Online Calculator to Evaluate the Impact of Airtightness on Residential Building Energy Consumption and Moisture Transfer

ABSTRACT

Energy consumption in residential buildings is primarily driven by space conditioning applications. Space heating and cooling, on average, consume approximately 50% of the energy in the residential buildings in the U.S. The primary energy use due to infiltration is more than 2.8 Quads (2.95 EJ), which is 29% of primary energy consumption attributable to fenestration and building envelope components in residential buildings in US in 2010. There are advanced air barrier technologies and construction practices to reduce air leakage in buildings, which are currently available in the market. However, the lack of adequate information on their impact on energy consumption and the durability of buildings has caused the slow adoption of these technologies and construction practices. In the past, the authors developed an online calculator that estimates the potential energy and cost savings in major U.S., Canadian and Chinese cities from improvement in airtightness in commercial buildings. The calculator is being expanded by adding residential and additional commercial building data. In this paper, we present the impact of airtightness in residential buildings on energy consumption and moisture transfer. The study includes the analysis of airtightness in 52 major cities in the U.S. and 5 cities in Canada on a residential building that includes a crawlspace and has a gas furnace. The results of impact of infiltration on energy consumption and moisture transfer is provided. In addition, example of the regression coefficients calculated from these results are provided which were used in the air-infiltration calculation tool. By decreasing the air leakage rate of the building such from 13 h^{-1} to 0.6 h^{-1} at 50 Pa (0.00725 psi), the reduction in electricity consumption was up to 9% for climate zone 8 and the reduction in natural gas consumption for space heating was more than 40% for a majority of the climate zones . The moisture transfer due to infiltration was also reduced by at least 70% in all the climate zones when reducing the air leakage rate from 13 h^{-1} to 0.6 h^{-1} at 50 Pa (0.00725 psi).

INTRODUCTION

Infiltration is one of the primary causes of heating and cooling energy demand in buildings, resulting in 2.95 EJ (2.8 Quads) of primary energy consumption in residential buildings (U.S. Department of Energy 2014). However, improving air tightness of the buildings is often overlooked. Khemet and Richman analyzed a database of nearly 900,000 single family Canadian homes where they found 72% of homes had air leakage rates greater than or equal to 4 air changes per hour (h^{-1}) at 50 Pa (Khemet and Richman 2018). A study shows that 25% reduction in air leakage in the U.S. single-family housing stock can achieve annual electricity savings of 9 TWh (30.7 TBtu) (Wilson et al. 2017). One of the reasons for less attention to air tightness is the lack of awareness of the impacts of infiltration on building energy use and durability. Thus, a framework to easily evaluate the energy and cost savings potential of air barriers is crucial to increase the penetration of air barriers and improve the building air tightness.

Belleudy et al. investigated the impact of air leakage on the hygrothermal field in the ceiling section insulated with blown-in cellulose, which separated the attic from heated indoor space (Belleudy et al. 2015). The results from the study showed that even relatively small airflow through the construction elements has significant impact on hygrothermal fields within the building envelope. In the study, it is also stated that the air leakage has become one of the considerable challenges for creating low-energy and durable buildings. Similarly, air leakage was identified as a major cause for condensation problems in lightweight roof systems in cold climates (Janssens and Hens 2003). A study of wall retrofits with materials of different air/vapor permeance revealed that the permeance of the material impacted the moisture content of air at interstitial layers in the assembly (Armstrong et al. 2010). A simulation study of buildings in north China showed 12.6 % reduction in district heating energy by reducing the air leaking from 0.98 h^{-1} to 0.5 h^{-1} at 50 Pa (0.00725 psi) (Chen et al. 2012). However, energy simulation software used for whole building energy simulations has limited capabilities for infiltration calculation and rely on empirical equations that are not applicable to all building types and ventilation systems (Ng and Persily 2011). A study of air infiltration through building entrances showed that CONTAM (Dols and Polidoro 2020), which is an airflow and contaminant simulation tool, provides physics-based airflow results for energy reductions compared to the EnergyPlus infiltration model (Goubran et al. 2017).

