Memo to:

Prepared by: Kara Fedors, Chad Telarico, C.D. Nayak, Chris Williams, Clare Fitzgerald, DNV

Massachusetts Program Administrators Research Team and Energy Efficiency Advisory Council EM&V Consultants

Copied to:
Wendy Todd, Sue Haselhorst, DNV

Date: April 19, 2021

MA20C17-G-INFIL: Air Infiltration Savings Calculator Review Final Memo

1 INTRODUCTION

The Massachusetts Program Administrators (PAs) currently incentivize new construction commercial buildings for energy efficiency improvements beyond the prevailing energy code, such as high-efficiency mechanical equipment and systems, their controls, building envelopes, and lighting. However, as the building systems efficiency requirements get tighter each code cycle, the savings opportunities for PA-sponsored energy efficiency measures diminish.

One savings opportunity that has gone largely untapped in current offerings is improvement in building infiltration load reduction which can reduce natural gas consumption for commercial buildings in the Mass Save program. This is because the current new construction incentive does not have a defined approach for estimating infiltration savings, and one of the major reasons is due to limitations of the building simulation software (eQuest) commonly used for new construction projects savings estimates. eQuest underestimates the commercial building infiltration loads and its impact on building cooling and heating loads as the infiltration algorithm used in eQuest was originally developed for low-rise residential buildings. However, various research in past years, including that conducted by the National Institute of Standards and Technology (NIST) have proposed corrective modeling approaches that can reduce the limitation of the current building simulation software, such as EnergyPlus and eQuest using DOE-2 engine. The modifications suggested by NIST on DOE-2 based simulation software appropriately account for the weather induced infiltration by revising the underlying infiltration algorithm used in DOE-2 engine. The PAs have identified a new vendor (VEIC) that has a tool that can run large numbers of building simulation models consistent with NIST suggested modifications and generate a simple spreadsheet analysis model for PAs. The VEIC tool presented to the Mass Save PAs is an in-house tool that incorporates NIST suggested changes to DOE-2 based on a large set of building simulation outputs. This spreadsheet analysis can be tailored to use different building characteristics, such as floor area, number of floors, and building type. The spreadsheet can be used to estimate the infiltration measure savings and its features can be modified as the program needs change.

Through a series of working group meetings consisting of members of DNV; the MA PAs, including implementers; and the Energy Efficiency Advisory Council (EEAC), the team shared key insights gathered from their research and discussed the viability of the infiltration tool and path forward. This memo is the final deliverable for the Air Infiltration Savings study and includes a summary of key steps, results, and recommendations for further exploration.

2 WORKING GROUP MEETINGS

Feedback from the draft Stage 3 work plan led to the decision to form a collaborative working group to discuss questions and concerns stemming from the proposed validation and measurement of the air infiltration tool. The team broke the working group sessions into four areas of focus, with key go/no-go decisions made at the close of two of the discussions.

2.1 First Working Group: Implementer proposal, background research, go/no-go decision

This first working group session was held on 12/4/20 and was used to understand how the air infiltration measure would be implemented and tested. The team presented on existing background research, which included:

- An overview of the new construction program and lack of an incentive for building air tightness or reduced air infiltration rate
- Discussion around the preferred simulation tool used by the MA PAs(eQuest) and its inability to estimate air infiltration savings for mechanically ventilated commercial and high-rise buildings
- A review of NIST model simulation tools using the EnergyPlus (EP) simulation engine along with OpenStudio (OS) and how these model outputs were analyzed to transform the results into an easy-to-use Excel-based regression modeling tool developed by a third-party vendor

The PA implementers who originally expressed interest in this review provided additional information as to what they foresaw as future program requirements, including:

- The PAs would not be involved with the architect or building design for this proposed program
- The PAs confirmed they would use an independent third-party to conduct building pressurization testing as part of this proposed program to confirm enhanced air infiltration savings
- The PAs need additional information to determine whether the measure is cost effective
- Measurement would be conducted by the PAs during construction, and the reports would be shared with the third-party evaluator after the fact. The baseline that will be used to compare savings against will be building code to be consistent with the NIST tool.

The EEAC has a strong interest in exploring the potential for this air infiltration tool to measure savings potential in existing buildings as well as new construction with an initial focus on new construction.

After the initial working group meeting, a decision was made to move on to the next phase of the research for the air infiltration study.

