PARAMETRIC ANALYSIS OF ENERGY RECOVERY VENTILATION PERFORMANCE IN THE HIGH RISE RESIDENTIAL SECTOR: A TORONTO CASE STUDY

By

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Parametric analysis of energy recovery ventilation performance in the high rise residential sector: A Toronto case study

Abstract

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The performance of energy recovery ventilation (ERV) units is analyzed for high rise residential buildings in the Toronto climate. ERV units are scrutinized by their ability to recover heating and cooling energy throughout the year. The rated effectiveness of ERV units is well documented through applicable Standards. Several factors are identified which have the potential to influence the impact of ERVs under actual operation conditions, including infiltration rate, ERV leakage flows, temperature set points, and operation schemes. *EnergyPlus* is used to represent a typical residential suite, through which the impacts of the parameters are studied. Performance of the ERV model is validated through comparison to collected temperature and humidity data from an operating ERV unit in the GTA. Results indicate that leakage flows within the ERV represent the highest potential contributor to ERV performance. Economizer control strategies are determined as a viable option for improving performance during warmer seasons.

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ASHRAE – American Society of Heating, Refrigeration and Air-Conditioning Engineers

AHRI – Air-Conditioning, Heating and Refrigeration Institute

DOE – U.S. Department of Energy
EATR – Exhaust Air Transfer Ratio
ERV – Energy Recovery Ventilation
GJ – Gigajoules
MURB – Multi-Unit Residential Building
NECB – National Energy Code for Buildings (Canada)
NRCan – Natural Resources Canada

1.0 Introduction

The use of mechanical ventilation for fresh air delivery in residential buildings has gained prominence in recent years. In part this is due to an improvement in building air tightness, reducing ventilation from infiltration air flows [1]. Adequate ventilation has now become a competing priority in many modern building codes, demonstrated by the *ASHRAE 62.1* Standard series, which stipulates minimum outdoor rates for occupied spaces [2]. In a cold climate, however, providing more fresh air equates to increasing the energy required for heating in the winter and cooling in the summer. Therefore a tradeoff between outdoor air delivery and energy consumption must be reached. As building envelope quality increases, ventilation becomes all the more important as it becomes a more defining factor in terms of both the overall heating loads due to increased insulation levels, and the indoor air quality due to reduced infiltration [3].

Typical high rise residential construction over the past several years has utilized a corridor pressurization system as a means of both combating stack flows and providing fresh air to suites. In this system, outdoor air is provided to the corridors of the residential building via a centralized make up air system to create a positive pressure differential. Air is then theoretically transferred to the residential suites beneath the suite entry doors. Airflows needed to create this positive pressure differential are significant, which is problematic in terms of the energy needed to heat and cool this air. More recently, higher performance residential building have revised this strategy by providing fresh air via much smaller air handling units within each suite. Coupled with compartmentalizing the suite from the corridor by installing weather-stripping at the suite entry door, suites are sealed off from the rest of the building in terms of airflow. As a result, the total volume of pressurization air per suite can be reduced, and therefore total energy consumption is reduced as well.

With local exhaust and local supply air directly in the suite, an energy recovery ventilation system can be utilized to further reduce energy consumption. This simple technology works by passing the exhaust air stream of a building by the incoming outdoor air supply, often through a wheel or plate type device. Heat, in the case of heat recovery ventilation (HRV), or heat and moisture, in the case energy recovery ventilation (ERV) is passed between the two air streams, providing a buffering effect to the incoming air. The performance of the ERV in this study is defined as the rate of heating or cooling recovery at any given time which is passed through the ERV. While HRV devices are capable of sensible energy recovery, ERV devices are capable of both sensible and latent recovery. ERV units are compatible with many types of mechanical systems in several different building types, for example in office, warehouse or residential buildings. The use of ERV devices in high rise residential condominiums is of primary concern in the current study, due to the prevalence of condominium building construction in the Toronto market. These units are typified by small amounts of ductwork and often simplified control schemes compared to centralized, large scale ERVs typical of office buildings. Building types which may utilize similar ERV devices to those analyzed here may include hotel room or small scale retail spaces.

ERV units have been shown to be effective in reducing the heating and cooling load of the ventilation air in residential buildings through experimental analysis and modeling. Effectiveness, however, is often based on testing in laboratory conditions, and does not necessarily reflect the true operation of the unit. The Air-Conditioning, Heating and Refrigeration Institute (AHRI) has developed and maintained Standard 1060, for *Performance Rating of Air-to-Air Exchangers for Energy Recovery Ventilation Equipment*, which stipulates the conditions under which ERV devices are rated [4]. In reality, many external factors can impact the operation of ERV units, threatening to reduce the real world performance. As identified in the literature, this includes room infiltration [5,6,7], unbalanced airflows encountered through the ERV due to leakage [5,6], unanticipated temperature set points [3,8,9] or operation of the unit [1,10]. As these issues are often presented in isolation, their relative significance under real world operating conditions is unclear.

Creating an energy model of a typical residential suite acts as a test bed in which the impacts of these factors can be analyzed and compared. Utilizing the *Energy Plus* energy modeling software allows the manipulation of complex airflows within the suite, as well as the modification of temperature set points and ERV operation. In turn the impact to ERV performance during peak periods and throughout the year can be quantified as a function of these factors. Comparative analysis can further determine the relative significance of the parameters in question.

