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Energy Modeling of Commercial Gas Rooftop Units in Support of CSA P.8 Standard: Thermal Efficiencies of Industrial and Commercial Gas-Fired Furnaces

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Acknowledgements

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- Cadeo Group, for coordinating with multiple organizations for inputs to this report, and for the final development of this report;
- Pacific Northwest National Laboratory (PNNL), for modifying building prototype models and developing simulations results, as well as other technical support; and
- Energy 350, for modifying an existing jacket loss calculator to provide greater detail and providing other technical support.

We are appreciative of the opportunity to be part of CSA Group's consensus-based effort to improve the test methods and performance criteria for determining the efficiency of packaged furnaces.

Executive Summary

Background

The current (second) version of the CSA P.8 standard, Thermal Efficiencies of Industrial and Commercial Gas-Fired Package Furnaces, uses the operating thermal efficiency of the gas burner to rate the performance of three-phase and large single-phase commercial gas-fired packaged furnaces. Because this current methodology does not consider the efficiency of the entire commercial gas-fired packaged unit, it does not allow users to make informed decisions about the overall energy consumption of rooftop or make-up air units, especially at lower outdoor temperatures or manufacturers to effectively distinguish more efficient units.

To address this inconsistency, the CSA P.8 standards committee pursued a direction of modifying the test conditions and calculations to be more reflective of actual rooftop unit operation, and to more clearly distinguish between models that are more efficient on annual energy basis. An update to the P.8 standard would reflect the value of higher efficiency commercial gas furnace units over less efficient units based on their P.8 ratings, thus driving decreased energy consumption and aiding consumers in selecting units that use less energy.

To inform the CSA P.8 revisions, this project used EnergyPlus simulations of commercial gas furnace equipment in typical building applications to better understand the operating modes and heating season energy consumption of different equipment efficiencies and configurations. This work involved simulations of numerous combinations of operational modes, equipment configurations, climate zones, and building types across an entire heating season. Cadeo Group, together with Energy 350, NEEA and the CSA P.8 standards committee used the data derived from 120 modeling scenarios (developed by Pacific Northwest National Laboratory) to inform the development of a new, representative metric to more comprehensively describe commercial gas furnace performance. Specifically, the data facilitated evaluation of the extent to which the new metric represents actual rooftop unit operation and also yielded weights for proper balancing of each operating mode in the test method.

Findings

After completion of all 120 simulations, the resultant data was processed for use with the CSA P.8 standard. The team used the data to understand the variability of energy consumption by climate zone, building type, and equipment configuration in order to develop representative inputs for operating mode weights and outdoor air temperature for use in the updated P.8 standard. The modeling also included several energy efficiency options for commercial gas furnaces and these efficiency scenario results allowed the team to establish expected benefits from various energy efficiency improvements in the field, for comparison to efficiency improvements represented by the metric.

Energy consumption by climate zone and outdoor air requirements – Not surprisingly, energy consumption increased with both colder climate zones and (considerably) with increased outdoor air requirements, more notably for the retail model than the warehouse model due to the former's higher return air setpoint.

Energy consumption by building type and stages of combustion – As with the distinctions among climate zone findings, these results likewise illustrated the greater impacts of ventilation air and climate zone on retail buildings' energy consumption than on that of warehouses. Assumptions used in the models meant that use of two- or multi-stage burners had no impact on energy consumption (a finding consistent with current literature).

Energy savings by efficiency option

The simulations also facilitated comparison of energy savings attributable to four modeled energy efficiency options: increased enclosure insulation, decreased damper leakage, addition of a condensing burner, and addition of a heat recovery ventilator. When viewed by climate zones, the impressive levels of energy savings (up to 55%) available through the addition of heat recovery, compared to savings through the other three efficiency options, is remarkable; this finding holds true across most of the 30% (62.1 compliant) and 100% outside air cases. Addition of a condensing burner in general produces the second-highest levels of energy savings, followed by increased enclosure insulation. Reducing damper leakage yields minimal energy savings. Some key observations by efficiency option across building types, outside air configurations, and climate zones/cities are summarized below:

- Increased enclosure insulation – This type of energy savings is more pronounced in the warehouse model than in the retail model, and for the 0% outdoor air case for both models. Increased enclosure insulation yields little difference in savings across climate zones.
- Decreased damper leakage – Energy savings through reduction of damper leakage are understandably highest in the 0% outdoor air case. This efficiency option also yields greater savings by increasingly colder climate zone for the 62.1 compliant warehouse case, with negligible impacts for the 62.1 compliant retail case, likely due to differences in occupied hours.
- Condensing burners – Virtually all scenarios demonstrate energy savings of around 10% with the addition of a condensing secondary heat exchanger. Savings were slightly higher in the colder climate zones, and higher for the warehouse model than the retail model in the 0% outdoor air case due to their differing loads.
- Heat recovery ventilator – The addition of a heat recovery ventilator to a building's HVAC system yields energy savings substantially greater than those observed for implementation of any of the three preceding efficiency options, due to both its role in assuming part of the furnace's heating capacity and through reduction of heat losses. The savings difference between the warehouse and retail models is lower for 100% outside air than the other outside air configurations due to the lower ventilation requirements for the warehouse model.

Time spent in each operating mode – Although consumption during full-fire and reduced-fire periods dominates overall unit energy consumption, most units spend a bulk of their time in either standby or ventilation-only mode; however, these non-firing periods contribute to a unit's energy consumption and thus necessitate consideration in accounting for all energy consumption over the entire heating season.

With regard to updated inputs for the test method in the forthcoming edition of the CSA P.8 standard, the representative weights were developed by averaging the percent operating hours for each operating mode across each climate zone and then across each building type; the numbers remained distinct for the separate ventilation types and combustion stages analyzed for each system.

Introduction

The CSA P.8 standard, Thermal Efficiencies of Industrial and Commercial Gas-Fired Package Furnaces, provides a testing and rating methodology for three-phase and large (>225 kBtu/hr) single-phase commercial gas-fired packaged furnaces. The current version[1] of the standard rates the performance of applicable units solely by the performance of their gas burner (operating thermal efficiency). While this methodology is representative of the efficiency of one component of a commercial gas-fired packaged unit, it is not representative of the efficiency of the unit as a whole.

The outcome is that some rooftop or make-up air units that would use less energy at lower outdoor temperatures are not being specified—in preference to more poorly-performing counterparts—because they both have the same or similar P.8 rating.

With this in mind, the Northwest Energy Efficiency Alliance (NEEA) has been working with the CSA P.8 standards committee to modify the test method to incorporate new test conditions and calculations that will better reflect the real-world operation of a rooftop unit and allow for a greater differentiation between cold climate adapted and non-cold climate adapted models/designs. The expected result will be reduced energy consumption from the greater uptake of higher efficiency rooftop or make-up air products.

The updated standard incorporates a key change: a metric that combines several operational modes covering energy usage across the entire heating season. To create the new metric, Cadeo Group worked with Energy 350, NEEA, and the CSA P.8 standards committee to develop several scenarios of different equipment configurations, across multiple climate zones, and building types to better understand how the equipment performed. These scenarios were then modeled based on building prototype models developed by Pacific Northwest National Laboratory (PNNL), and PNNL led the analysis. These simulations provide data to evaluate the representativeness of the new metric, and also provide weights to correctly balance each operating mode in the test method itself.

[1] The current version is the second edition of the standard, at the time of writing.

Methodology

Summary

To ensure the third edition standard metric was as representative as possible, PNNL used whole building energy simulations in EnergyPlus[2] to simulate the operation and energy consumption of commercial gas-fired packaged furnaces covered by the CSA P.8 standard throughout the heating season. Throughout the modeling development and analysis process, PNNL worked closely with Cadeo, Energy 350 and NEEA in defining the prototype buildings and implementing the EnergyPlus modeling.

In order to perform the energy modeling analyses, the following had to be determined:

- Selecting a number of representative climate zones and cities
- Selecting a number of representative commercial building types
- Selecting a number of baseline system options and higher-efficiency system options
- Selecting a duration for the heating season for analysis

For each unique scenario (climate zone, building type, system), an EnergyPlus model was run to simulate the operation of this particular case over the heating season. The results across all baseline runs were then averaged to obtain representative data for major commercial buildings in representative Canadian climates, and the results of all higher-efficiency runs were kept for comparison to the new metric results. This process is summarized in Figure 1 below and described in greater detail in the sections that follow.

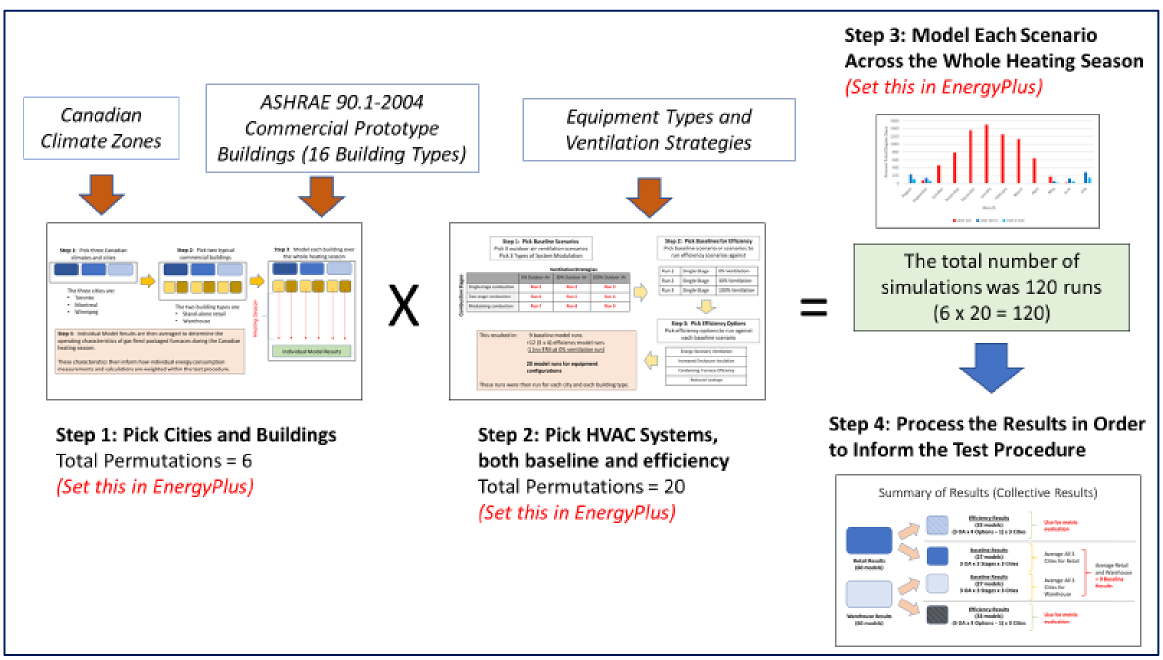

Figure 1: Summary of the Energy Modeling Analyses

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[2] EnergyPlus is a whole building simulation program whose development is funded by the U.S. Department of Energy (DOE). Additional information can be found at https://energyplus.net/.