2.2 Second Working Group: NIST papers deep dive, go/no-go decision

The second working group meeting was held on 1/15/21 and focused on the NIST research results and findings. At the end of this working group meeting, another go/no-go decision was planned, however, the working group requested additional details on the model validation process prior to making the go/no-go decision. The DNV team reached out to their NIST contacts and obtained additional documentation as to the validation process between buildings and the model. More details on the discussion are included below.

The second working group focused on comparing two modeling software programs: first, CONTAM 3.0 – multizone air flow distribution analysis software developed by NIST – and second, EnergyPlus (EP) – whole building energy simulation software developed by DOE. Both tools have distinct advantages. CONTAM can model pressurized buildings and can account for wind speed adjustments based on different terrain along with the impact of wind direction. Furthermore, NIST has already validated CONTAM in three real-world large commercial buildings for their infiltration rates and other pollutants such as CO2, VOC and PM 2.5. However, working with CONTAM requires specialized modeling skills, which restricts its usage. On the other hand, EP is a publicly available software and building simulation analysis that can be easily done using the code compliant baseline prototype models developed by NREL (National Renewable Energy Laboratory). These prototype models are referred in this study as “original EP.”

Since NIST has already validated multiple infiltration studies using CONTAM, it suggested some modifications to the original EP models to make them deliver results consistent with CONTAM results. NIST-suggested modifications, when applied to the original EP models, are called ‘modified EP’ models in this study. DNV reviewed NIST research papers that presented building infiltration analysis using CONTAM, specific modifications suggested by NIST for individual building types and how the results of modified EP models align with CONTAM. DNV presented our study findings before the working group, as listed below:

- The study covered sixteen reference buildings in eight climate zones. The initial study[1] conducted on ASHRAE 90.1 2004 prototype models found the difference in infiltration rates because of the following:
    - Inconsistent building leakage area. NREL models assumed the effective leakage area as 1.18. cm^2/m^2 of building area at 4 Pa pressure. NIST found this assumed leakage area was not consistent with prevailing commercial building airtightness data and suggested the leakage area be revised to 5.27 cm^2/m^2 of building area at 4 Pa pressure.
    - CONTAM can model pressurized buildings and includes weather effects which the original EP is not able to model.
- Based on the study discrepancies found above, NIST suggested revising the coefficients used in the EP simulation algorithm. Per the NIST study, these coefficients are to be different for different building types, and for each building type, there are two sets of coefficients. The first set is meant to be applied when HVAC is ON and the second set to be applied when HVAC is OFF.
- NIST suggested two separate methods to determine these infiltration coefficients: Method-1 and Method-2.
    - Method-1 developed 'building type specific' coefficients that update the infiltration coefficients for a specific building irrespective of its characteristics.
    - Method-2 developed coefficients that are based on 'key building characteristics specific,' such as building height, exterior surface to volume ratio, and net HVAC system flow normalized by the exterior surface area.
- NIST compared modified EP model infiltration rate with CONTAM, using Method-1 and Method-2 separately for HVAC ON and OFF modes and presented their R^2 and Standard Error. For both methods, the modified EP model infiltration rates exhibited significant correlations with their corresponding CONTAM results. However, NIST suggested using coefficients derived using Method-2.
- NIST repeated the same study in year 2017[2] with NREL's EP prototype models that are compliant with ASHRAE 90.1 2013. This latest study was conducted for the following building types: hospital, medium office, primary school, small hotel, and stand-alone retail.
- NIST suggested infiltration coefficients for MA climate zone (ASHRAE climate zone 5) are presented in Table 1. VEIC used these coefficients in their tool. While DNV was preparing this memo, the team learned that NIST had updated its findings in 2018 and the latest coefficients are presented in their most recent paper, published in March 2021[3].
- NIST came up with the following quantitative comparisons
    - Infiltration rate with air barrier was 74% less than that without an air barrier
    - Infiltration rate difference between CONTAM and modified EP with an air barrier was 0.0008 per hour

[1] NIST Technical Note 1829, "An improved method of modeling infiltration in commercial building energy models", Lisa C. Ng, Steven J. Emmerich, Andrew K. Persily, April 2014

[2] "Weather Correlations to Calculate Infiltration Rates for U.S Commercial Building Energy Models", Engineering Laboratory, Lisa Ng, Nelson Ojeda, William Dols, Steven Emmerich.