Prior to completing the parametric analysis, the energy model must be verified as operating as intended for a typical residential unit. Validation is done by making use of data collected from an installed, operational in-suite ERV unit in the Greater Toronto Area (GTA). By collecting temperature and humidity reading at the inlets and outlets of both the supply and exhaust air stream of the ERV unit, the installed ERV units core operating effectiveness can be estimated, as well as the sensible and latent recovery rates. To ensure proper operation in the model, the impact of variations in outdoor dry bulb temperature and outdoor humidity ratio on the sensible and latent recovery rates, respectively, can be scrutinized and compared between the measured and modeled ERV unit. These factors are of significance, as with all else equal they define the recovery rates and therefore performance of the ERV.

2.0 ERV performance review

There has been little shortage in the number of experimental or simulation studies undertaken to determine the resulting impacts on building energy performance from ERV unit installation. As a result, several parameters which influence actual ERV performance can also be found in the literature. A review of these parameters is presented in sections 2.2 through 2.5. Influencing factors of interest are those which have real world connotations with regard to ERV performance in a high-rise residential setting. These include infiltration, ERV unit leakage, indoor temperature set point, and ERV unit operation. The relative magnitude of these factors is also analyzed with respect to real world expectations in the high rise residential setting. A summary of the current industry standards used to rate ERV performance is presented in section 2.1 to provide a background of the performance evaluation of ERV systems.

2.1 Standard performance evaluation of ERVs

Manufacturers typically highlight an ERV units' ability to recover energy by reporting its sensible effectiveness, latent effectiveness and total effectiveness. As a means of standardizing the rating of ERV equipment, the AHRI has developed and maintained Standard 1060, for *Performance Rating of Air-to-Air Exchangers for Energy Recovery Ventilation Equipment* [4]. Sensible, latent and total effectiveness of an ERV are standardized by stipulating the dry and wet bulb conditions under which the ERV is tested, for both heating and cooling condition. Testing is done at 100% and 75% of the design flow, under balanced conditions (i.e. where the supply and exhaust flows are equal).

The AHRI provides the following equation to determine nominal sensible effectiveness of ERV cores:

$$\in_S = \frac{\dot{m}_S}{\dot{m}_{min}}\left(\frac{X_1 - X_2}{X_1 - X_3}\right) \qquad (1)$$

Where:

$\in_S$ = sensible recovery effectiveness
$\dot{m}_S$ = supply air mass flow rate
$\dot{m}_{min}$ = minimum of supply and exhaust air mass flow rates
X_1 = dry bulb temperature of the supply air entering the heat exchanger
X_2 = dry bulb temperature of the supply air leaving the heat exchanger
X_3 = dry bulb temperature of the exhaust air entering the heat exchanger

Latent effectiveness, meanwhile, is dependent primarily on the absolute humidity ratio of the airstreams entering and exiting the ERV core, rather than temperature. Therefore, to determine latent effectiveness, temperature is replaced by the absolute humidity ratio of the relevant conditions, as follows:

$$\in_l = \frac{\dot{m}_s h_{we}}{\dot{m}_{min} h_{we}} \left(\frac{HR_1 - HR_2}{HR_1 - HR_3}\right) \quad (2)$$

Where:

$\in_l$ = latent recovery effectiveness
HR_1 = humidity ratio of the supply air entering the heat exchanger
HR_2 = humidity ratio of the supply air leaving the heat exchanger
HR_3 = humidity ratio of the exhaust air entering the heat exchanger
h_{we} = heat of vaporization of water

The AHRI standard has also incorporated rating the proper construction of the unit by accounting for losses in airflow through leaks or cracks in the unit, referred to as the exhaust air transfer ratio (EATR). This is done via a tracer gas test through the ERV unit.

EATR is calculated by the equation:

$$EATR = \frac{C_{TG,2} - C_{TG,1}}{C_{TG,3} - C_{TG,1}} \quad (3)$$

Where:

$C_{TG,1}$ = The concentration of tracer gas entering the supply side of the ERV
$C_{TG,2}$ = The concentration of tracer gas leaving the supply side of the ERV
$C_{TG,3}$ = The concentration of tracer gas entering the exhaust side of the ERV

The EATR accounts for any transfer of tracer gas from the entering exhaust side of the ERV unit to the supply air stream. Effectiveness of the ERV is consequently impacted, as temperatures and flows through the unit are influenced by the EATR. EATR also provides a means to measure indoor air quality, as exhaust streams often originate from restrooms or other spaces with ostensibly poor air quality.

EATR can then be incorporated into equation 2 to determine a net, or overall effectiveness of the ERV unit, calculated as follows:

$$\epsilon_s = \frac{\dot{m_s}(X_1 - \frac{X_2-(EATR)X_3}{(1-EATR)})}{\dot{m}_{min}(X_1 - X_3)} \quad (4)$$

EATR is ideally reported alongside net and core effectiveness to provide a full understanding of ERV performance.

For testing of single family residential ERV units, the *Passiv Haus Institut* (PHI) provides its own guideline for certifying ERV performance. Testing is again performed under balanced flow and laboratory conditions, however goes beyond the *AHRI* by incorporating the electrical consumption of the unit itself into the overall effectiveness calculation [11]. The standard focuses on additional aspects of the ERV performance, such as frost protection, acoustic performance and controllability. Unlike *ARI Standard 1060*, the *Passiv Haus* also stipulate minimum performance characteristics, as it is interested in high performance operation.