Oak Ridge National Laboratory (ORNL), National Institute of Standards and Technology (NIST), Air Barrier Association of America (ABAA) and the US-China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE) collaborated to develop a free online calculator in 2016 (Shrestha et al. 2016). The tool utilized the simulation results of the building energy simulation tool EnergyPlus (DOE 2020) and the airflow simulation tool CONTAM to develop a simple calculator for the impact of air tightness on energy and hygrothermal effects. CONTAM is a multizone indoor air quality and ventilation analysis computer program than can calculate infiltration, exfiltration and room-to-room airflows in building systems due to temperature difference, wind pressure or building mechanical systems. The moisture transfer calculation was added to the calculator in 2019 (Shrestha et al. 2019). The calculator can be used for seven different types of commercial buildings. This paper describes the extension of the infiltration tool to residential buildings. Whole-building energy simulation software like EnergyPlus generally use effective leakage area (ELA) for residential building infiltration calculation. The method using ELA was developed using studies of low-rise residential buildings. Values for stack and wind coefficients in the ELA approach are available for buildings up to and including three stories (ASHRAE 2021). However, as this study will show, use of the ELA approach is often limited to the home types included in the original study (Sherman and Grimsrud 1980) . This results in higher uncertainty in capturing the impact of air tightness of buildings in terms of building energy consumption. Hence, we utilize CONTAM to create an annual schedule of hourly infiltration rates normalized by exterior surface area. This was the same approach for calculating infiltration for the commercial buildings in the infiltration tool. While residential infiltration has been studied by the authors (Nabinger, Nabinger, and Persily 2008; Persily, Musser, and Emmerich 2010) , this study extends the work to include energy simulations and quantification of moisture transfer. This tool was developed to benefit the design and construction industry by providing evidence of energy and cost savings from the reduction in air leakage in buildings. The main contribution of this work is that it will enable the building owners and the building construction industry to estimate the energy and moisture impact of different air tightness levels compared to a baseline in residential buildings.

METHODOLOGY

The International Energy Conservation Code (IECC) 2012 prototype residential buildings (DOE 2019) with a gas furnace heating system and crawlspace foundation were used for EnergyPlus simulations (a CONTAM version of this building was also created). The properties of the prototype residential building used for this study is 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 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. Simulations were performed for 57 locations throughout ASHRAE climate zones 1A through 8. For each location, the prototype building model corresponding to the climate zone of the location was selected (https://www.energycodes.gov/prototype-building-models). A Typical Meteorological Year 3 (TMY3) file was used as the weather data input (Wilcox and Marion 2008).

Table 1 Building characteristics of prototype building

Characteristics	Description
Total building floor area	441.6 m^2 (4753.3 ft^2)
Conditioned floor area	220.8 m^2 (2376.6 ft^2)
Gross window area	33.0 m^2 (355.2 ft^2)
6-sided envelope area of conditioned space	441 m^2 (4747 ft^2)
Cooling System	Central cooling with COP of approximately4 across the climate zones studied
Heating System	Natural gas furnace with efficiency of 0.8
Wall thermal resistance	In accordance with IECC 2012 (varies by climate zone)
Window U-value and Solar heat gain coefficient	In accordance with IECC 2012 (varies by climate zone)

In the prototype EnergyPlus building model, the "ZoneInfiltration:EffectiveLeakageArea" object was used to model the infiltration. A comparison of energy results obtained using this ELA approach and that using a CONTAM-generated schedule of infiltration rates is provided in results section. This schedule was input into the "ZoneInfiltration:DesignFlowRate" object in EnergyPlus as the infiltration rate.