[3] "Evaluating Potential Benefits of Air Barriers in Commercial Buildings using NIST Infiltration Correlations in EnergyPlus", Lisa C. Ng, W. Stuart Dols, Steven J. Emmerich, Building, Energy and Environment Division Engineering Laboratory, March 2021

- Greater HVAC energy savings were predicted using NIST suggested infiltration coefficients compared to the default coefficients that are included in NREL's prototype building models. Average infiltration measure electric savings increase by 3% and average NG measure savings increased by 8%.

Table 1: NIST Suggested Infiltration Coefficients for MA (ASHRAE Climate Zone 5)

	Hospital	Medium Office	Primary School	Small Hotel	Stand Alone Retail
Airtightness @ 75 PA (m3/h/m2) – 6 sided	5				
Volume (m3)	79802	19741	27484	11622	13984
Exterior surface area – 5 sided (m2)	8937	3638	9383	2698	3471
Exterior surface area – 6 sided (m2)	13107	5299	16254	3702	5765
Idesign @ 4 Pa (m3/s/m2) – 5 sided	0.00030388	0.00030176	0.00035891	0.00028424	0.00034412
	Chicago (CZ 5)				
Aon	0.1397	-0.0634	-0.0134	0.0336	-0.0277
Bon	0.0007	0.0024	0.0027	0.0067	0.0044
Don	0.0045	0.0219	0.0333	0.0076	0.0290
Aoff	#N/A	0.0000	0.0000	#N/A	0.0000
Boff	#N/A	0.0156	0.0065	#N/A	0.0102
Foff	#N/A	0.0347	0.0421	#N/A	0.0506

Results

DNV presented the study limitations and future opportunities:

- EP engine has been updated over time to account for adjusting the local wind speed with zone height
- EP in its current form does not account for Variable Air Volume (VAV) impact on infiltration rate, which may be an opportunity for future modifications
- NREL has already published an updated version of OS measure based on NIST's latest study in 2018. This update added infiltration correlations for specific building types and climates and incorporates infiltration that varies with weather and HVAC operation. It accounts for building geometry (height, above-ground exterior surface area, and volume)

At the close of the second working group meeting, the team requested additional content on the building validation process as opposed to comparisons among various models.

- Additional research papers utilized tracer gas in buildings to compare with the CONTAM model and found that the results compared statistically. Additional research compared the model predictions against building test data. The results showed that the model behaved similarly to a real building.

On 1/29/21 the EEAC, National Grid, and Eversource provided a “Go” decision to move on to the next phase of the model review. The EEAC recommended that if air infiltration becomes an incentivized measure, the PAs should test the validity of the model against data collected from buildings in Massachusetts. The PAs agreed to this model quality control check.

2.3 Third Working Group: Vendor tool deep dive

The third working group meeting was held on 3/15/21 and discussed the findings from the Vermont Energy Investment Corporation (VEIC) tool, including whether these results were robust enough to meet evaluation, measurement, and verification (EM&V) needs. The following sections discuss our evaluation goals on the vendor tool and our findings.

Goals of Vendor Tool Evaluation

- Evaluate VEIC infiltration tool to determine if the NIST suggested inputs and procedures are being implemented accurately and the parametric analysis procedure is adopted to develop the vendor tool.
- Work with VEIC to decide on building characteristic variables that affect the infiltration and impacts for PA measure claims.
- Provide VEIC the list of building variables and their ranges along with specific building types to perform the parametric runs using Boston, MA TMY3 weather data that will be used for our study.
- Discuss with VEIC to determine how the simulation models adjust the building characteristics and the building systems size when specific building parameters change during the parametric runs.
- Obtain 8,760 hourly reports for zone-level infiltration rates along with infiltration affected outputs, such as zone sensible cooling and heating loads, zone air temperature and RH, fan power, and building electric and natural gas (NG) consumption.
- Analyze the above 8,760 hourly outputs to determine their characteristic profiles based on building occupancy, weather, and building geometry, and develop correlations between these outputs.
- Summarize and present the analysis results to the working group and collect their feedback. Provide a recommendation as to viability of the VEIC tool to estimate impacts from infiltration measures along with the relative magnitude of opportunities and limitations.

The key parameters used to develop the models for this study are outlined in Table 2: . The study used models for three building types – Large Office, High School, and Multi-family – of two different surface areas and were simulated using original EP and modified EP. Each model used four different infiltration rates representing different levels of building tightness and were run with TMY3 weather data for Boston, MA.

