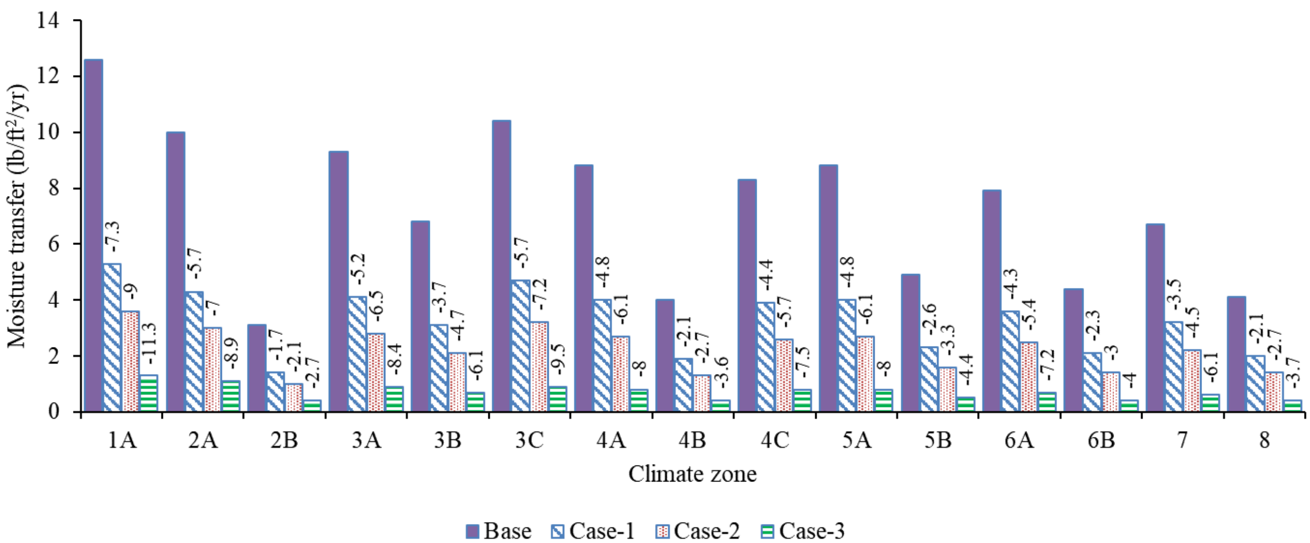

Figure 14 Moisture transfer from building envelope at four levels of air leakage for strip mall (reduction compared to the Base case indicated by numbers above each bar).

4. CONCLUSIONS

In 2016-17, ORNL, NIST, ABAA, and CERC-BEE collaborated and developed a user-friendly online air leakage calculator that is free to the public. In this work, databases for two commercial buildings and a residential building were added to the online calculator. The simulations for commercial buildings were done for four leakage rates 9 L/s/m^2 converted to a six-sided envelope leakage rate, 2 L/s/m^2,1.25 L/s/m^{2,} and 0.25 L/s/m^2 at 75 Pa. For residential buildings simulations were performed at four different air leakage rates which correspond to air changes per hour of 13 h^{-1}, 8.5 h^{-1}, 5 h$^{-1,}$ and 0.6 h^{-1} at 50 Pa. The overall site energy savings potential of air barriers was found to be higher in colder climates for both commercial and residential buildings. The higher energy savings was from a reduction in the usage of natural gas required for heating in colder climates. The reduction in absolute moisture transfer was highest in warmer climates compared to colder climates. The correlation between the energy/moisture transfer with the air leakage rate was used by the calculator to determine energy consumption and moisture transfer for user-defined air leakage rates. The calculator is a powerful and easy-to-use tool that designers, and those developing codes and standards, could utilize to estimate the energy and cost savings that could be achieved by reducing air leakage in buildings. The availability of this tool also allows marketers of air barrier systems to demonstrate the benefits of their products to prospective purchasers.

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