Building Types

The U.S. Department of Energy has developed a set of Commercial Prototype Buildings to use in its EnergyPlus analyses of buildings and climates. There are 16 distinct building types, which together represent 80% of new commercial and multifamily buildings in the U.S. and are likely representative of buildings across the U.S. and Canada.[3] To determine the representative operation of gas rooftop units (RTUs) covered by the CSA P.8 standard, the modeling team worked with NEEA and the CSA P.8 standards committee to select several building types that most commonly use large gas-fired packaged furnaces in the Canadian market. Of the 16 building types, the standards committee chose the following two building types to be modeled, as representative of the majority of commercial building stock with gas RTUs in Canada:

- Warehouse
- Stand-alone Retail

Initially, a third building type, full-service restaurants, was considered as well. However, after preliminary analysis of the restaurant case, the modeling team recommended dropping the restaurant case due to: (1) the complexity associated with modeling air transfer from the dining room to kitchen (which is a unique case),[4] (2) the dominance of the cooling load in the kitchen zone due to high internal loads from cooking appliances, and (3) the fact that the results for the dining area in the restaurant, which are more generalizable, were similar to the results from the stand-alone retail model. The stand-alone retail model was treated as representative of fully-conditioned spaces with typical commercial operating hours and the warehouse model was treated as representative of non-fully-conditioned (i.e., low-heating thermostat setpoint) spaces. Thus, only these two building types were used and the results were averaged to generate representative weights for gas-fired packaged furnaces in commercial buildings. We recognize that this is a simplification, but note that the major variables analyzed in the models (weights in the different operating modes and relative energy performance of different gas RTU system configurations) are not that sensitive to the different building types, as shown in the Findings and Conclusions section. However, the results and weights could be improved in the future through more detailed modeling of additional building types.

Climate Zones

Canada has six major climate zones, as modeled by national Canadian codes. The modeling team chose three Canadian climate zones to model based on those in which the majority of the Canadian population is located. Canadian climate zones are described in Figure 2 below.

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[3] https://www.energycodes.gov/development/commercial/prototype_models

[4] The kitchen model currently takes some make-up air from the dining area, in addition to that provided by the dedicated make-up air unit. Some system scenarios and efficiency options are, therefore, not applicable to this case.

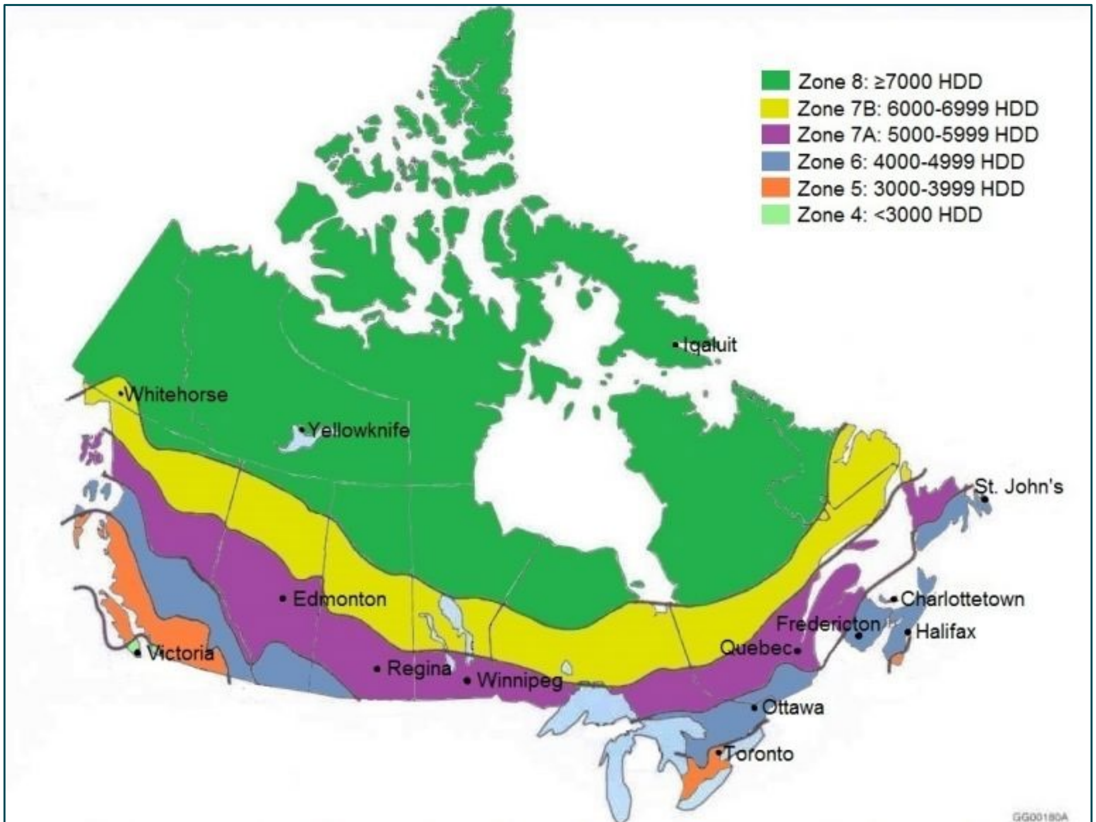

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Figure 2: Climate Zones in Canada
Source: http://www.naimacanada.ca/codes-standards/

The modeling team picked the most populous city within each climate zone as the representative weather files for each climate. These three cities were used as inputs to the EnergyPlus models, with their TMY3 weather data used to determine building loads and equipment operating hours. The three cities selected are listed in Table 1 below.

Table 1: Cities and Climate Zones used for Simulation Analyses

Climate Zone	Representative City (most populous within each climate zone)	Heating Degree Days
5	Toronto	3000-3999
6	Montreal	4000-4999
7	Winnipeg	5000-5999

Equipment Types and Efficiency Options

Once the building types and the climate zones were determined, the modeling team, in conjunction with NEEA and the CSA P.8 standards committee, determined 20 unique gas RTU system configurations to model. The following gas RTU equipment attributes were varied to understand the impact of these different system configurations on the performance and operation of the unit being modeled:

- Outdoor air ventilation scenarios
- Staging or modulation of the burners
- Efficiency options that represented improvements over baseline units

The general selection process is described in Figure 3 below.

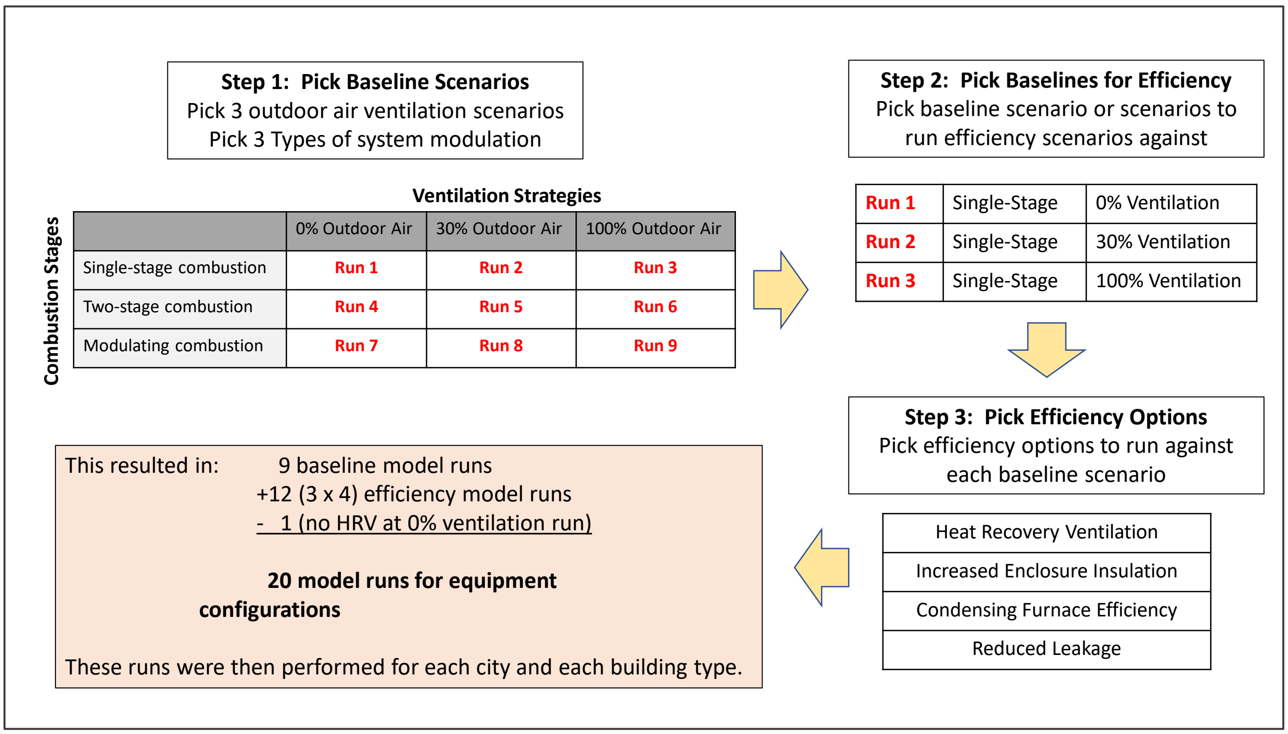

Figure 3: Analysis Description for System Configurations

Outdoor Air Ventilation Requirements. The project team selected three ventilation capabilities. Table 2 describes each of the selected ventilation equipment configurations.

Table 2: Types of Outdoor Air Configurations for Equipment Simulations

Ventilation Capability	Unit Description
0% ventilation	Gas-fired packaged furnace that does not include outdoor air dampers for ventilation air but may include outdoor air dampers for economizing during the cooling season.
62.1 Compliant	Gas-fired packaged furnace that provides typical ventilation air to occupied spaces consistent with minimum ASHRAE 62.1 requirements. This typically results in approximately 30% outside air, on average. This setting is applicable to a gas-fired packaged furnace that includes fixed outdoor air dampers and has the capability to heat and cool a range of outside air from 0% up to 90%, but does not have the capability to heat and cool 100% outside air.
100% ventilation	Gas-fired packaged furnace that provides 100% outside air, such as a dedicated outdoor air system (DOAS) or make-up air unit. This setting is applicable to gas-fired packaged furnaces that include outdoor air dampers and that have the capability to heat and cool 100% outside air.

Number of Combustion Stages. Three combustion burner types were selected and implemented in the EnergyPlus models. Table 3 describes each of the burner types simulated as part of the modeling runs.

Table 3: Types of Combustion Configurations for Equipment Simulations

Combustion Modularity Types	Description
Single-stage furnace	A static control that cycles a burner between the heat input rate and OFF.
Two-stage furnace	A modulating control that both cycles a burner between the reduced heat input rate and OFF, and between the maximum heat input rate and OFF. It can also switch between OFF, reduced fire, and high fire under certain load conditions.
Modulating furnace	A modulating control that can smoothly ramp a burner input rate between the maximum input rate and OFF under all load conditions.

Finally, the modeling team selected four distinct efficiency configurations that represented improvements over the baseline systems. Each of these efficiency configurations (and their comparison to the baseline configuration) is described in Table 4 below.