Testing ERV performance under ideal laboratory conditions and balanced flow provides an adequate means of standardizing the playing field in which manufacturers state ERV unit performance characteristics. However, as a reflection of actual operating conditions, tested results may be inaccurate for various reasons. Several recent studies have been interested in the in-situ performance testing of ERV units in an attempt to determine their real world impact. As with the configuration and use of energy recovery ventilation devices themselves, this analysis covers a wide range or building types and air handling applications, including small, room scale plate-exchange ERV devices to central air handling units with energy recovery wheel type devices.

2.2 Infiltration

Roulet *et al*. point out that due to infiltration flows, the real heat recovery efficiency cannot equal the nominal heat recovery efficiency [5]. Analysis found that this was partially a result of infiltration airflows entering the space, representing a ventilation load on the building which is not passed through the heat exchanger. Infiltration flows therefore impact the flow through the ERV, as well the temperature which the exhaust stream of the ERV encounters. While Roulet *et al.* focused on large scale, centralized air handling system, other studies have compared ERV performance over a range of building types and HVAC system configurations. The general finding that building envelope tightness plays a fairly significant role is repeated in these studies. These studies concluded that ERV savings are maximized in a more passive building design with a tight envelope, compared to traditional construction methods [7].

These findings makes sense, considering higher infiltration flows essentially represent outdoor airflows which circumvent the ERV core. This means the interior space will approach the outdoor condition more closely than if it was to pass through the ERV. In turn this reduces both the indoor-outdoor temperature and humidity ratio differential, impacting ERV performance. A recent study compared the utilization of ERV units across several building types, including standalone homes and condominium units [12]. Results indicated that more recovery potential existed in the condo unit. Additional recovery was primarily due to a lower air infiltration rate, which allowed the interior space temperature to be on average 2°C higher. Due to this, more heat recovery in winter months is possible, as the temperature differential remains higher in the condo unit [12].

Air infiltration in high rise residential units can vary widely, dependent on numerous factors including location and height within the building, exterior wall construction, degree of compartmentalization and wind patterns. Infiltration rates can be determined through blower door testing, typically run at high pressure differential such as 50 or 75 Pascals. Referenced by the ASHRAE Handbook of Fundamentals, early estimates from 1978 assume air leakage rates 0.51, 1.52 and 3.04 L/s/m^2 of exterior wall area for a tight, average and leaky building envelope respectively, at 75 Pa [13]. For the sake of energy modeling for Code compliance, infiltration is often assumed to be 0.25 L/s/m^2 at nominal conditions, which can be assumed to be approximately a 4 Pa pressure differential [14].

More recently, an extensive study was undertaken to characterize air leakage rates in several high-rise residential building in Canada [1]. Air leakage data was compiled for 43 buildings, ranging in age from the mid 1950s to 2011. Surprisingly, the overall average air leakage was shown to be higher than the leaky value given in [13], at 3.65 L/s/m^2 of exterior wall area at 75 Pa. Air leakage rate were shown to improve with newer buildings, with an average value of about 1.53 L/s/m^2 at 75 Pa, for building constructed after 1990, corresponding more favourably with the assumptions in [13] for the average building. The study further analyzes in isolation residential units which are compartmentalized, noting a leakage rate similar to most newly constructed building, of 1.67 L/s/m^2 at 75 Pa [1].

To estimate air leakage in a tight, high performance building envelope, the *Passiv Haus Institut* provides guidance, stipulating that air leakage cannot exceed 0.6 air changes per hour (ACH) under a 50 Pascal pressure differential, in either an over-pressurized or under-pressurized scenario [15]. However, defining air tightness in terms of air changes per hour has been noted as problematic, as it depends on the buildings volume [1]. For example, in the case of a typical compartmentalized residential suite which has a volume of 189 m^3 and exterior wall area of 18.9 m^2, as described in section 3.2, an infiltration rate of 0.6 ACH translates to a less tight envelope than the typical value of 1.67 $L/s/m^2$ at 75 Pa for a compartmentalized suite. When considering a residential condo unit, the volume to exterior wall area ratio is much less than a standalone residential building, which is the primary focus of the *Passiv Haus* standard. Therefore it follows that the overall infiltration rate is less, supported by the results in [12]. Comparison of infiltration rates in condo units and standalone houses indicates that air tightness in newer, compartmentalized residential suites is generally very good. A possible explanation is that many buildings with this system are now attempting LEED® certification, and thus project teams must now pay attention to this metric in order to qualify [1].

To determine a stringent target of air tightness for comparison in high rise residential suites, the United States Army Corps of Engineers (US ACE) requirements are therefore relied on. The US ACE requires air tightness testing of all its buildings, and stipulates a performance standard of 1.27 $L/s/m^2$ at 75 Pa, which represents increased air tightness over the typical rate for compartmentalized suites [1]. In this study, this value will represent a best practice in terms of suite air tightness.

2.3 ERV Unit Leakage

Additional parasitic airflows or unintended recirculation of air will further reduce the actual heat recovery efficiency to something below its rated value. A product of poor design or construction, these parasitic flows can occur in a number of scenarios – including poorly sealed ductwork causing leakage, poor sealing of the ERV units themselves, directly interrupting the ERV performance, or external short-circuiting, where exhaust flows are located adjacent to air intakes [5]. Parasitic flows are related to the EATR, described in section 2.1, however actual operation, rather than rated test conditions in the case of defining EATR, is of interest to this study.