The schedule file exported from CONTAM results is a 15-minute interval schedule of air leakage per unit exterior surface area for the whole building. In this study, we considered four levels of air tightness listed in Table 2 with the corresponding h^{-1} at 50 Pa (0.00725 psi) . Exhaust-only ventilation would depressurize the building and be the driving force for infiltration rates. The resulting infiltration would not be dependent on envelope airtightness or weather. Therefore, a balanced HVAC system that delivered outdoor air was modeled in CONTAM so that infiltration would be dependent on building airtightness and weather, as intended.

Table 2 Four level of air tightness used for airflow and energy simulation of residential building

Case	Description	Air tightness L/s-m^2 (CFM/ft^2) at 75 Pa (0.0108 psi)	h^{-1} at 50 Pa (0.00725 psi)
Base	Without air barrier	7.4 (1.46)	13
Case-1	IECC 2012 minimum airtightness for climate zone 1-2	4.9 (0.96)	8.5
Case-2	IECC 2012 minimum airtightness for other climate zones (except 1 and 2)	2.8 (0.55)	5
Case-3	Passive house (Passive House Institute US 2019)	0.4 (0.08)	0.6

RESULTS

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 correlation between energy consumption and moisture transfer at different air tightness levels are provided for three different climate zones. Finally, a comparison is made between the energy consumption calculated using CONTAM results and results using the ELA approach in EnergyPlus.

Energy consumption

Figure 1 shows the results for HVAC-related electricity consumption and energy savings from reduction of air leakage compared to the base case. The negative number on top of each bar represents the reduction in electricity consumption for that particular case compared to base case. Both electricity consumption and savings are higher in hotter climate zones (1 and 2). This is because the heating is provided by natural gas, thus, the electricity consumption for HVAC is higher where more cooling is needed. If electricity were used for space heating, the electricity consumption would have been higher in locations where more heating is needed. The highest reduction in electricity consumption was 1117 kWh (3808 kBtu) in climate zone 1A for Case-3. The highest percentage reduction in HVAC-related electricity consumption was 20%, observed in climate zone 8 for

Case-3. In climate zone 3C an increase in HVAC-related electricity was seen from reduced infiltration which was 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 majority of the time rather than adding heat to the buildings in other climate zone. Climate zones 3A, 4A, 5A and 6A are humid climate zones and have higher respective reduction in electricity consumption compared to their drier counterparts (e.g., climate zone 3B, 4B, 5B and 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.

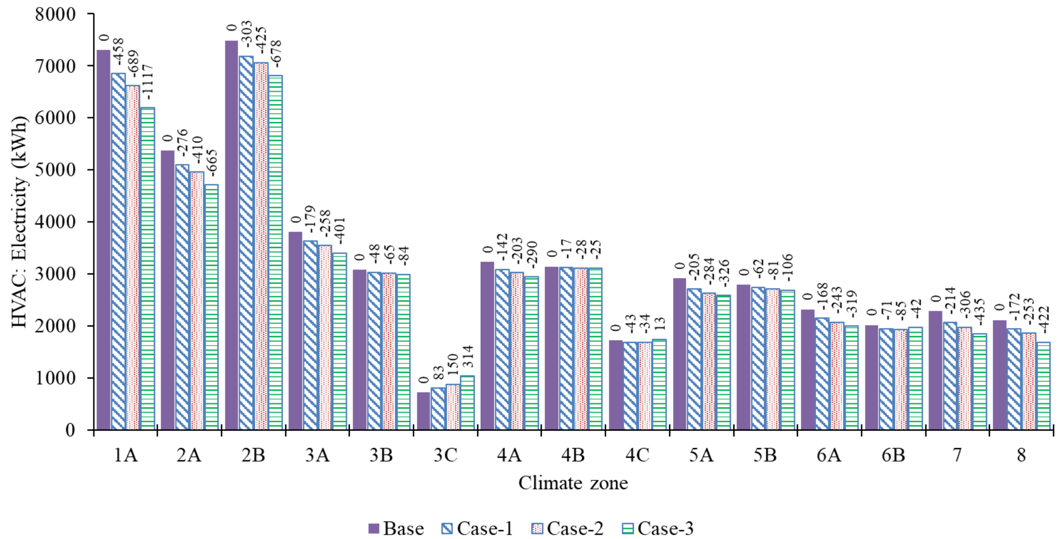

Figure 1 Electricity consumption and savings for HVAC-related electricity use at four levels of air leakage compared to the base case

Figure 2 shows the results for HVAC-related gas consumption and gas savings from reduction of air leakage compared to the base case.