Table 4: Description of Baseline and High-Efficiency Equipment Configurations

Efficiency Scenario	Baseline Description	With Efficiency Option Description
With energy recovery ventilator (ERV)	No ERV Total recovered heat is zero	ERV present Sensible effectiveness value of 0.7 and latent effectiveness value of 0.6 at 100% of heating airflow
With increased enclosure insulation	Enclosure insulation value of R-2.3 (IP) Insulation thickness of 0.6 inches using fiberglass insulation	Enclosure insulation value of R-8 (IP) Insulation thickness of 2 inches using Armaflex insulation[5]
With reduced damper leakage	Leakage rate (when damper closed): 167 cfm	Leakage rate (when damper closed): 67 cfm
Non-condensing vs. condensing	Operating Thermal Efficiency[6] values for non-condensing units (all combustion stages): 0% Ventilation: 0.678 62.1 Compliant: 0.744 100% Ventilation: 0.797	Operating Thermal Efficiency values for condensing units (all combustion stages): 0% Ventilation: 0.768 62.1 Compliant: 0.834 100% Ventilation: 0.887

Available modeling parameters and configurations for central gas furnaces in EnergyPlus were as follows:

- A maximum supply air temperature setpoint of 104 °F was used for packaged single zone constant air volume (CAV) system.
- Furnaces are automatically sized by EnergyPlus to be sufficient to cover most of the heating load during heating design days.
- Furnace operating thermal efficiency (combination of combustion efficiency and jacket loss impact) is as specified in Table 4.
- The furnace part load curve, which accounts for efficiency losses due to transient coil operation, only impacts furnace gas consumption and not run time hours. The default EnergyPlus curve was used and was identical between the single-stage, two-stage, and modulating furnace due to limited data availability on cycling behavior and efficiency losses for commercial gas furnaces. In the future, testing results may help define new curves.
- Supply fan mechanical efficiency and motor efficiency were the same among all gas RTU scenarios.
- Central system OA intake was used, which accounts for 0%, 62.1 compliant, and 100% OA cases, as well as for the additional damper leakage. The adjustment in damper leakage is modeled as additional OA intake when the damper is closed in the simulation model.
- The airflow through the ERV is assumed to be the design OA intake.

Additional details on the EnergyPlus simulation files and parameters are included in Appendix A.[7]

[5] http://www.armacell.us/products/aparmaflexsaaparmaflexfssa/
[6] The Operating Thermal Efficiency takes into account jacket and combustion losses and is therefore lower than traditional Thermal Efficiency values.
[7] Additional detail can also be found in DOE's Prototype Models, https://www.energycodes.gov/development/commercial/prototype_models.

EnergyPlus cannot dynamically model enclosure losses from the combustion chamber to the ambient temperature. It also cannot model conductive losses through the damper when the damper in closed. In order to account for these factors in this project, the team created an external Excel calculator to calculate total enclosure and damper leakage losses separately, and then used an effective operating thermal efficiency as an input to the EnergyPlus models. The final jacket losses implemented in the model were 1.3% for the 100% outside air case, 6.6% for the 62.1 compliant case, and 13.2% for the 0% outside air case. These losses were subtracted from the calculated thermal efficiency of the unit to determine a representative "operating thermal efficiency" for the units that includes full enclosure losses during the heating season.

These losses assume that:

- the unit is losing heat to the surroundings whenever the internal temperature is greater than the outdoor air temperature,
- when the unit is firing or ventilating, the interior cabinet temperature is equivalent to the mixed air temperature based on a 70 °F[8] return air temperature and given percentage of outside air, and that
- when the unit is off (not firing or ventilating), the fan is off and the dampers are closed. During this period, the temperature inside the unit is assumed to be equivalent to the temperature of the building due to heat transfer from the building into the unit.

Therefore, heat loss through the unit cabinet (containing the furnace, the mixing chamber, blower, and ERV, if present) occurs consistently throughout the heating season (except for ventilating periods for 100% outside air units). Heat loss and leakage through the dampers occurs only when the dampers are closed. Note, these jacket loss corrections were performed only for the Toronto retail model; those losses were assumed to be representative of the additional building type.

The detailed Enclosure Loss spreadsheets are included as Appendix B, which also includes additional assumptions and information on the enclosure losses.

Heating Season

Defining the duration of the heating season constituted a key decision for the new metric and simulation analysis. In order to determine the duration of the heating season, the standards committee analyzed the heating degree days (HDD) and cooling degree days (CDD) within all modeled cities to determine a heating season that best captures the total duration of heating energy use by gas-packaged furnaces, while capturing minimal cooling energy use. The standards committee referenced 3-yr and 5-yr historical weather data obtainable from degreedays.net for the analysis but compared these data to the TMY3 HDD and CDD values, to ensure the historical climate data were reasonably representative. Figure 4 below shows a month-by-month chart of the weighted averages of HDD and CDD occurring in each month for the representative Canadian climate (population weighted average of the five most populous Canadian cities: Vancouver, Toronto, Montreal, Calgary, and Edmonton).

[8] The model also includes a nighttime set-back to 60 °F between 6PM and 6AM.

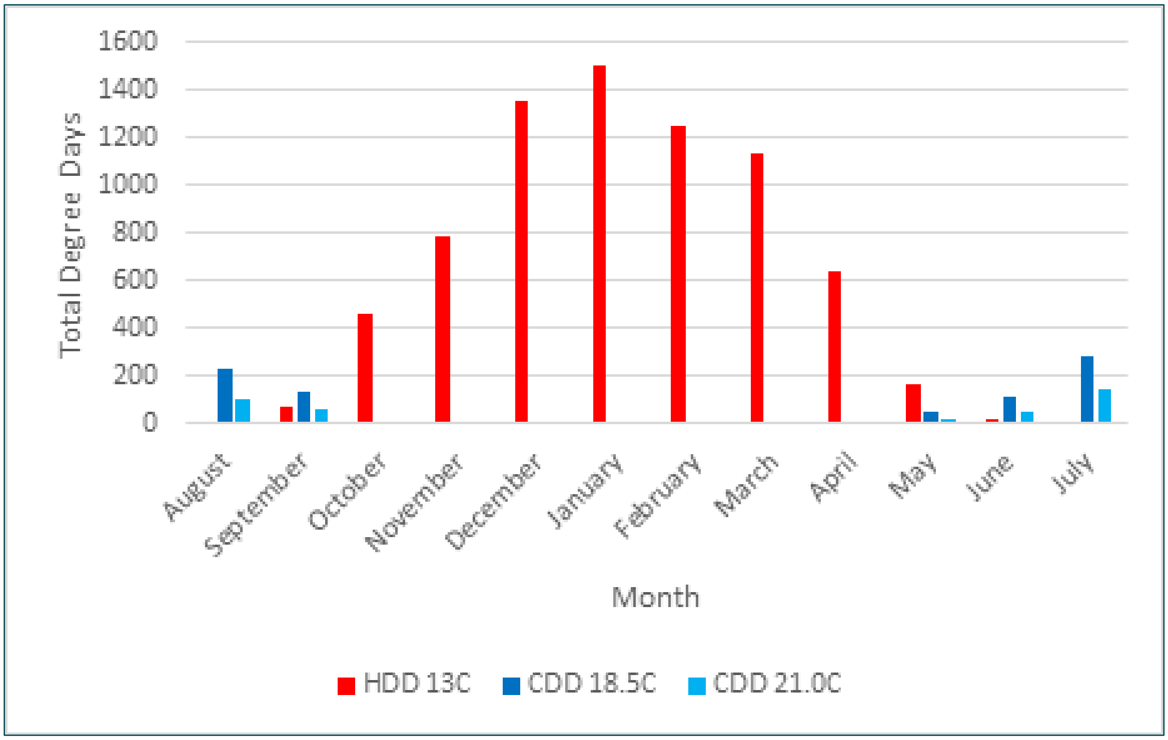

Figure 4: Average Canadian Heating and Cooling Degree Days by Month

The standards committee considered which months should be included in the heating season, based on the number of HDD and CDD present in each month. Based on these data, the committee defined the heating season as October through April, with a total of 5250 hours. This 7-month period represents 96% of the heating load and virtually 0% cooling load, as shown in Table 5.

Table 5: Options Considered for the Heating Season Duration

Potential Season for Analysis	% of HDD	% of CDD
6 Mos (Nov-April)	92	0
7 Mos (Oct-April)	96	0 to 1
8 Mos (Oct-May)	99	6 to 8
9 Mos (Sept-May)	100	21 to 23

This time period was used to analyze the simulation results to determine energy performance and operating hours in each of the representative operating modes.

Results of Simulations

Summary of Analysis Approach

Once the full set of 120 modeling scenarios was complete, the data had to be processed for use with the CSA P.8 standard. The three main outputs of each simulation were:

- The percentage of time each simulated unit spent in each operating mode over the course of the heating season (the selected operating modes are described in more detail below)
- The average outdoor air temperature during the heating season
- Total furnace gas consumption and total fan electric consumption during the heating season

These outputs are described in Figure 5 below.

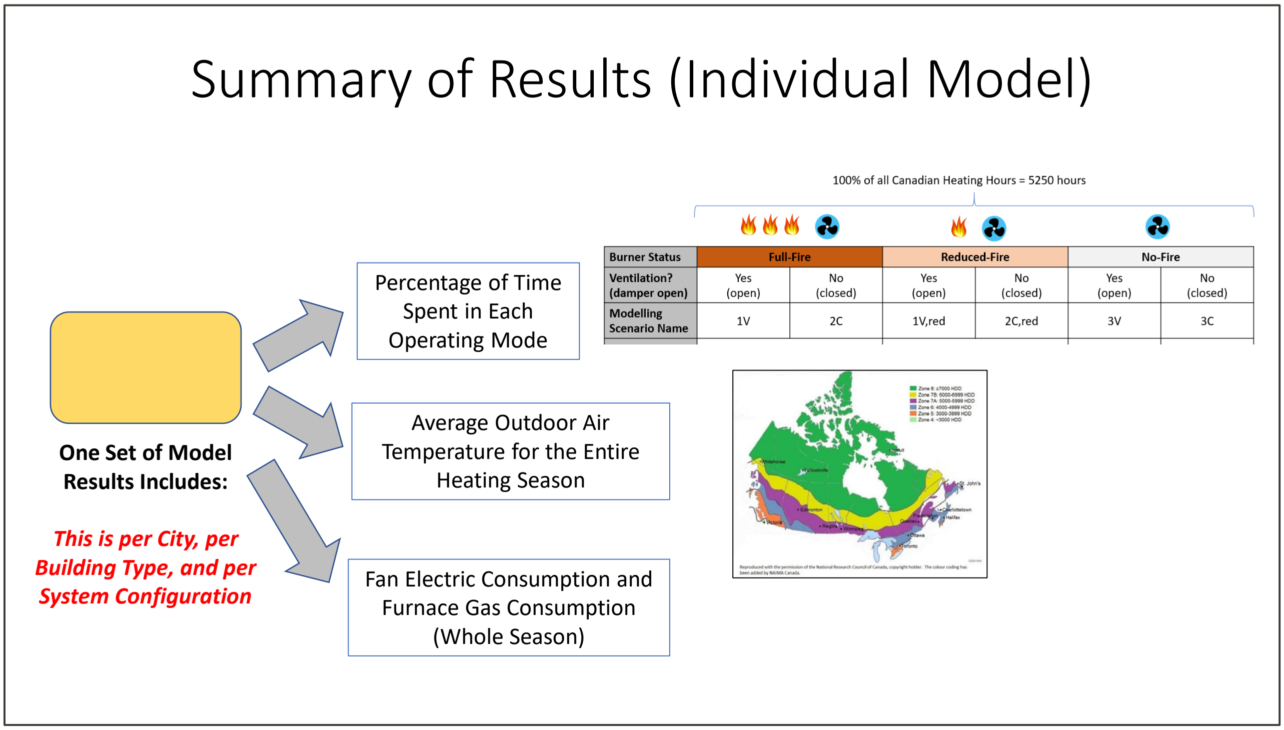

Figure 5: Description of Results from Each Individual Simulation Run

These outputs were then processed for use with the standard. In general, the baseline results from all building types and climate zones were averaged to determine representative operating hour weights and outdoor air temperature inputs for the standard. Specific operating hour weights are defined for each combination of outdoor air percentage and stages of combustion, as these two factors affect run-time and, thus, the operating hour weights. The efficiency scenario results are used to determine the relative energy efficiency benefit expected from different efficiency improvements in the field, which can be used for comparison to results from the metric to ensure the metric is providing reasonable and realistic efficiency comparisons among different units.