Table 2: Scope of Model Study and Evaluation Tasks

Parameters	Description
Building Prototypes	Large office, High school, Multi-family. Based on NREL 2013 prototype
Simulation engines used	Original EnergyPlus (EP) and Modified EP with NIST infiltration coefficients
Infiltration rates used	0.1, 0.3, 0.5, 0.7 cfm/sq. ft. of building envelope area
Building surface areas	Office – 320,000 sq. ft. and 640,000 sq. ft.

	High school – 320,000 sq. ft. and 960,000 sq. ft. Multi-family – 60,000 sq. ft. and 100,000 sq. ft.
Zone height from the ground	Used three different zones – top story, mid story, bottom story. Multiple zones per story
Weather data used	TMY3 weather for Boston, MA. DBT, WBT, Wind speed, Wind direction
Model outputs	Zone infiltration rates (kg/s) Zone sensible cooling load (W) Zone Sensible heating load (W) Zone air temperature (C) Zone air relative humidity (%) Fan electric power (W) Building electricity and NG consumptions

DNV reviewed the 8,760 hourly outputs from these parametric runs. We developed time-series and scatter charts from the model outputs and studied the following correlations for zone infiltration rates and effect of zone infiltration rates on zone energy and building energy:

- Infiltration rate variation based on zone heights and zone orientations: The zones located at higher heights have higher infiltration rates (cfm/ft^2) compared to the zones at lower elevations. Infiltration rates are uniform across all four-building orientations, and the infiltration rate is independent of the direction of the building surface.
- Infiltration rate variation during different months of a year and different time of a typical day: Since infiltration rates vary based on two weather-induced parameters (temperature differential between outside and inside and windspeed), the infiltration rate varied over different months of a year and different hours of any given day. However, for any given day, the infiltration rate reduced significantly as the building becomes occupied and the building HVAC system comes ON.
- Infiltration rate variation based on HVAC ON vs. HVAC OFF.
- Infiltration rate correlation with wind speed, outside air temperature, fan power, zone temperature, zone sensible cooling and heating loads.
- Overall building energy consumptions when compared between a tight building with a leaky building and when compared between original EP model with NIST modified EP.
- Calibration of model output with the actual building energy consumption.

Findings from Large Office and High School Models

- Winter months – The average infiltration rate calculated using modified EP over a typical day was higher than the infiltration rate calculated using original EP. Higher infiltration rates are evident for both HVAC ON and HVAC OFF modes. Refer to Figure 2.
- Summer months – Infiltration rate profile for summer does not show the same trends seen for winter months. Infiltration rates using modified EP tends to be less than that calculated using original EP during HVAC OFF periods. Refer to Figure 2.

- Both EP and modified EP exhibited a common trend – Infiltration rates reduce drastically when HVAC comes ON. This indicates that HVAC introduces significant building pressure when it comes ON and reduces the infiltration rate significantly. Refer to Figure 2.
- Zone air temperature variation and infiltration rate variation have direct correlation.
- Zone sensible heat rate variation and infiltration rate variation have direct correlation.
- Infiltration rate varies as HVAC comes ON and OFF
    - Zone temperature and sensible heat rate infiltration have direct correlation-as it goes up, so does the other. See appendix for additional information.
- The scatter plot between windspeed and infiltration rates measured at three zone elevations exhibited. Refer to Figure 1:
    - Scatter plots for EP and modified EP show that the infiltration rate is relatively higher for zones at higher elevations.
    - EP model output shows linear correlation between wind speed and infiltration rate. This is consistent with the governing equation used for infiltration in EP.
    - Modified EP output shows a parabolic correlation between wind speed and infiltration rate, which is consistent with the governing equation used for infiltration in modified EP.
    - The amount of scatter seen in the modified EP plot is higher than the scatter in the original EP. This is because in modified EP, both wind pressure and temperature differentials act as variables while the original EP has only one variable.