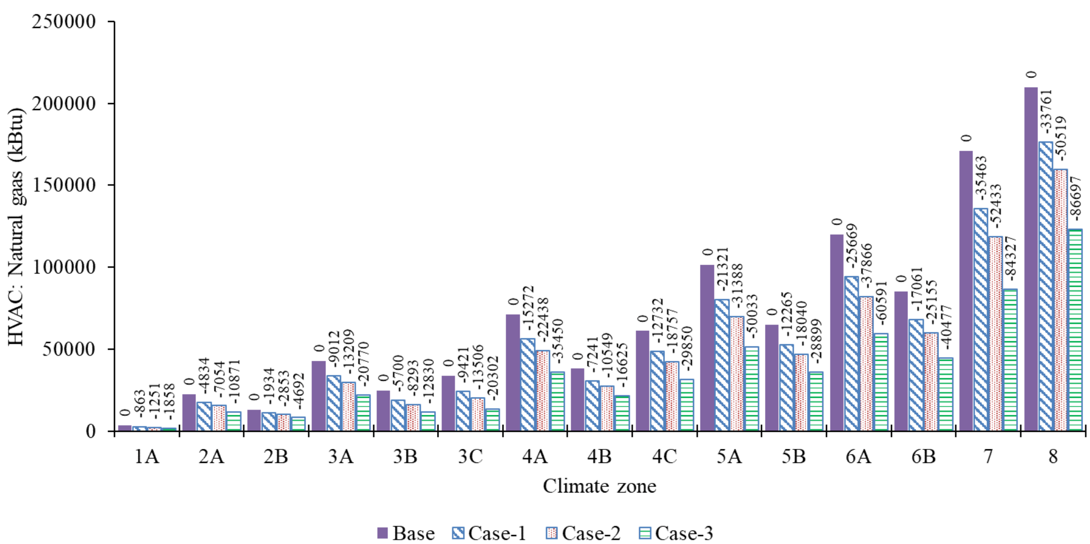

Figure 2 Natural gas consumption and savings for HVAC-related gas use at four levels of air leakage compared to the base case

In Figure 2, higher consumption, and also greater reduction of natural gas for heating is observed in colder climate as expected. The reduction of natural gas consumption from increasing the air tightness (Case-3) was more than 40% for a majority 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 (25408 kWh) in climate zone 8. In terms of site HVAC-related energy consumption, the reduction is higher in colder climates compared to the warmer climates when both heating and cooling are considered.

Moisture transfer

Hourly transfer of water vapor was calculated by multiplying the mass of hourly infiltration by the outdoor air humidity ratio during that hour. The hourly transfer of water vapor was summed up for the whole year to get the theoretical annual rate of water vapor transferred into the building. Figure 3 shows the results for the moisture transfer through the building envelope from infiltration at different leakage rates. The moisture transfer is expressed in terms of moisture transfer per unit of 6-sided envelope area of the conditioned space of the building. The moisture transfer from infiltration is generally higher in warmer climates since these climates are also more humid compared to the colder climates. Case-3 resulted in the moisture transfer from infiltration being reduced by 70% or more in every climate zone. The percentage reduction in moisture transfer is slightly higher in humid climate zones (A's) compared to dry or marine climate zones. In absolute terms, the reduction in moisture transfer is also highest in the warmer climate zones.