Figure 6 below summarizes how the collective results were processed and used.

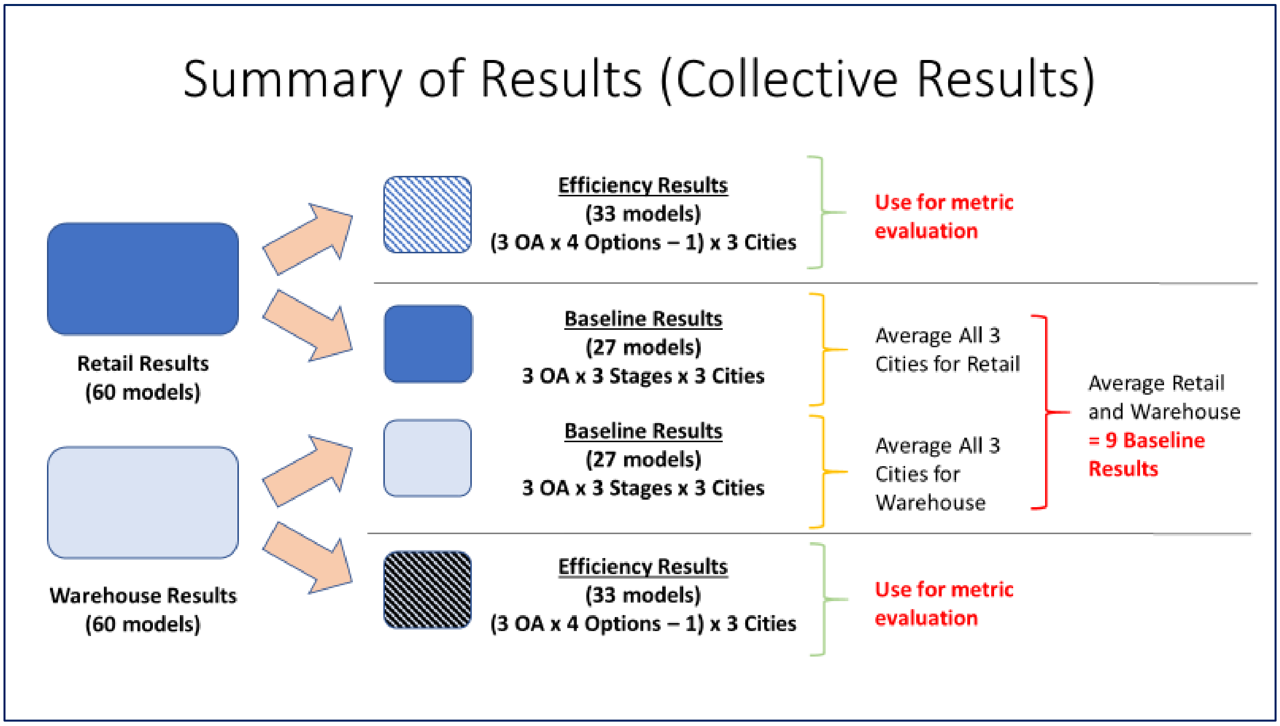

Figure 6: Description of How All Simulation Runs Are Combined

Operating Modes

The original CSA P.8 standard did not contain weighting factors because the standard considered energy performance only when the unit was on (i.e., steady-state operating thermal efficiency). Notably, the standard did not account for losses and resultant energy consumption during ventilating modes or when the unit was not firing. However, as the results below demonstrate, typical gas RTUs spend a considerable amount of time in these operating modes and their performance in these operating modes has a significant effect on the overall efficiency of the unit. Therefore, the new CSA P.8 metric and test method require weighting factors to combine the efficiency contributions of each operating mode, to account for operation and performance during the entire heating season.

The six unique operating states are defined based on two primary factors: (1) the firing status of the unit (full, reduced, or non-firing), and (2) the ventilation mode (ventilating or not), as listed in Table 6 below.

Table 6: Description of All Six Operating Modes in the Simulations

Burner Firing Mode	Ventilation Active or No Ventilation	Equipment Operating Characteristics	Direct Energy Consumption	Losses
Full-Fire	Ventilation Active	Burner operating at 100% Fan operating at full load Outdoor air damper open	Q_{in}, KW_{HS}	Cabinet losses, jacket losses, ERV influence
	No Ventilation	Burner operating at 100% Fan operating at full load Outdoor air damper closed	Q_{in}, KW_{HS}	Cabinet losses, jacket losses, damper losses
Reduced-Fire	Ventilation Active	Burner operating at reduced load Fan operating at reduced load Outdoor air damper open	Q_{in_red}, KW_{LS}	Cabinet losses, jacket losses, ERV influence
	No Ventilation	Burner operating at reduced load Fan operating at reduced load Outdoor air damper closed	Q_{in_red}, KW_{LS}	Cabinet losses, jacket losses, damper losses
No-Fire	Ventilation Active	Burner is off Fan operating at fan-only load Outdoor air damper open	KW_{FO}	Cabinet losses, ERV influence
	No Ventilation	Burner is off Fan is off Outdoor air damper is closed	E_{SB}	Cabinet losses

The EnergyPlus simulation results were used to categorize each operational timestep into one of the above operating modes based on: (1) the heat output of the unit during that timestep (to determine the firing status) and (2) whether the space was occupied (to determine the ventilation status, assuming that the unit is ventilating during all occupied periods).

Findings and Conclusions

As described earlier, the results of the energy modeling can be split into two key findings:

1. Energy consumption and energy savings results (kWh or Btus) and
2. Identification of inputs for use in the forthcoming (third) edition of the CSA P.8 standard

The energy consumption and savings results can be used to analyze relative performance, energy consumption, and efficiency of the simulated units by climate zone, building type, outdoor air requirement, and efficiency scenario. These results are helpful for understanding the expected relative energy consumption and savings among different gas RTU equipment configurations and for assessing the representativeness of the new metric and CSA P.8 test method.

The CSA P.8 inputs include distribution of hours within each operating mode and average outdoor air temperature during the heating season (which can be separately determined in each operating mode).

These results are presented in the graphs and tables below.

Energy Consumption by Climate Zone

The following three graphs show the energy consumption by climate zone (based on representative city) for the baseline scenarios. They demonstrate the differences in total energy consumption by building and by ventilation type, when holding the climate zone constant.

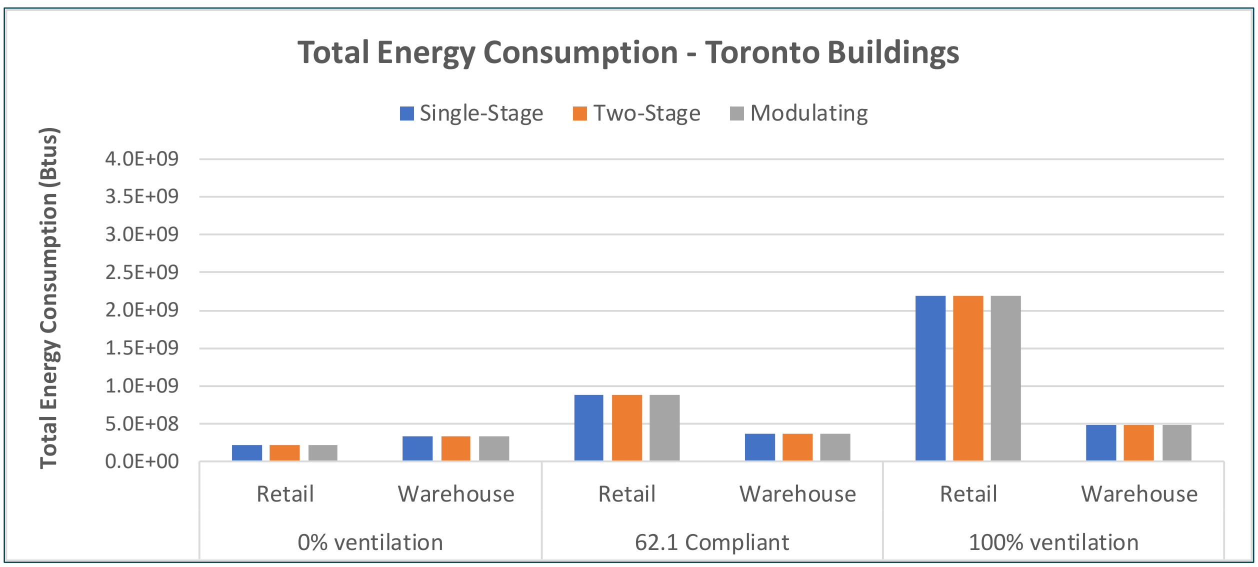

Figure 7: Total Energy Consumption Outputs from Baseline Simulations – Climate Zone 5 (Toronto)