Figure 1: Comparison of infiltration rate variation with zone height

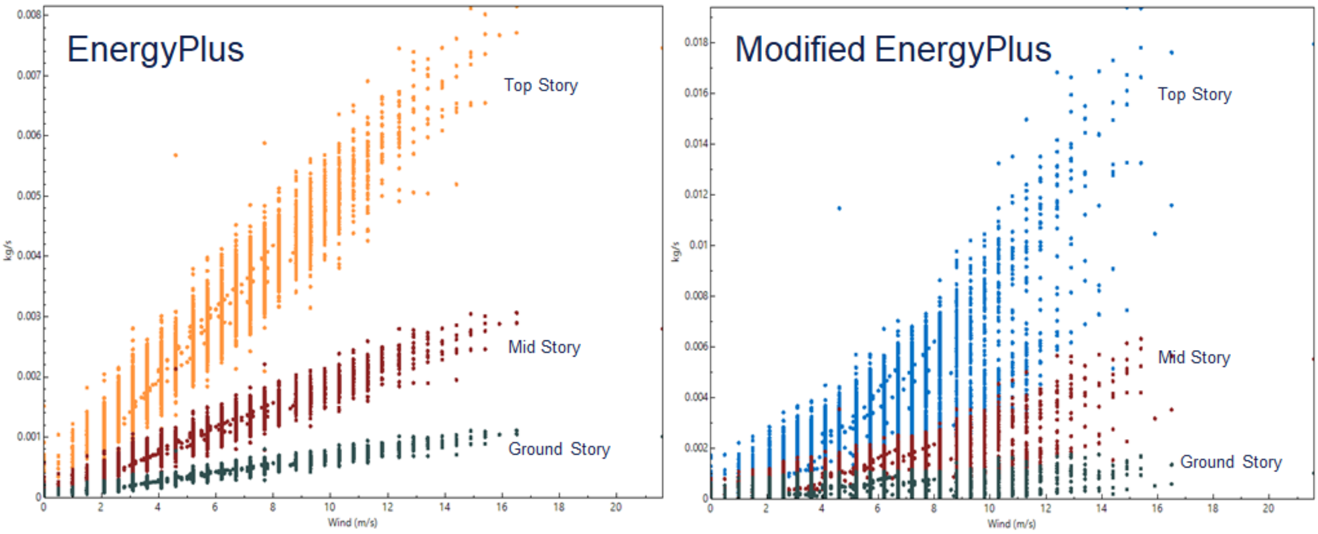
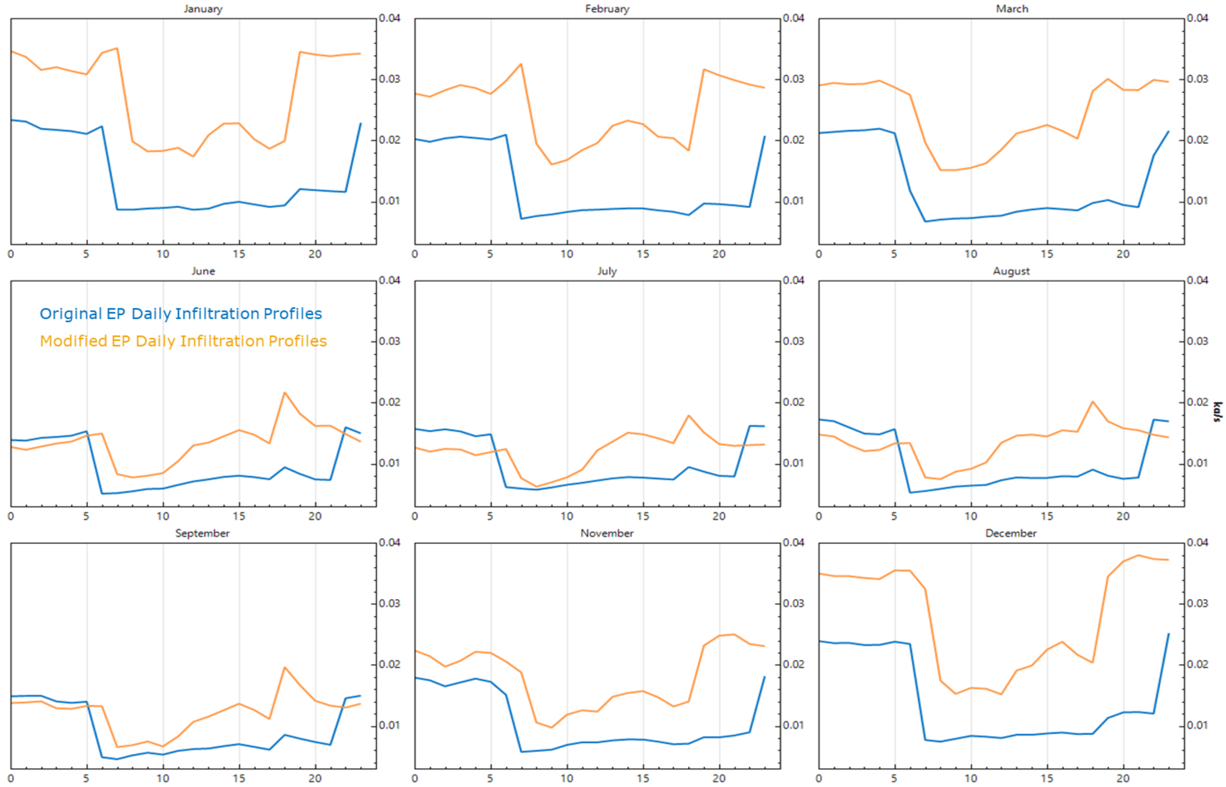