In a recent study, the impact of flow leakage was demonstrated though airflow measurement in 10 centralized heat recovery units throughout Germany. Findings indicated that buildings with poor ERV unit construction can experience significantly reduced real recovery efficiency, by factors of between 50 and 90% [5]. The authors further argue that ventilation fans will consume electricity in serving their function of ventilating the building, pointing to the importance of selecting efficient supply fans for the air handling unit as well. It is worth noting, however, that all residential buildings will require some form of mechanical ventilation to comply with current Building Code minimum ventilation rates, so this argument is not reserved for buildings employing heat recovery devices. Fan system efficiency should be considered for all ventilation systems.

The impacts of short circuiting ERV units has also been analyzed in single room, smaller ventilation units more typical of the residential unit installation. Several recent studies seeking to investigate the performance of these smaller units have been identified [3,6,7,8,16].

Manz *et al.* at first noted that high rates of energy recovery can theoretically be realized [16], however go on to demonstrate that air leakage and short circuiting of air flows remains a problem in single room ERVs [6]. Further to the findings in [5], the authors demonstrate three unintentional airflows in smaller ERV devices which play a role in performance: external flow of exhaust air into the fresh air supply due to proximity of supply and exhaust registers; mixing of supply air into the exhaust air within and upstream the ERV unit; and mixing of exhaust air into the fresh supply air within and upstream of the ERV unit. All of these flows are a product of poor construction or design. Using tracer gas techniques, flows were measured in an experimental set up, demonstrating through measurement and numerical modeling that even under ideal balanced flow conditions, the heat recovery of ERV units can be overestimated by as much as 63% [6]. As a point of comparison, *ASHRAE Standard 62.1-2007: Ventilation for Acceptable Indoor Air Quality* has recently addressed transfer of air in heat exchangers, which suggests that anything above a 10% is unacceptable in terms of supply air quality [2].

Parasitic flows can be subdivided further into one of the two internal leakage flows, or the external leakage flows identified above. Leakage ratios in single room ERVs were calculated to be between 2% and 10% for external short circuits, and between 22% and 58% from short circuiting within the ERV itself. As stated above, this impacts both performance and indoor air quality. For the purposes of this study, external leakage flows will not be analyzed, as this leakage does not modify the flow through each side of the ERV core and into the unit. Nor will flows from the exhaust air stream to the supply air stream of the ERV core by considered. These flows are primarily of concern in relation to the impact of air quality entering the suite, as they represent the flow of exhaust air back into the suite. Impacts to indoor air quality from ERV unit cross contamination has been studied recently in the Toronto residential market [17], and therefore these issues are not considered here. External short circuiting of flows in particular can be remedied by proper placement of ERV intake and exhaust grilles by ensuring they are not located adjacent to each other.

Flows from the supply side of the ERV to the exhaust side are of concern to this study, as they represent a reduction in flow through the supply side of the ERV, and therefore a reduction in recovery potential. This flow may be accounted for elsewhere in a balanced system, for example through induction of increased infiltration, or may simply result in decreased supply flow rates. Of the internal short circuiting flows determined in [6], flows from the supply to the exhaust side were noted to be between 17% and 34% of nominal flow. The mid-lower range of internal short circuiting flows defined can represent typical ERV construction. The higher internal short circuiting flows may represent more extreme cases where ERV construction is particularly poor. To determine a point of comparison for particularly good ERV flow control, the *Passiv Haus Institut* is consulted. Under their standard, the *Passiv Huas Institut* will only certify ERVs which can demonstrate a leakage rate of 3% or less of the typical supply flow rate, representing a best practice in ERV construction [11]. A leakage value of 3% is therefore considered to represent an ERV core constructed to particularly high standards, and a best case scenario.

2.4 Temperature Set Points

Fernandez-Seara e*t al.* analyze the performance of plate type heat exchangers under experimental conditions, with analysis primarily concerned with the effect of varying outdoor temperature and humidity set points [8]. Findings demonstrated a near linear relationship of declining recovery rates with increasing fresh air temperature under a heating condition. Following equation 1, this represents a reduction of the temperature differential between the outdoor and indoor temperatures, or X_1 and $X_{2.}$ Under operating conditions, outdoor temperature and humidity can of course not be altered; however a change in indoor temperature set point has also been shown to impact the performance of ERVs. A concern therefore arises in residential buildings, as temperature is typically controlled by the individual tenant, with varying thermal comfort preferences, and there is ultimately very little influence from building managers and operators. Analysis has shown that higher set points can lead to ERVs becoming uneconomical, as this can lead to recovery of excessive heat in the cooling season, or vice versa in the heating season [8]. An example of this may occur during the night time in early summer, where outdoor temperatures fall below indoor temperatures, but recovery of indoor heat is not necessarily desired. Temperature set point have therefore been shown to be highly dependent on climate [9].

Kim *et al*. corroborate this, further noting the importance of temperature set points on energy recovery effectiveness while studying their impact in a temperate region of China [3]. Kim *et al.* concluded that with typical temperature set points (i.e. not overly warm or cool), continuous ERV operation leads to optimal savings throughout the year, meaning that the balance point of heating and cooling energy consumption, and measured recovery rates, does not indicate that a reduced or somehow optimized schedule should be used. Again this analysis is highly dependent on the climate being analyzed, as well as the building occupancy.