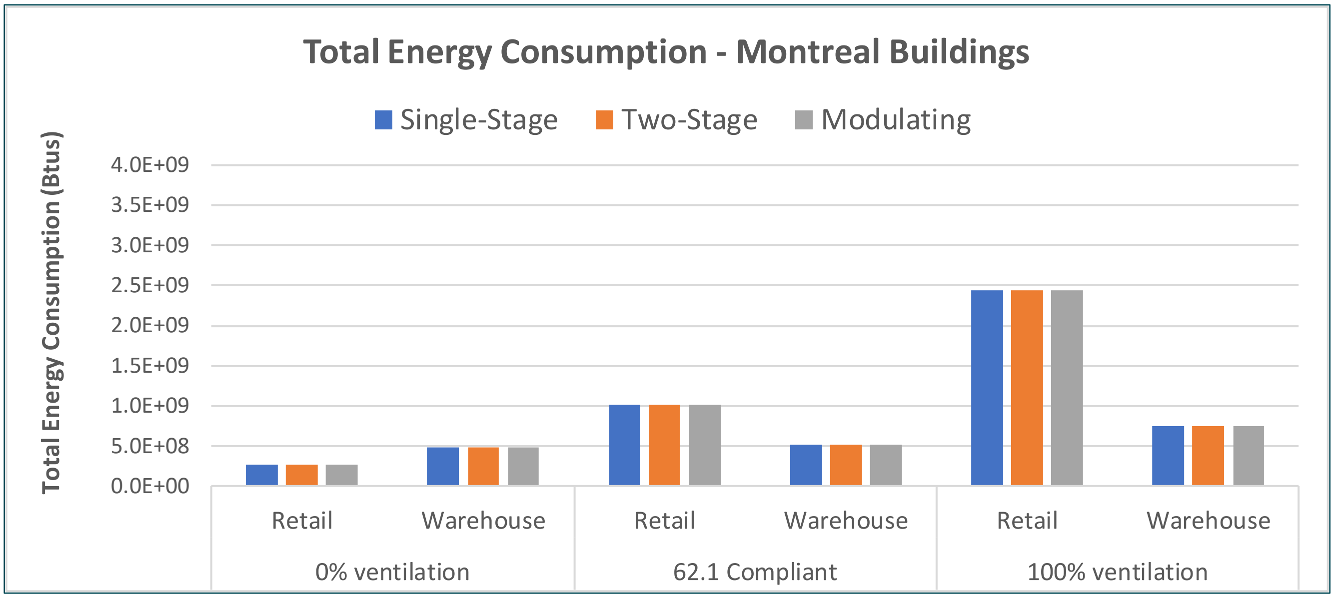

Figure 8: Total Energy Consumption Outputs from Baseline Simulations – Climate Zone 6 (Montreal)

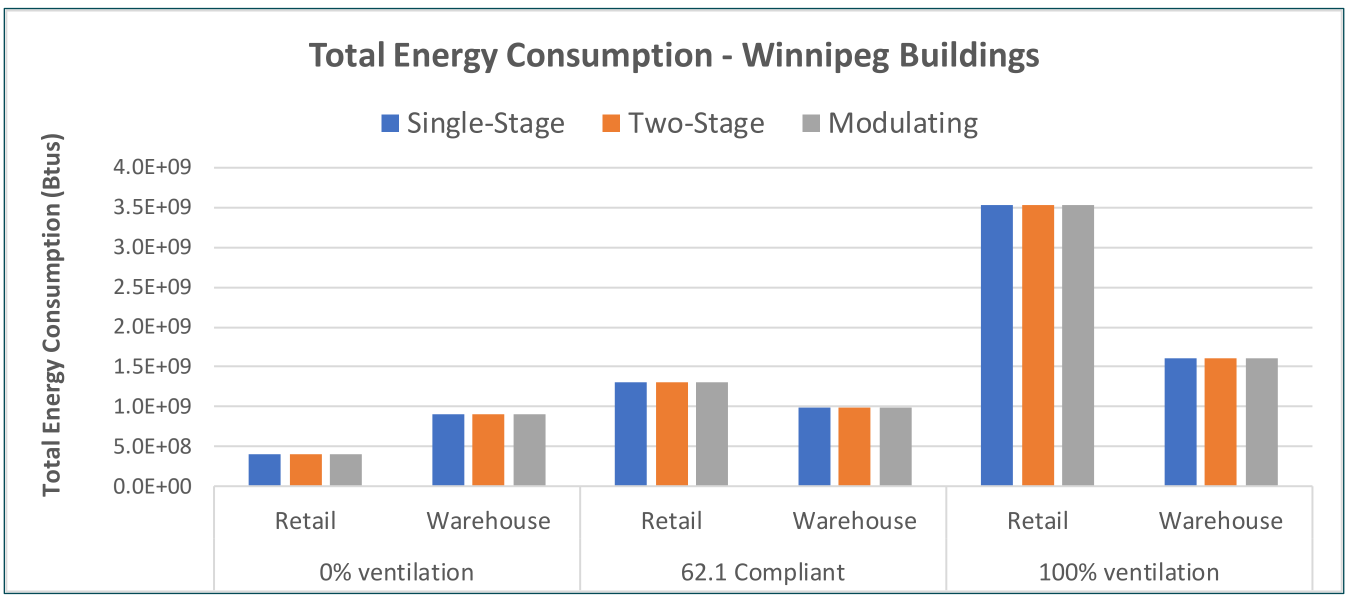

Figure 9: Total Energy Consumption Outputs from Baseline Simulations – Climate Zone 7 (Winnipeg)

As expected, the energy consumption increased for colder climates (see Table 1) and increased significantly with higher outdoor air requirements. The increase is more dramatic for the retail case, since the ventilation requirements are higher and the space is fully conditioned to a 70 °F return air setpoint. In contrast, the warehouse model conditions the space to only 50 °F, which mitigates the increases in both HDD and outdoor air requirements.

Energy Consumption by Building Type and Stages of Combustion

The following three graphs show the energy consumption for the baseline scenarios, divided by building type and stages of combustion. The same trends from the previous graphs are apparent in that these illustrate the greater impacts of ventilation air and climate on the energy consumption of retail buildings compared to warehouses.

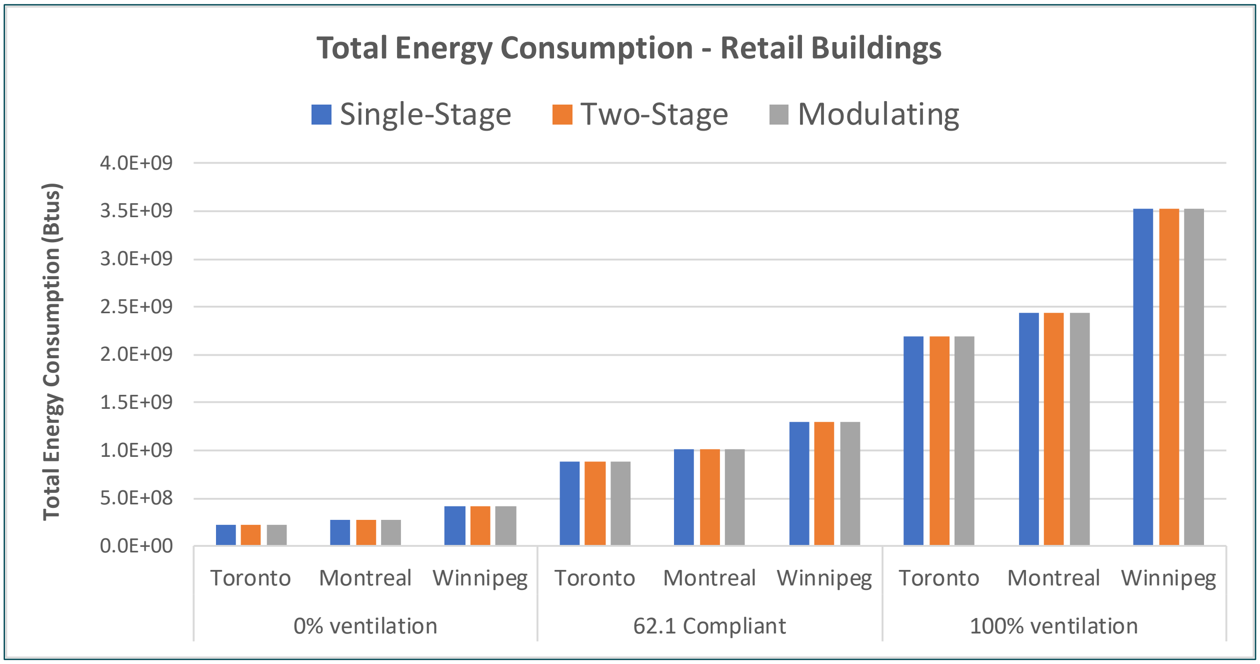

Figure 10: Total Energy Consumption Outputs from Baseline Simulations – Retail Buildings

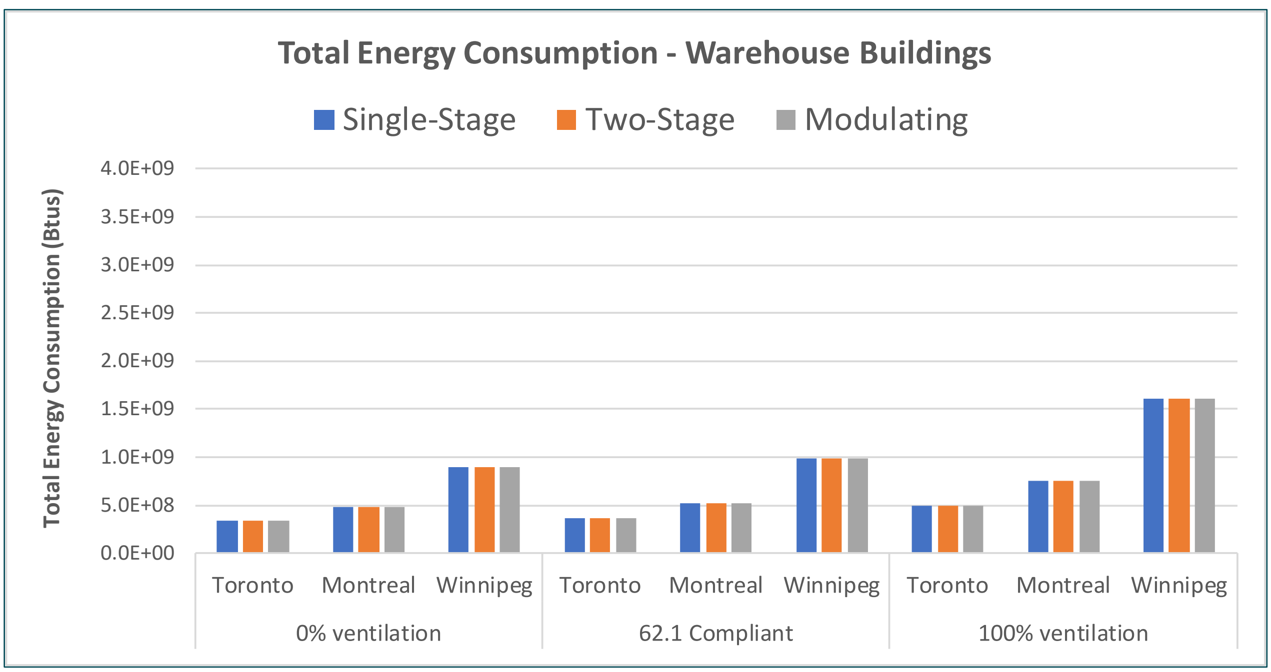

Figure 11: Total Energy Consumption Outputs from Baseline Simulations – Warehouse Buildings

Another finding apparent from Figure 10 and Figure 11 is the impact of the stages of combustion. As the EnergyPlus models assumed equivalent efficiency at full and part load and similar cycling performance across the models, there is no energy consumption impact associated with two- or multi-stage burners. This assumption and result are consistent with existing literature, which suggests a minimal impact of cycling losses for commercial gas furnaces, with comfort as the primary driver for considering multi-stage operation.

Energy Savings for Various Efficiency Options

The EnergyPlus simulations can also be used to evaluate and compare energy savings for the four efficiency options:

1. Increased enclosure insulation
2. Decreased damper leakage
3. Condensing burner
4. Heat recovery (energy recovery ventilator (ERV)

The calculated energy savings were obtained by the following formula:

% Energy Savings = (Baseline Energy Consumption – Efficiency Energy Consumption) / Baseline Energy Consumption

Each efficiency option was paired with a corresponding baseline that matched the city, building type, outdoor air requirement, and combustion stages used for the efficiency option.