Figure 2: Comparison of daily infiltration profile using original EP and modified EP



2.4 Fourth Working Group: Vendor tool usability

The final working group meeting was also held on 3/15/21 as part of the third working group meeting. During the discussion, DNV provided recommendations for key input parameters and assumptions, such as the definition of the baseline infiltration rate and schedule based on a building's operation. The working group also determined the requirements for building pressurization tests to provide infiltration rate inputs for the tool.

3 CONCLUSIONS

Based on our evaluation of model output, we concluded the following:

- Weather induced infiltration impacts are real and significant. The preferred modeling software the MA PAs use (eQuest) does not have the ability to determine the infiltration-related impact on building energy consumption.
- The VEIC model has been tested for multiple building types to determine weather impacts, identifying which building types can implement infiltration measures.
- Vendor model results replicated NIST findings and can update the models as NIST comes up with new findings[4]
- Vendor tool has ability to perform extensive runs and post run analytics. This will help VEIC determine the significant building characteristic variables that affect the infiltration rate.
- Once VEIC comes up with final results, it will develop a simplified and easy-to-use spreadsheet model for the MA new construction program.

Opportunities and Limitations of Energy Savings

Table 3 compares a sampled leakiest Large Office building of 640,000 sq. ft. (with infiltration rate at 0.7 cfm/ft^2) to the tightest building of identical size (with infiltration rate at 0.1 cfm/ft^2). The results were obtained with both original EP and modified EP. The red highlights compare the building energy consumption between the leakiest building and the tightest

[4] "Evaluating Potential Benefits of Air Barriers in Commercial Buildings using NIST Infiltration Correlations in Energy Plus", Lisa C. Ng, W. Stuart Dols, Steven J. Emmerich, March 2021

building using the original EP model. The blue highlights compare the building energy consumption between the leakiest building and the tightest building using the modified EP model. Since the program is interested in infiltration measure potential in NG savings, the following discussions are focused on NG only:

- Infiltration NG savings are more than two times higher if the NIST modified infiltration coefficients are used instead of the original EP.
- Though our study results shown in Table 3 suggest a relative magnitude of more than double NG savings using modified EP, the expected relative magnitude will be significantly less for the new construction program. This is because the baseline building is not as leaky as 0.7 cfm/ft^2 (around 0.4 cfm/ft^2 to match with ASHRAE 90.1 2013) and the measure case infiltration may be higher than 0.1 cfm/ft^2. The intention of Table 3 is to show that with modified EP, one can expect higher savings from the proposed infiltration measure in the New Construction program. The values in Table 3 will be updated as VEIC plans to update Figure 3 following work with the MA PAs to conduct more extensive simulation runs with increased sample sizes and a greater number of variables.

Our study results shows that the absolute magnitude of NG savings obtained either through EP model or modified EP is insignificant for a Large Office building of 640,000 sq. ft. as seen in Table 3. This is because the NREL 'Large-Office' prototype used for this study includes space used as data centers thus explaining why the baseline model NG consumption is not as significant as seen for a Large Office building of this size.

To overcome such issues, VEIC plans to engage program staff to calibrate NREL's baseline EP model to ensure consistency with the MA New Construction EUI (kBtu/ft^2) requirement, which includes:

- Adjusting NREL's baseline EP model to make them consistent with MA New Construction program EUI for various building end-uses, such as lighting, ventilation fan, cooling, heating, plug-load, etc.
- The modified baseline models to match MA specific EUI assumptions
- Once the updated baseline EP models are established, the parametric analysis will be conducted on the adjusted baseline model to determine the savings.

Large offices may not a good candidate for this type of measure, as it is positively pressurized most of the time and has large amounts of internal heat load that offsets infiltration savings.