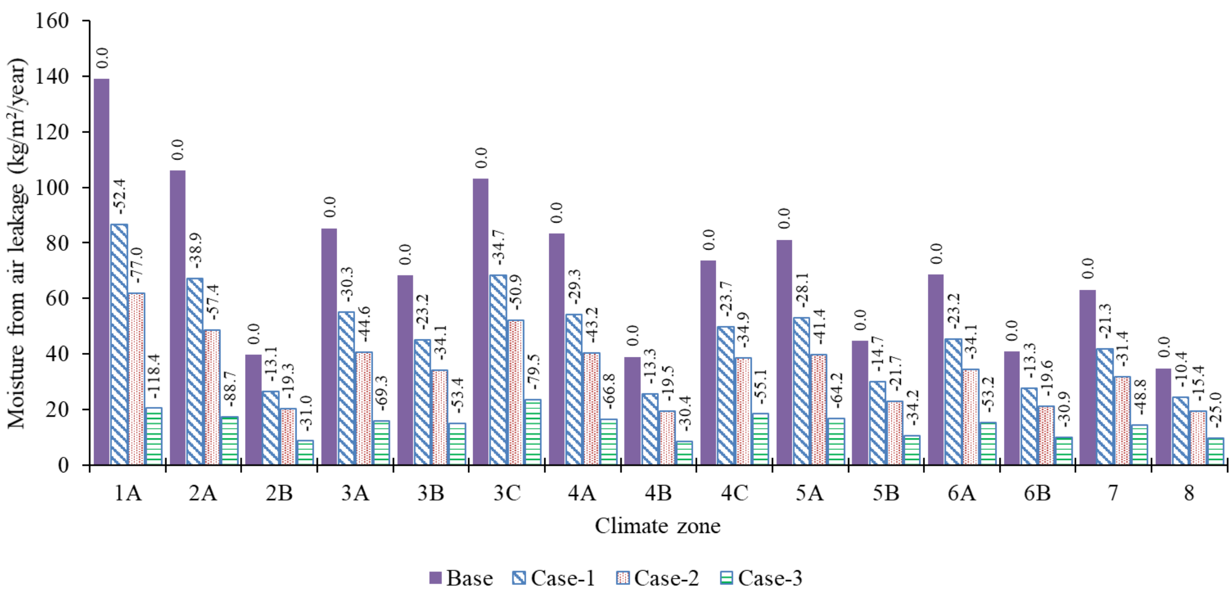

Figure 3 Moisture transfer per unit envelope area from infiltration at four levels of air leakage and reduction in moisture transfer compared to the base case

Correlation of HVAC-related energy usage 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 the commercial buildings in the online calculator in previous work done by authors (Shrestha et al. 2016; 2019). The leakage rate was the independent variable and electricity consumption, natural gas consumption and moisture transfer rate respectively were the dependent variables. Figure 4 shows an example of the relationship between the dependent and independent variable for three locations: Miami

(FL), Baltimore (MD) and Minneapolis (MN) which are located in climate zones 1A, 4A and 6A, respectively. The figure shows that the coefficient of determination (R^2) is greater than 0.97 for all of the cases tested. 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 air tightness level that is not any of the values in Table 1.

The figure shows that for electricity consumption C_1 is very high compared to compared to C_2 in Miami and Minneapolis. $C_1$is very high for Miami (i.e., there is higher increase in HVAC-related electricity consumption at Miami when infiltration increases by same amount in Baltimore and Minneapolis). For the HVAC-related natural gas consumption both C_2 and C_1 were high for Minneapolis (38.5 and 4263 respectively), while it was lower for Miami (3.4 and 100 respectively). These coefficients indicate that the heating gas consumption increases significantly in Minneapolis with increase in infiltration. Thus, the air tightness has higher impact on cooling energy consumption in a hot climate and comparatively lower impact for mild/cold climates. In case of heating energy demand, the impact of air tightness is very high in a cold/mild climate, with negligible impact in a hot climate.