The following graphs are broken out by efficiency option to allow comparison of relative performance across multiple cities, buildings, and ventilation types.

Increased Enclosure Insulation. Figure 12 shows the savings from increased enclosure insulation, which is relatively consistent across climate zones (as conveyed by the three cities) and varies from 1% to 11% among the modeled scenarios. Increased enclosure insulation saves more in the warehouse model than in the retail model due to the following factors:

- Both the retail building and the warehouse building save the same percentage of gas with the increased insulation, and
- The warehouse building uses more gas as a percentage of total energy than does the retail building, so the percentage of energy saved is higher

Increased enclosure insulation also saves by far the most energy in the 0% outdoor air case in both the retail and warehouse models, also primarily due to the warmer return air temperature (since outside air is not mixed in in the enclosure).

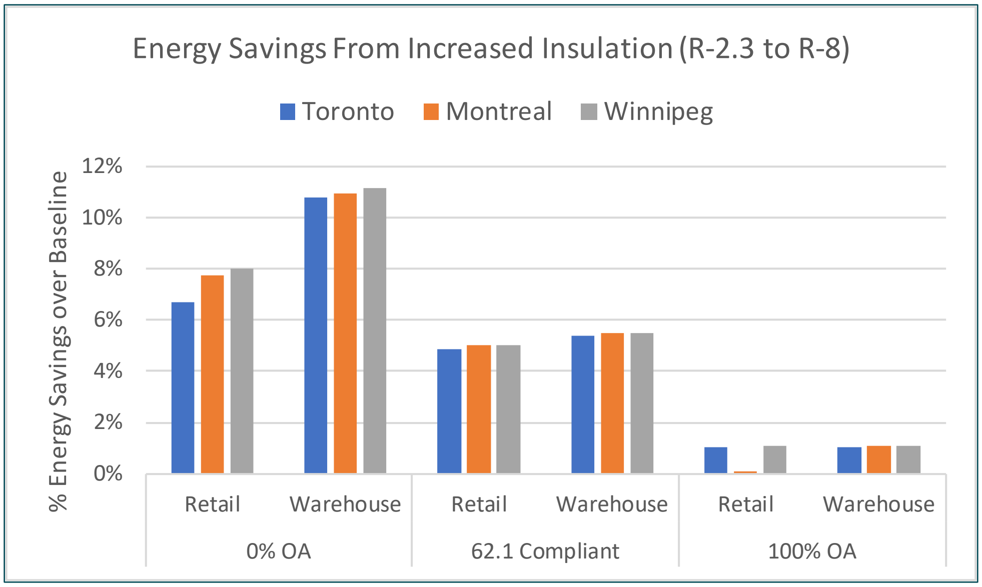

Figure 12: Modeled Energy Savings – Increased Enclosure Insulation

Decreased Damper Leakage Figure 13 shows the energy savings from decreased damper leakage, which is also greatest for the 0% outdoor air case. The 0% outdoor air case assumes the presence of a leaking damper, and thus presents the greatest opportunity available for improvement. Damper leakage also contributes increasingly-higher impacts in the 62.1 compliant warehouse case in colder climates. This is likely due to lower occupied hours (and therefore more hours with the damper closed) for the warehouse case compared to the retail case, with the impact increasing as the climate gets colder.

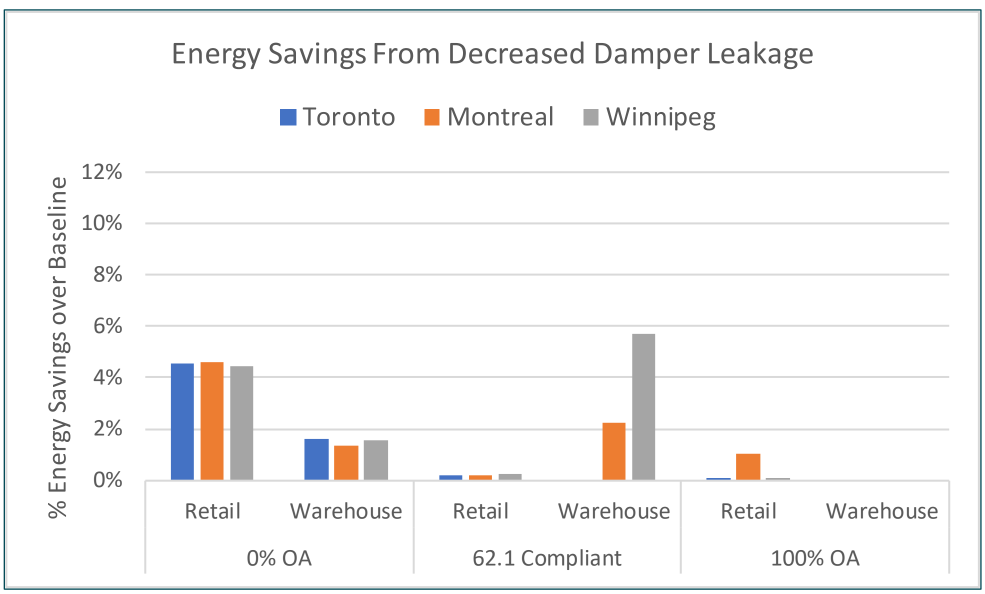

Figure 13: Modeled Energy Savings – Decreased Damper Leakage

Condensing Burners Figure 14 shows the energy savings from adding a condensing secondary heat exchanger to the unit, which results in higher thermal efficiencies for gas consumption. The majority of the scenarios show consistent savings of 9% to 10%, with slightly higher savings for colder cities with a higher percentage of operating hours. In the 0% outdoor air case, the differences in building loads between the retail and warehouse models result in a larger savings difference.

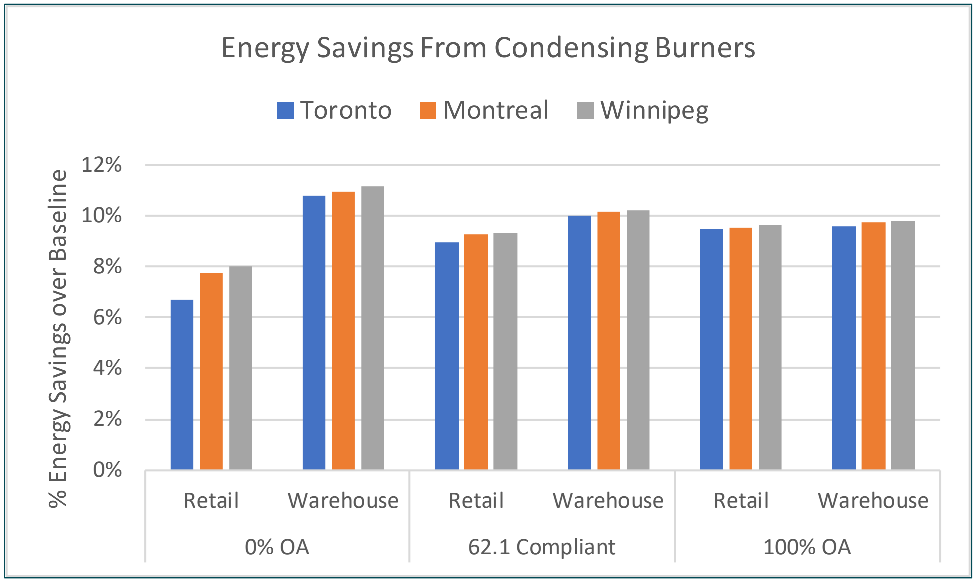

Figure 14: Modeled Energy Savings – Condensing Burners

Heat Recovery Ventilator Figure 15 shows the energy savings from adding a heat recovery ventilator to the building's HVAC system. The savings attributable to the HRV/ERV are much higher than those shown for any of the previously discussed efficiency options. This is because the HRV/ERV takes on part of the heating capacity of the system, reducing the amount of heating capacity the furnace must deliver. This results in considerably more savings than just elimination of heat losses. Because the warehouse model has lower 62.1-compliant ventilation requirements than does the retail space, it exhibits a smaller difference in HRV/ERV energy savings.

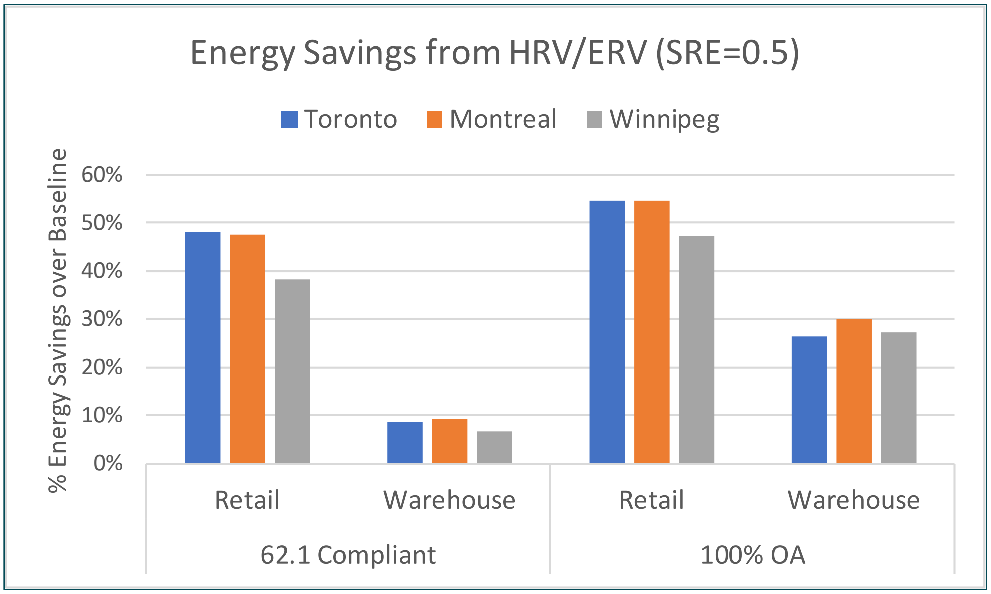

Figure 15: Modeled Energy Savings – Heat Recovery Ventilation

The following graphs, Figure 16, Figure 17, and Figure 18, show the same information as above, broken out by city. These graphs allow for comparison of the performance of different efficiency options by building and by ventilation type. The most striking characteristic observed in these figures is the significant energy savings from adding heat recovery (ERV), which saves up to 55% and delivers the maximum savings for most of the 62.1 compliant (30% outside air) and 100% outside air cases. The next most beneficial energy efficiency option is the condensing gas furnace, which saves between 6% and 11% in both retail and warehouse models and across the outside air scenarios. Increased enclosure insulation can save similar amounts across all three cities in the 0% outside air case, but delivers consistently lower savings for the 62.1 compliant and 100% outside air cases. Finally, decreased damper leakage delivers only minimal savings due to the limited amount of heat lost through the damper compared to overall unit consumption, and to the limited applicable hours, since improved damper leakage is relevant only when the damper is closed.