Table 3: Comparison of Energy Consumption between Leakiest and Tightest Building

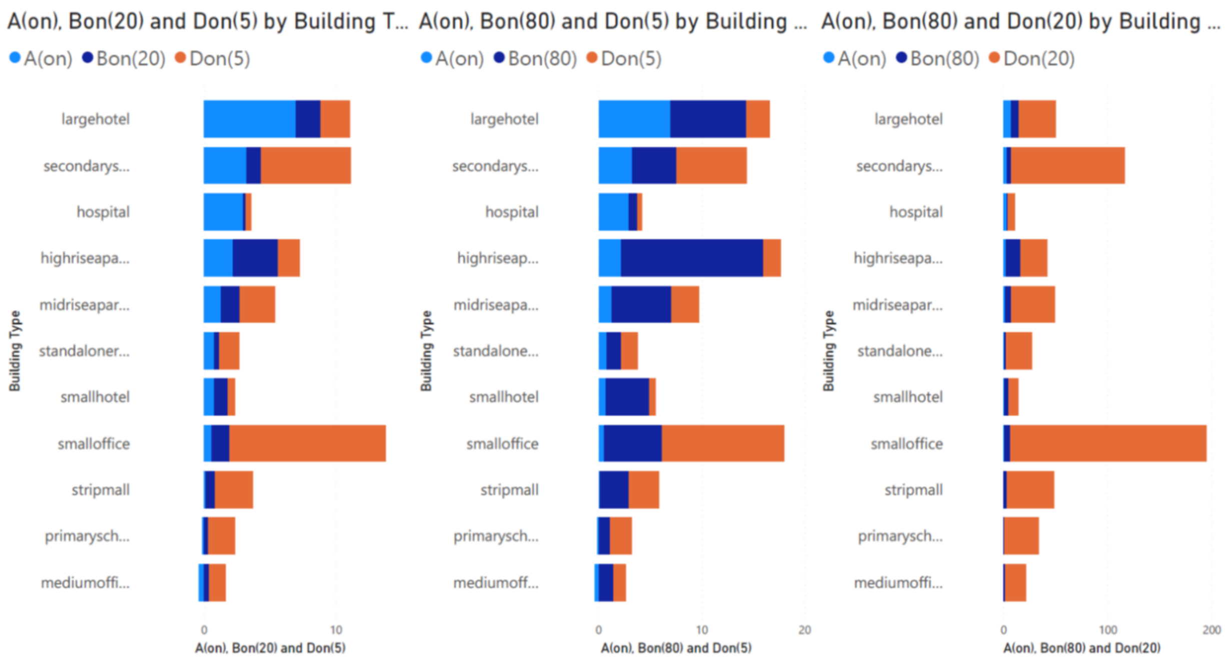
Building Types	Total_Floor_area [sf]	Infiltration_Rate [cfm/sf]	Infiltration_Method	Peak_Electric_Demand [kW]	Electricity_Usage [kWh]	Results.EUI [kBtu/sf]	Natural_Gas_Usage [MBtu]	Max Electricity Savings [kWh]	Max NG Savings [MBtu]
Large Office	640000	0.1	DOE2/AppG	2,403	11,033,044	61	1,445		
	640000	0.1	NIST 2017	2,405	11,033,218	61	1,459		
	640000	0.7	DOE2/AppG	2,400	11,031,692	61	1,502	-1,353	56
	640000	0.7	NIST 2017	2,401	11,032,553	61	1,584	-665	125

There is a substantial savings opportunity associated with air infiltration in several building types. Figure 3 shows the impact of weather induced infiltration rates for different building types. Factor A (light blue) represents fixed infiltration, factor B (dark blue) represents infiltration induced by the temperature differential between outside and building temperature, (stack effect), and factor C (orange), represents the impact of wind speed. The bar chart on the left shows the base condition with a temperature differential of 20 °F and wind speed of 5 mph. The middle bar shows the effect of increased temperature differential and the right bar chart shows the effect of both increased temperature differential and wind speed.

Figure 3 shows the relative opportunity of infiltration savings for various building types. One can see, for Small Office, the temperature differential induced infiltration increases significantly as the temperature difference increases from 20 °F to 80 °F. However, the temperature induced infiltration does not have a similar effect on a Medium Office. For a small

Office, the effect of wind speed is more pronounced when both temperature differential and wind speed increases simultaneously (refer to right chart for Small Office). This indicates that for a Small Office, the weather induced infiltration effect can be better quantified with the NIST modified EP model. VEIC plans to update Figure 3 as needed for MA PAs if this measure is pursued.