The key factor in this analysis is the temperature differential between indoors and outdoors, meaning a more conservation indoor temperature set point (i.e. cooler in the summer and warmer in the winter) will allow for more heat recovery. The benefits of this may be quickly undermined when considering the energy needed to bring the room to the specified set point in the first place, however this warrants further investigation. As indoor temperature set points are highly dependent on the tenants individual comfort requirement, they are therefore difficult to determine for any given residential suite. Modeling standards such as the National Energy Code for Buildings (NECB) in Canada point to typical set point of 24°C during the cooling season, and 22°C in the heating season, with a setback to 18°C overnight [14]. To evaluate the relative impact of temperature set point on winter and summer heat recovery in the Toronto climate, tenants with differing thermal comfort requirements can also be analyzed. By widening these set points to be 26°C in the cooling season and 21°C in the heating season, a 'conservative' tenant who is more concerned with their utility bill is represented. Conversely, a 'liberal' tenant more concerned with thermal comfort is represented by setting the thermostat to a constant 23°C year round.

2.5 ERV Control Strategies

While temperature set points are of potential significance to ERV performance, control of ERV units based on temperature set points is more typical in office rather than residential buildings. Rasouli *et al.* studied the impact of ERV operation in a range of climates. In their study they noted a negative effect if ERVs are left uncontrolled in an office with a centralized HVAC system [18]. In cold climates, this becomes an issue when the ERV is operating during the summer. In this situation, the unit may recover unwanted heat when the outdoor temperature falls below the room temperature, but cooling loads remain due to internal and solar gains [18]. Realizing that summer recovery is primarily influenced by latent recovery in a cold, humid region (such as Toronto), Rasouli *et al.* note that increasing latent effectiveness of the ERV will prolong beneficial operation of the ERV throughout the year. Otherwise, the authors recommend that the ERV unit operation is limited based on the ratio of the sensible and latent effectiveness [18].

While effective in office buildings, this presents a potential issue in residential suites. Typical MURB ERV unit installations give users the capacity to turn on or off the ERV within their unit with a push button controller, often in conjunction with bathroom fan use. However there are no control strategies that operate the ERV automatically based on temperature or humidity differentials. Rather, ERV operation is often left to the discretion of the user, and any control is done manually by a tenant who may or may not have an understanding of ERV performance. Such controls are difficult to estimate given the large range of user preferences that exist, and a current lack of documented knowledge regarding how tenants operate their ERV units. Occupant operation of HVAC set points has been further determined to be impacted by the type of HVAC installation and their familiarity with them, adding to the problem when complex mechanical systems are introduced to the average residential tenant [10]. Without further information regarding how the tenant controls the ERV, it is reasonable to assume that it is left default as running continuously, year round. This operation strategy is common for energy modeling in high rise residential buildings for Code compliance, as minimum ventilation rates are achieved continuously.

Due to this potential improper use, an automated ERV controller may be warranted in residential suites, and its potential inclusion as a control options can be analyzed. In order to maintain ventilation rates, the ERV device must be equipped with a bypass, to allow economizer operation when it is beneficial. Economizer control strategies respond to outdoor air temperatures by bypassing any mechanical cooling equipment to allow outdoor air to enter the space directly. Economizers are typically operated to bypass a cooling coil when a set point is desired, but outdoor temperatures are able to provide comfortable temperatures without the use of a cooling coil. In this case, the ERV core is bypassed to provide free cooling, potentially reducing the impact of unwanted heating from the ERV core. Standard *ASHRAE 90.1-2010* recommends that economizers are given a high limit shutoff of 24°C in the Toronto climate, above which economizer operation does not occur [19].

As mentioned, alternatively the impact of user control of the ERV by anticipating manual shutting down and starting up of the unit, in conjunction with opening of suites windows or balcony doors, could be estimated. However, given the range of tenant behaviour which may be encountered, and the limitations of the current literature to estimate this type of operation, this is not studied further.

2.6 ERV Performance Concluding Remarks

To summarize, the current literature points to numerous issues which may impact real ERV operation. In single room ERV units in particular, the impacts of primary interest include increased infiltration rates, short circuiting of air flows from poor ERV unit construction, and reduced optimization of recovery due to atypical indoor temperature set points, or ERV control schemes.

A review of current literature, as well as applicable Codes and Standards, reveals the anticipated range of values and operation schemes which can be expected with regard to these parameters. By considering this, the parametric analysis is based in reality, and allows the relative degree of influence between parametrics to be scrutinized. The range of expected values and operating schemes are noted above, and form the basis of the parametric analysis undertaken. A summary of the expected values follows.

Infiltration:

a) Expected low infiltration rate of 1.27 L/s/m^2, at 75 Pa, as per US ACE requirements [1]
b) Expected typical infiltration rate of 1.67 L/s/m^2, at 75 Pa, as per a typical newly constructed, compartmentalized unit [1]
c) Expected high infiltration rate of 3.65 L/s/m^2, at 75 Pa, as per average high-rise residential building stock [1]

ERV Leakage:

a) Expected attainable low leakage rate of 3% of supply flow, as per *Passiv Haus Institut* requirements [11]
b) Expected typical leakage rate of 17% of supply flow, as per the lower range of leakage rates measured in [6]
c) Expected typical leakage rate of 34% of supply flow, as per the higher range of leakage rates measured in [6]

Temperature Set Point:

a) Typical cooling set point of 24°C. Typical heating set point of 22°C, with 18°C overnight set back, as per the NECB [14]

b) Conservative cooling set point of 26°C. Conservative heating set point of 21°C, with 18°C overnight set back. Modeling assumption.

c) Liberal set point of 23°C, annual. Modeling assumption.