Miami also had the highest C_2 and C_1 terms for moisture transfer among the three cities. The C_2 and C_1 terms for moisture transfer in Miami (0.029 and 1.52 respectively) were approximately twice the value for both Baltimore (0.0117 and 0.79 respectively) and Minneapolis (0.0135 and 0.78 respectively). Thus, it could be concluded the impact of infiltration on moisture transfer is similar in cold and mild climates and higher in warmer climates.

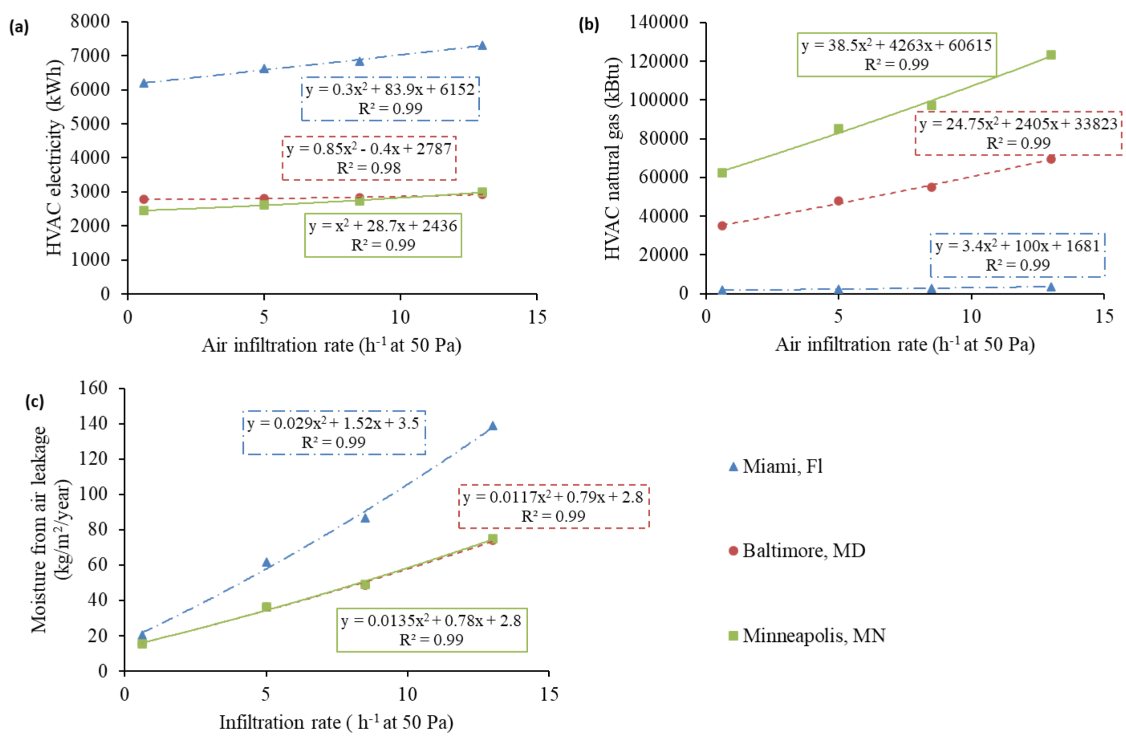

Figure 4 Quadratic regression with infiltration rate as dependent variable (a) HVAC electricity consumption (b) HVAC natural gas consumption (c) Moisture transfer from air leakage

EnergyPlus ELA approach vs CONTAM

The air leakage rates in Table 1 were converted to ELA (Equation (1) (Chan, Joh, and Sherman 2013)) to use with the ELA approach in EnergyPlus for infiltration (e.g., "EnergyPlus ELA" approach). The energy results were then compared with the results presented above using CONTAM generated infiltration rates in EnergyPlus (e.g., "EnergyPlus+CONTAM" approach).