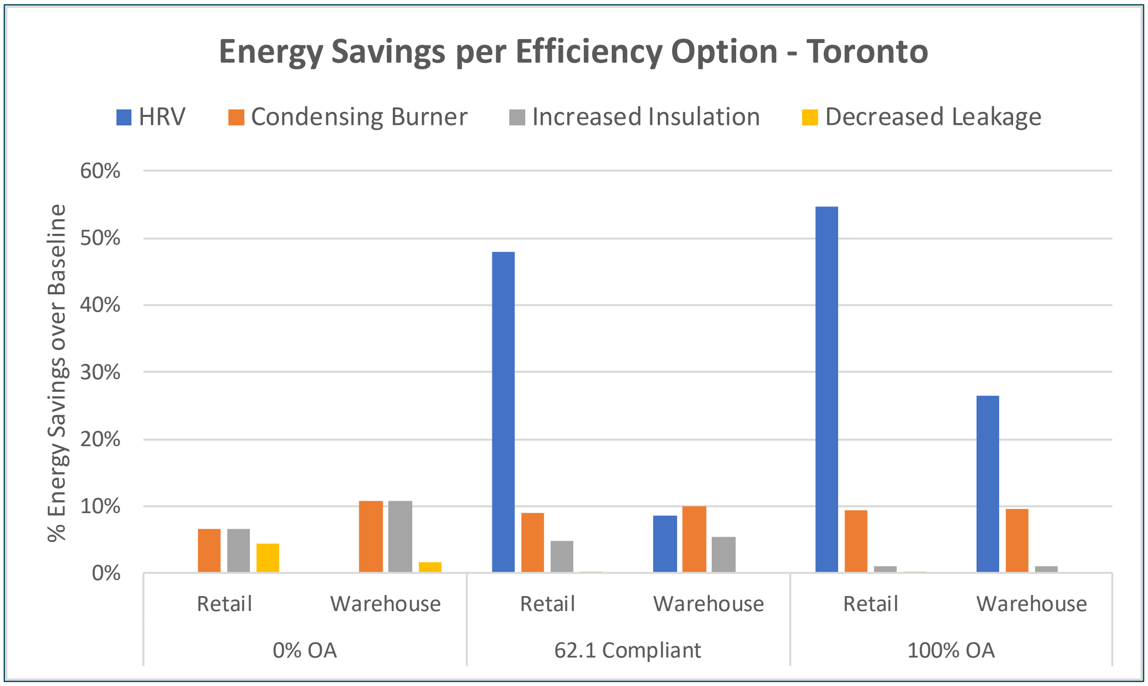

Figure 16: Modeled Energy Savings – Climate Zone 5 (Toronto) Models

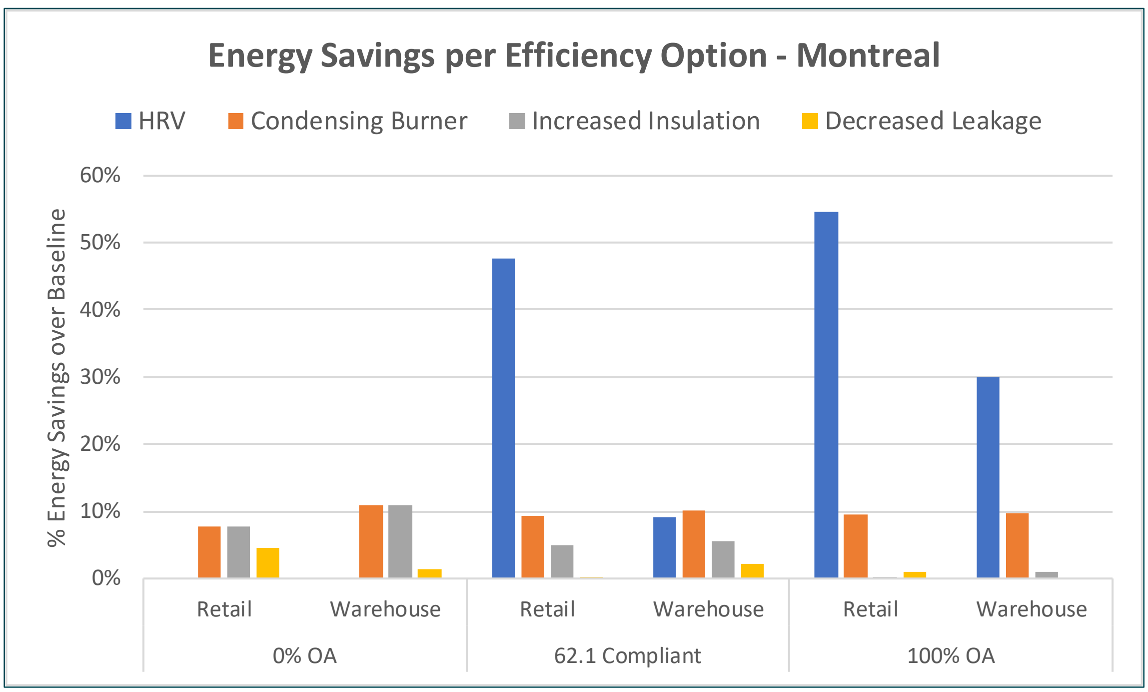

Figure 17: Modeled Energy Savings – Climate Zone 6 (Montreal) Models

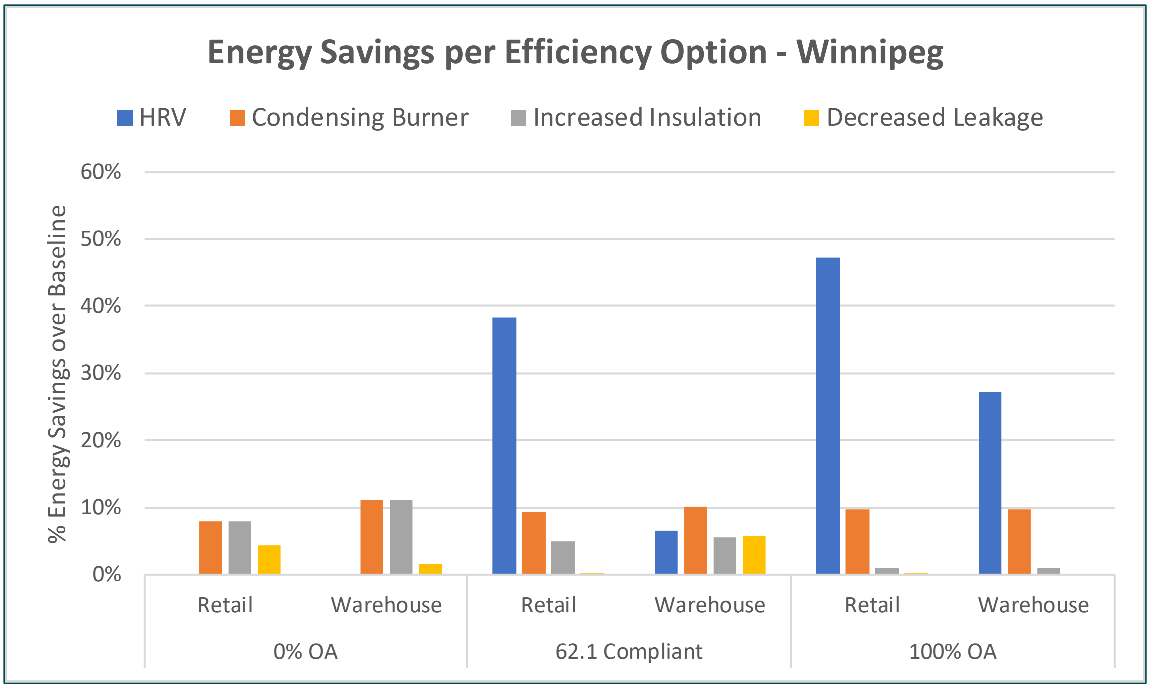

Figure 18: Modeled Energy Savings – Climate Zone 7 (Winnipeg) Models

Time Spent in Each Operating Mode

The EnergyPlus models also revealed the percentage of time the unit spent in each operating mode (described in Table 6) throughout the course of the assumed heating season.

Figure 19, Figure 20, and Figure 21 below show these data. The graphs are split up by city/climate zone.

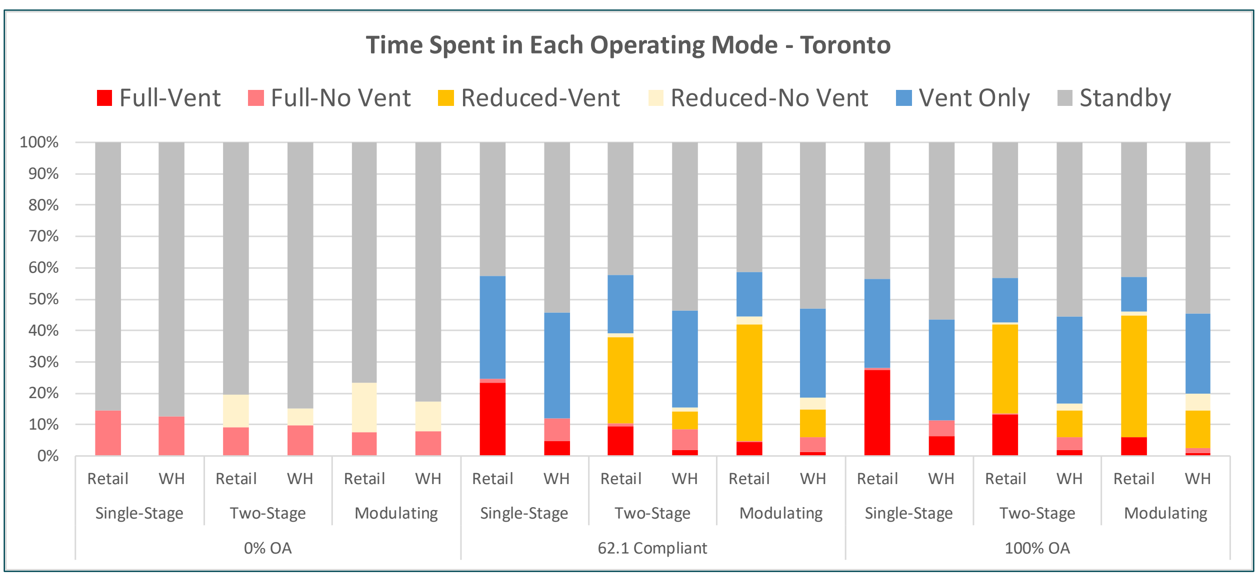

Figure 19: Percentage of Time in Each Operating Mode – Climate Zone 5 (Toronto)