ERV Operation Strategy:

a) Continuous operation, representing uncontrolled operation in a typical residential suite.

b) Economizer by-pass optional control strategy. High limit shut off of 24°C, as per ASHRAE 90.1-2010 [19]

3.0 Methods and Approach

Several parameters which potentially impact ERV performance have been identified. To determine their relative impacts on ERV and energy performance, an energy simulation of a typical residential suite can be utilized. *Energy Plus,* the dynamic energy simulation engine, was used to test the impacts of the parameters identified.

The purpose of this section is to provide an overview of the inputs to the energy model. A description of the mechanical system follows in section 3.1. Inputs and assumptions made regarding the energy model are presented in section 3.2. Rated performance data as per *AHRI Standard 1060* is presented in section 3.3. A summary of the parametric analysis undertaken is presented in section 3.4. Finally, a description of key modeling strategies, as they relate to infiltration and ERV leakage, are presented in section 3.5 and 3.6, respectively.

3.1 Mechanical System Description

Conventional ventilation strategies in MURB buildings often rely on corridor pressurization. In this strategy, the building's corridors are pressurized with fresh air, which is then delivered to the suites through openings at the suite entry doors. Corridor pressurization is less beneficial in terms of energy performance as it is typified by much lower ventilation delivery efficiencies, meaning more outdoor air and therefore more heating and cooling energy is required to provide the same fresh air delivery. The strategy also does not easily allow for ventilation energy recovery due to the location of supply and exhaust duct work.

The mechanical ventilation strategy of interest here is an in-suite ventilation system. A representation of the typical suite's mechanical layout is shown in figure 1. In this strategy ventilation is provided directly to the suite via intake louvers located at the suite's balcony, passing through an ERV device. Fresh air is then ducted directly to occupied spaces within the suite. The exhaust side of the ERV unit typically originates in the suite bathroom, and is exhausted through exhaust grilles at the suite's exterior wall. The ERV can either be ducted in series or in parallel with an in-suite fancoil unit, which provides heating and cooling as demanded by the suite thermostat. In the case analyzed here, the ERV is integrated within the fancoil unit, and so is ducted in series with the heating and cooling coil. The fancoil is served by hot water and chilled water coils from a central boiler and chiller plant. Finally, the residential suite is compartmentalized from the corridor and rest of the building through weather-stripping and sealing of the suite entry doors.

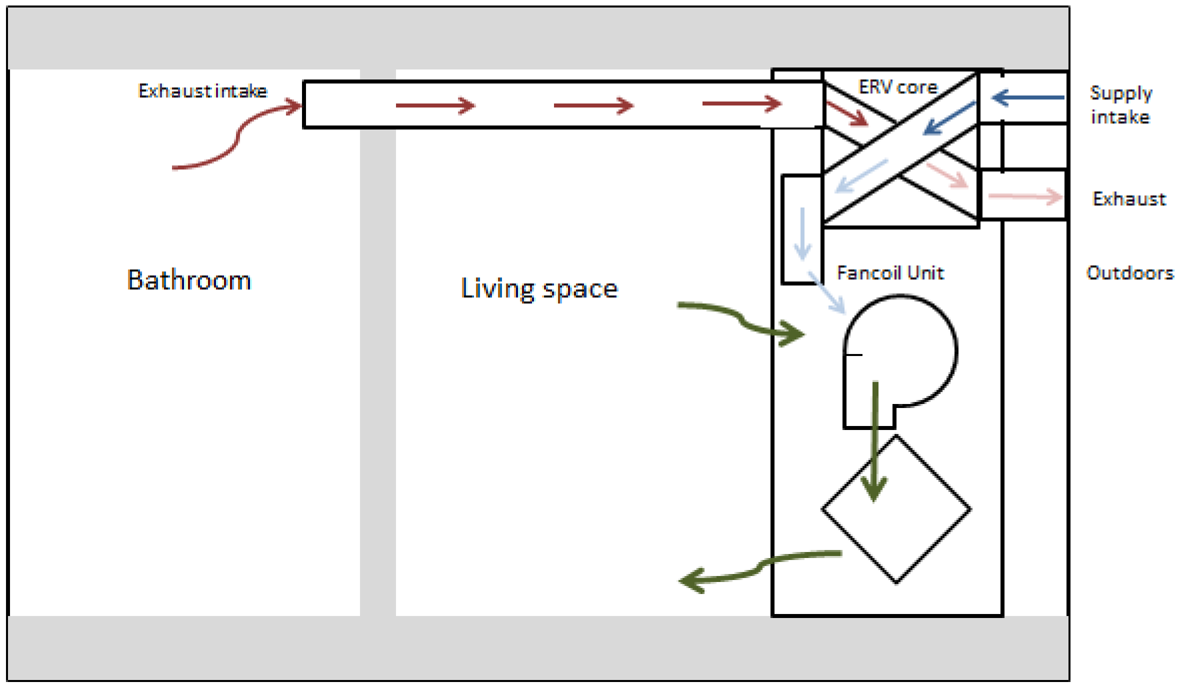

Figure 1 - In suite mechanical system layout

This strategy is increasingly common with developers seeking to construct a 'high performance' residential building.