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

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 1, 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 1 were respectively 60, 503, 855 and 1307 cm^2. Figure 5 shows the HVAC-related electricity and natural gas consumption at different air leakage rates for the two approaches for incorporating infiltration in EnergyPlus. The differences between the two approaches are shown graphically in Figure 5 for Baltimore only. The comparison of the two approaches is not shown for Miami and Minneapolis because they are similar to Baltimore. Figure 5a shows that the EnergyPlus ELA approach results in increasingly higher electricity consumption as the air leakage increases. This was also found for the commercial buildings (Shrestha et al. 2016). Figure 5b shows that the HVAC-related natural gas consumption using the EnergyPlus ELA approach is lower than the EnergyPlus+CONTAM approach at the lowest air leakage rates simulated but then higher at the higher air leakage rates. These results may indicate that the EnergyPlus ELA approach may be reasonable for buildings with lower air leakage rates but may be overestimating energy use for leakier buildings.

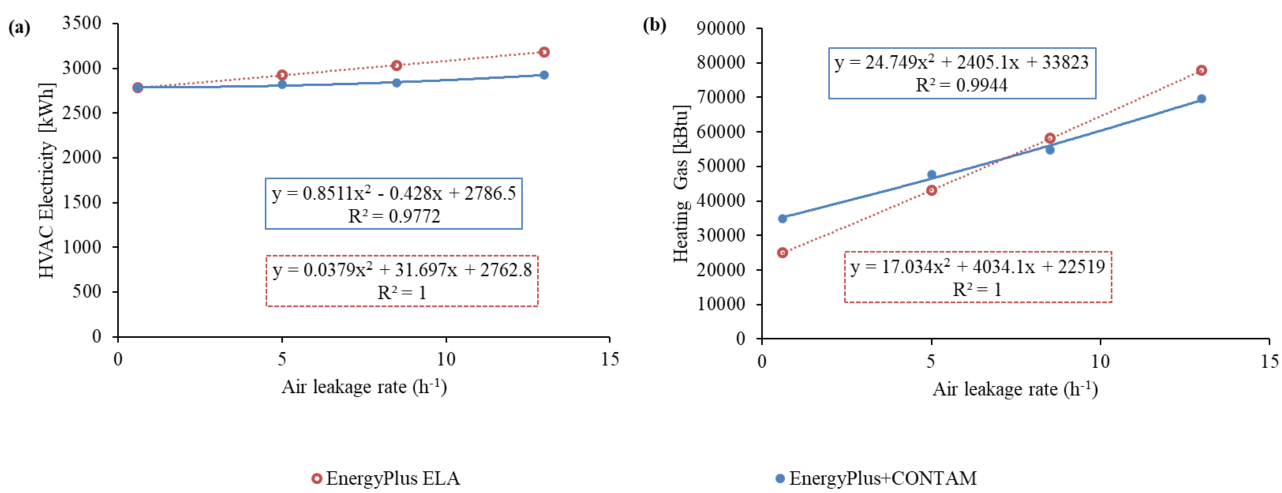

Figure 5 Comparison between energy consumption using EnergyPlus ELA and EnergyPlus+CONTAM approaches for incorporating infiltration at different air leakage rates in Baltimore, MD

CONCLUSION

Results from a residential building were added to the online calculator developed by the authors to evaluate the impact of air tightness on a home's energy consumption and moisture transfer. Results are included at four different air leakage rates which corresponds to air changes per hour of 13 h^{-1}, 8.5 h^{-1}, 5 h^{-1} and 0.6 h^{-1} at 50 Pa (0.00725 psi). This paper discussed the simulations and how the results were incorporated into the calculator. This paper also discussed the impact of infiltration on energy consumption and moisture transfer in different climate zones. The overall energy savings potential of air barriers was found to be highest in colder climates. The relative reduction in moisture transfer due to airtightening was more than 70% in all climate zones. The reduction in absolute moisture transfer was highest in the warmer climates due to these climates also being more humid. The energy results were also correlated to air leakage rate in order to provide the calculator a way 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 contractors can utilize to estimate the energy and cost savings that could be achieved by reducing the air leakage.

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