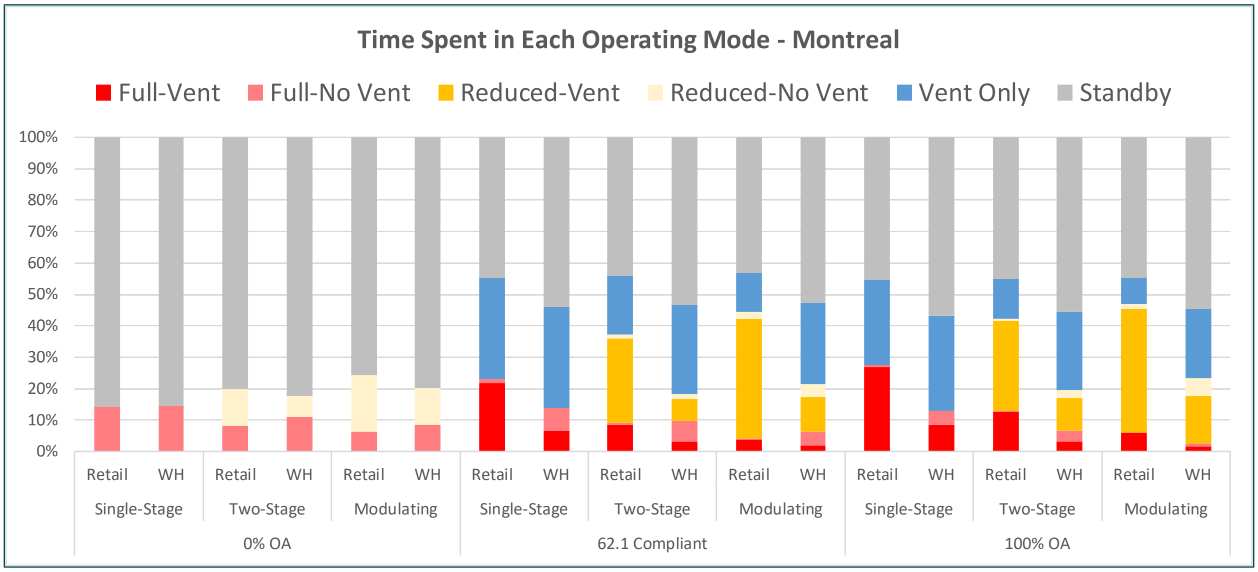

Figure 20: Percentage of Time in Each Operating Mode – Climate Zone 6 (Montreal)

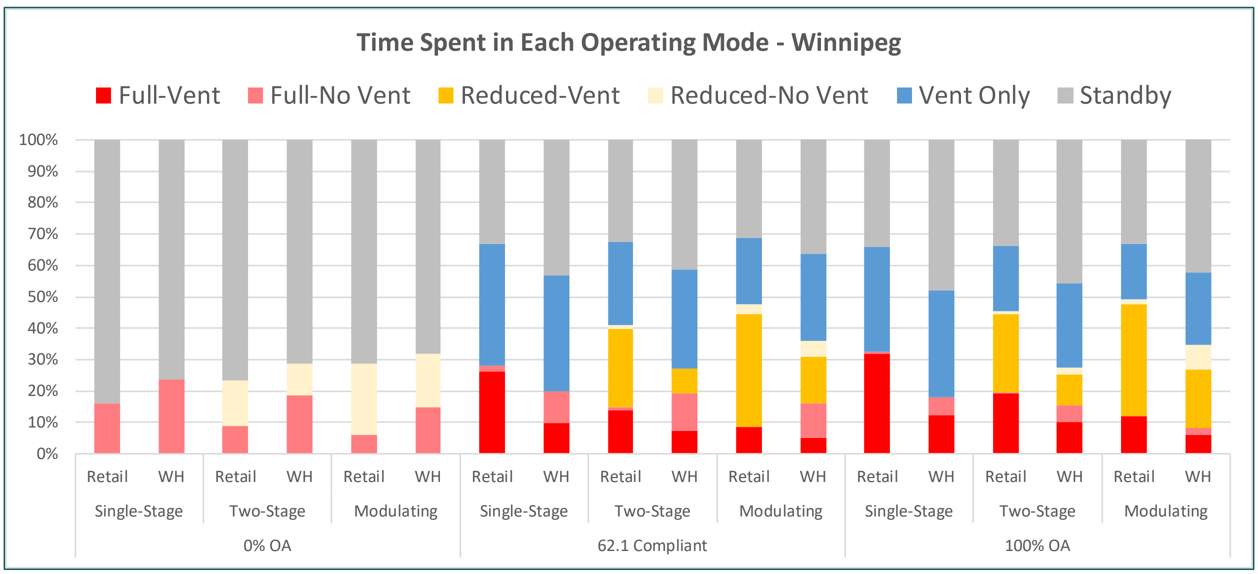

Figure 21: Percentage of Time in Each Operating Mode – Climate Zone 7 (Winnipeg)

As the three preceding charts illustrate, most units spend a significant amount of time (ranging from about 60% to 85%) in a non-firing mode, either standby mode or ventilation-only mode. While overall energy consumption is still dominated by consumption during the full-fire and reduced-fire periods, the additional enclosure losses and electrical energy consumption during the standby and non-firing periods are non-trivial portions of the overall energy consumption of the unit; accounting for them is necessary to accurately describe the energy consumption of the unit over the entire heating season. The specific values are also provided in tabular form in Table 7 and Table 8, below.

Table 7: % of Heating Season Weights, Retail Models (averaged for all 3 climate zones)

Efficiency Scenario	Ventilation Mode	Number of stages for heating	Full Load w/ Ventilation 1V	Reduced Load w/ Ventilation 1VRED	Full load w/No Ventilation 2C	Reduced Load w/No Ventilation 2CRED	Non-firing w/ Ventilation modes 3V	Non-firing w/No Ventilation 3C
Single-Stage furnace	0% ventilation	1	0.0%	0.0%	14.6%	0.0%	0.0%	85.4%
	62.1 Compliant	1	23.3%	0.0%	1.4%	0.0%	33.2%	42.2%
	100% ventilation	1	27.9%	0.0%	0.5%	0.0%	28.5%	43.0%
Two-stage furnace	0% ventilation	2	0.0%	0.0%	8.9%	11.5%	0.0%	79.7%
	62.1 Compliant	2	9.8%	27.0%	0.8%	1.2%	19.7%	41.6%
	100% ventilation	2	13.9%	28.1%	0.2%	0.6%	14.4%	42.7%
Modulating furnace (modeled as four-stage)	0% ventilation	4	0.0%	0.0%	7.0%	17.6%	0.0%	75.5%
	62.1 Compliant	4	4.7%	37.4%	0.3%	2.6%	14.3%	40.7%
	100% ventilation	4	6.8%	38.6%	0.0%	1.4%	11.0%	42.2%

Table 8: % of Heating Season Weights, Warehouse Models (averaged for all 3 climate zones)

Efficiency Scenario	Ventilation Mode	Number of stages for heating	Full Load w/ Ventilation 1V	Reduced Load w/ Ventilation 1VRED	Full load w/No Ventilation 2C	Reduced Load w/No Ventilation 2CRED	Non-firing w/ Ventilation modes 3V	Non-firing w/No Ventilation 3C
Single-Stage furnace	0% ventilation	1	0.0%	0.0%	14.7%	0.0%	0.0%	85.3%
	62.1 Compliant	1	6.1%	0.0%	7.8%	0.0%	33.5%	52.7%
	100% ventilation	1	12.9%	0.0%	0.0%	0.0%	31.6%	55.5%
Two-stage furnace	0% ventilation	2	0.0%	0.0%	11.5%	6.4%	0.0%	82.1%
	62.1 Compliant	2	3.0%	6.5%	7.4%	1.2%	30.0%	51.9%
	100% ventilation	2	7.5%	11.7%	0.0%	0.0%	26.6%	54.2%
Modulating furnace (modeled as four-stage)	0% ventilation	4	0.0%	0.0%	9.1%	11.3%	0.0%	79.6%
	62.1 Compliant	4	1.9%	10.5%	5.5%	4.1%	27.3%	51.3%
	100% ventilation	4	3.4%	19.9%	0.0%	0.0%	23.8%	53.2%

To develop a single set of representative weights for the forthcoming edition of the CSA P.8 test method, these weighting factors (percent operating hours) for each operating mode were averaged, first across each climate zone and then across each building type, while keeping the numbers distinct for the separate ventilation types and combustion stages analyzed for each system. The final CSA P.8 inputs are shown in Appendix C.

Appendix A: EnergyPlus Simulation Inputs and Results

Combined
EnergyPlus Results_

Appendix B: Enclosure Loss Spreadsheet

The three spreadsheets contain the assumptions and calculations used to derive the enclosure and damper losses that were used as inputs to the EnergyPlus simulations.

Jacket Loss Toronto-0%-PNNL_M

Jacket Loss Toronto-33%-PNNL_

Jacket Loss Toronto-100%-PNNL

Appendix C: Results for CSA P.8

The following tables for the CSA P.8 standard were produced using the data presented in this report. They are:

- Fraction of yearly hours of operation for burner and fan modes
- Ratio of hours that the outdoor damper is open and closed for each control type, mode of fire, and percent of return air from outside for ventilation
- Weighted average outdoor air temperature and mixed air temperatures (with and without automated internal dampers) for calculation of enclosure losses

The data in these tables are calculated using the results of the energy modeling. The tables represent an average of the different buildings, cities, and control types, when applicable. The values of the three cities were averaged using the following weights:

- Toronto: 50.5%
- Montreal: 36.3%
- Winnipeg: 13.2%

All other averages were taken at equal weights among all elements. In some cases, the weights of the operating modes were used to calculate average temperatures during the heating season.

Table 9: Fraction of Yearly Hours of Operation for Burner and Fan Modes

Control Type	Percent of return air from outside for ventilation, %OA	High Fire, W_{HS}	Low Fire, W_{RED}	Fan only, no fire, W_{FO}	Standby, burner off, fan off, W_{SB}
Single Stage	0	0.147	0.000	0.000	0.853
Single Stage	30	0.192	0.000	0.333	0.474
Single Stage	100	0.207	0.000	0.301	0.493
Two Stage	0	0.102	0.089	0.000	0.809
Two Stage	30	0.105	0.179	0.249	0.467
Two Stage	100	0.108	0.202	0.205	0.485
Modulating	0	0.080	0.144	0.000	0.775
Modulating	30	0.062	0.273	0.208	0.460
Modulating	100	0.051	0.299	0.174	0.477

Table 10: Ratio of Hours that the Outdoor Damper Is Open and Closed for Each Control Type, Mode of Fire, and Percent of Return Air from Outside for Ventilation

Control Type	Percent of Return Air from Outside for Ventilation, %OA	Ratio of hours when the outdoor air damper is closed and at full fire, D_{IN}	Ratio of hours when the outdoor air damper is closed and at reduced input, D_{RED}	Ratio of hours when the outdoor air damper is closed or not present and the furnace is not firing, D_{off}	Ratio of hours when the outdoor air damper is open and the fan is on and the furnace is firing, D_{vent}
Single Stage	0	1.000	NA	1.000	0.000
Single Stage	30	0.238	NA	0.587	0.480
Single Stage	100	0.133	NA	0.621	0.480
Two Stage	0	1.000	1.000	1.000	0.000
Two Stage	30	0.390	0.066	0.653	0.480
Two Stage	100	0.194	0.073	0.703	0.480
Modulating	0	1.000	1.000	1.000	0.000
Modulating	30	0.465	0.123	0.689	0.481
Modulating	100	0.151	0.120	0.732	0.481

Table 11: Weighted Average Outdoor Air Temperature and Mixed Air Temperatures (With and Without Automated Internal Dampers) for Calculation of Enclosure Losses

OA%	Temperature of air °C	T_{mixed} without automated internal dampers °C	T_{mixed} with automated internal dampers °C
0	-2	21.1	2.3
30	-2	17.8	7.0
100	-2	10.0	-1.2