3.2 EnergyPlus Model Inputs

The energy model was built using the *Open Studio* plug in for *Google SketchUp®*, which allows creation of geometry and other simplified inputs. Inputs and operating schedules were then refined using the *Energy Plus IDF Editor* interface. The energy model was built to represent a suite typical of new high rise residential construction in the GTA.

The typical suite was assumed to be approximately 74.3 m^2 (800 sq.ft), representing a one-bedroom condo unit with two person occupancy. This suite has a single exterior wall on one side, and five interior sides, assumed to be adiabatic. In the model used, the single exposed wall and window are both South facing. As the model represents a test bed and not an actual operating suite, steps were taken to estimate the loads and characteristics of the suite as per applicable standards. The initial inputs to the model as they relate to the parametric runs undertaken represent the 'typical' operating conditions described in section 2.6.

An overview of the inputs to the baseline energy model is provided below:

- **Area:** Assumed 74.3 m^2 (800 sq.ft) to represent typical one-bedroom apartment size.
- **Height**: 3m ceiling height.
- **Occupancy:** 2 people, assuming 2 people per typical 1 bedroom condo unit.
- **Lighting Power Density:** 6.5 W/m^2, following *ASHRAE 90.1-2010 Table 9.5.1* assumption [19]
- **Receptacle Power Density:** 5 W/m^2, following *NECB* assumption [14]
- **Schedules:** Assumed to follow *ASHRAE 90.1-2010 Users Manual* schedules for residential building types
- **Wall Construction:** Typical spandrel panel wall system. Assumed overall RSI 1.76 m^2K/W. Single south facing wall exposed to exterior conditions. All other exposures adiabatic.
- **Window Construction:** Typical double glazed assembly with low-e coating, argon fill, and thermally broken aluminum frame. Assumed overall USI 2.56 W/m^2K. Overall SHGC of 0.35.
- **Window to wall ratio:** 60%
- **Heating**: Provided by suite fancoil on as demand basis. Heating provided by central boiler plant.
- **Heating Set point:** 22°C, 18°C overnight set back as per [14], as determined in section 2.4.
- **Cooling**: Provided by suite fancoil on as demand basis. Cooling provided by central chiller plant.
- **Cooling Set point:** 24°C as per [14], as determined in section 2.4.
- **Ventilation**: Flow rate of 23.58 L/s, as per rated ERV outdoor air flow capacities. Continuous operation.
- **Infiltration:** 1.67 $L/s/m^2$ at 75 Pa, per typical compartmentalized, as determined in section 2.2 [1].
- **ERV Leakage / Flow Imbalance:** 17% of supply flow, internal leakage from supply side to exhaust side, as determined in section 2.3 [6].

A representation of the ERV system as it is modeled in *Energy Plus* is shown in figure 2:

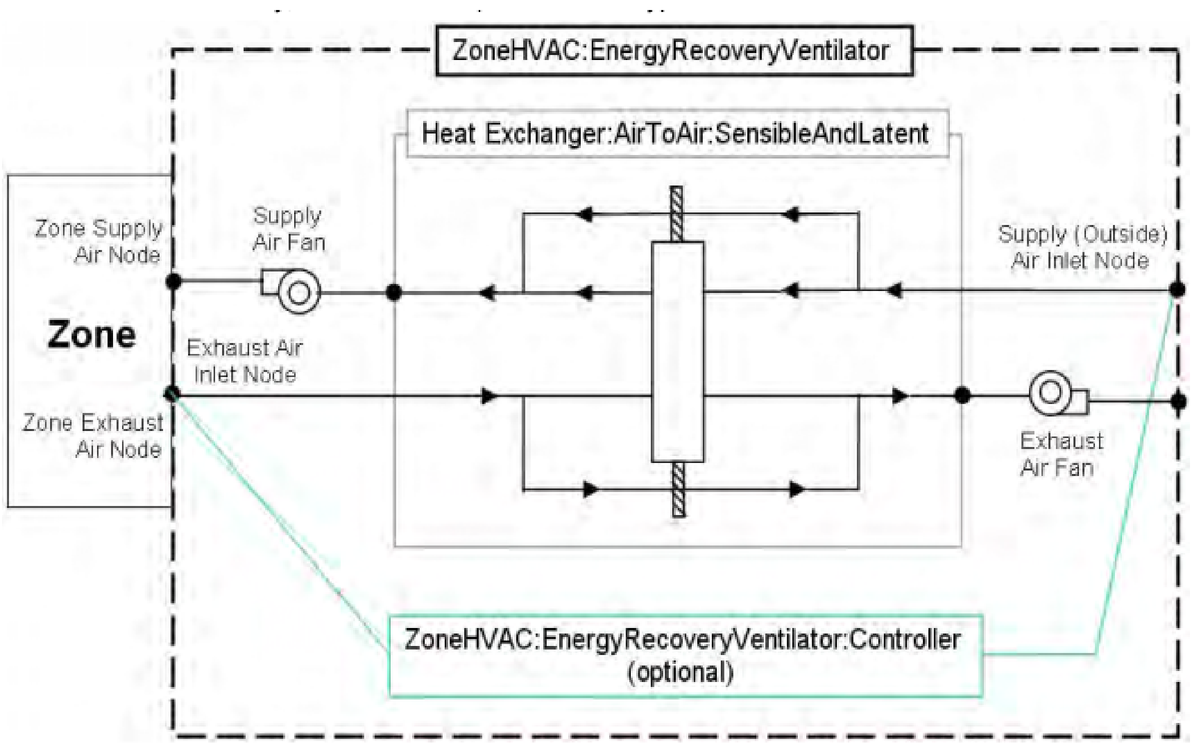

Figure 2 - Representation of *EnergyPlus* zonal ERV model [20].