Figure 3: Energy savings potential per building type[5]



4 RECOMMENDATIONS

Throughout the study, several recommendations were documented during working groups and are summarized here for reference.

- The EEAC recommended the PAs move away from eQuest and instead use an updated modeling tool: OpenStudio. Using OpenStudio would also diminish any potential interactive effects and to kickstart the transition, recommended training new construction program vendors with OpenStudio.
- Develop validation protocols to ensure they are acceptable to evaluation for the proposed air infiltration program in the form of a checklist.
- Leverage the tool (if acceptable) for existing buildings as well as new construction.
- If the measure is not cost-effective utilizing code as the baseline, determine if the measure merits more research to identify if standard practice is below code. This activity is also recommended for the measure if it is cost effective as the review could glean additional savings.
- If model is accurate, propose a small evaluation of several small projects to compare the evaluation results against the modeled results. Document how any differences can be addressed through updated model assumptions to ensure ongoing improvements in accuracy of the model.

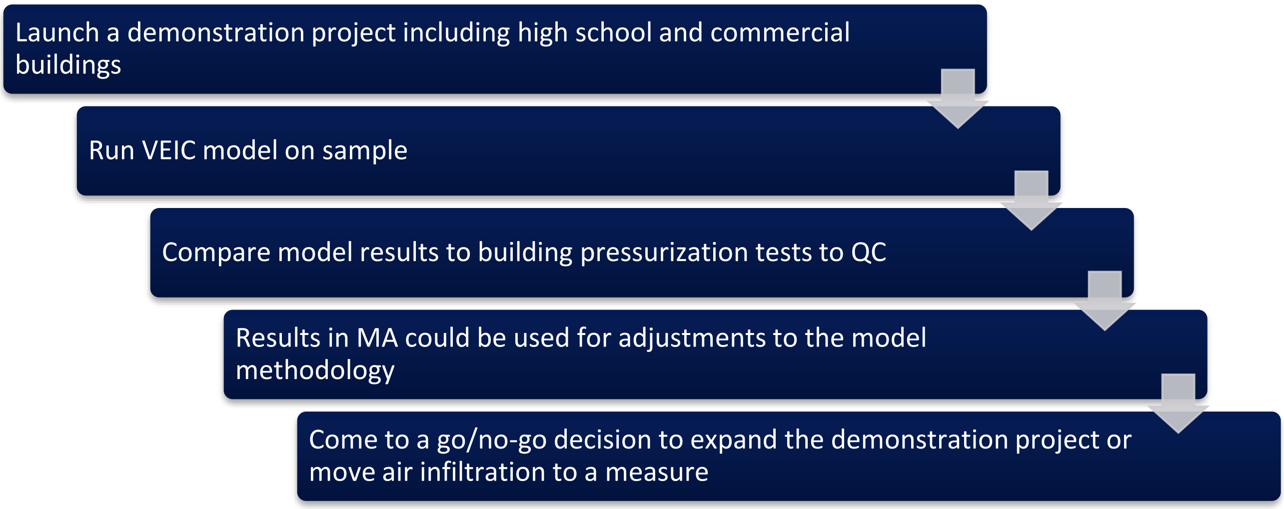
[5] "Infiltration Modeling in High-Performance and Low-Load Buildings", Craig Simmons, Presented at the 2019 Building Performance Analysis Conference, Denver, Colorado, September 25-27.

- Although it was found that the NIST model was better than available alternatives it has not been validated for infiltration analysis. As a result, the EEAC believes that to deploy this solution in Massachusetts would require empirical testing as part of the deployment of a future proposed program.
- The EEAC recommended a discussion with a panel of building commissioning experts to better understand air infiltration impacts.
- Work with VEIC to establish a Massachusetts baseline based on EUI and end-use.

5 NEXT STEPS

To further test the feasibility of air infiltration as a potential savings measure, the team recommends pursuing a small scale project in the Commonwealth as outlined in Figure 4.

Figure 4: Next steps to evaluate air infiltration potential



At the end of the third and fourth working group meeting, the EEAC approved the next step of conducting a small-scale demonstration project to model air infiltration for a set of buildings and compare the results to a blower door test. Upon reviewing the results, the MA PAs and EEAC will consult to determine whether to expand the demonstration project. The DNV team is available to assist in these endeavors as needed.