3.3 ERV Rated Performance

To properly simulate the performance of the ERV core, published manufacturer's data was used. This information highlights the ERV core's latent and sensible performance under a range of operating conditions, tested as per the AHRI Standard 1060. Data presented represents the performance of the ERV under ideal, balanced flow conditions. Published effectiveness of the ERV core is shown in Table 1.

Table 1 – Published ERV Core performance per AHRI Standard 1060

	Summer Effectiveness		**Winter Effectiveness**	
Flow Rate (L/s)	Sensible	Latent	Sensible	Latent
18.87	73%	45%	73%	49%
23.58	71%	42%	71%	46%
28.30	70%	39%	70%	43%
33.02	68%	37%	68%	40%
37.74	66%	35%	66%	38%
42.45	65%	33%	65%	36%
47.17	63%	31%	63%	35%

To simulate this performance in *Energy Plus,* eight value entries are required. Entry points represent the sensible and latent effectiveness at 100% of design flow and 75% of design flow, under both heating and cooling conditions. As stated in section 3.2, the design flow of the ERV is typically set at about 23.53 L/s (approximately 50 cfm), and the effectiveness at this flow is given by the manufacturer. This flow rate is set by the manufacturer to run continuously, and provides adequate ventilation to the suite under the ASHRAE 62.1 minimum ventilation standard [2]. This continuous nominal flow follows the assumptions regarding ERV operation above. The effectiveness of the ERV at 75% of this flow was then extrapolated from Table 1. The resulting values entered into the model which describe the ERV effectiveness are shown in Table 2.

Table 2 –ERV core performance model inputs

	Summer Effectiveness		**Winter Effectiveness**	
	Sensible	Latent	Sensible	Latent
100% of Flow	71.0%	42.0%	71.0%	46.0%
75% of Flow	74.2%	46.2%	74.2%	50.2%

3.4 Parametric Analysis Overview

Section 2.6 forms the basis for a series of parametric runs which can now be implemented in the baseline *Energy Plus* model. Based on these factors, the following parametric runs are undertaken:

1) Baseline scenario, with inputs as defined in Table 1.
2) Expected low infiltration rate of 1.27 L/s/m^2, at 75 Pa, per Section 2,6.
3) Expected high infiltration rate of 3.65 L/s/m^2, at 75 Pa, per Section 2,6.
4) Expected low ERV supply flow leakage rate of 3% of supply flow, per Section 2,6.
5) Expected high ERV supply flow leakage rate of 34% of supply flow, per Section 2,6.
6) Expected ‘conservative’ temperature set points, per Section 2.6.
7) Expected ‘liberal’ temperature set points, per Section 2.6.
8) Economizer by-pass control option.
9) “Design Stage Energy Model” assumptions.

Parametric run 1 forms the baseline operating scenario under the typical conditions determined above. Runs 2 through 8 seek to explore the individual impact from the range of factors that were determined in chapter 2. Factors relate to infiltration rate, ERV flow imbalance, temperature set point and economizer versus uncontrolled operation. Finally, run 9 represents the typical assumptions an energy modeler might assume in the design stage of a building's development. Energy modeling is now often relied on by design teams to determine qualification for building permit, or LEED® energy reduction point targets [21]. Given the limited information available at this stage, assumptions must be made regarding equipment operation. As it is typical for design stage energy models to represent ideal operating conditions, it is of interest to compare these assumptions to the typical operating conditions in section 3.2. The idealized, design stage model assumes no ERV leakage flows, and infiltration rates as per the NECB, which is assumed to be a nominal 0.25 L/s/m^2 of exterior wall area [14].

3.5 Determining Modeled Infiltration Rates

For energy modeling purposes, the infiltration rates per square meter of exterior wall area at high pressure differentials of 50 or 75 Pa, determined through blower door testing, represent extreme conditions. To model representative infiltration rates at more typical operation conditions, considered to be approximately 4 Pa pressure differential, equation 5 is used.

$$Q = C_d A \sqrt{\frac{2\Delta p}{\rho}} \tag{5}$$

Where:

Q = design flow rate (m^3/s)
Δp = pressure differential at condition analyzed (75 Pa or 50 Pa)
ρ = air density (1.2 kg/m^3)
C_d = discharge coefficient, assumed to be 0.61 for 'crack' orifices
A = surface opening area (m^2)

From this the effective surface area opening, *A,* at the conditions of the blower door testing can be determined for each flow rate. This value is then used in equation 5 with a pressure differential of 4 Pa. The nominal design flow rate can then be determined.

Nominal rates included in the parametric models are shown in Table 3.

Table 3 –Modeled Nominal Infiltration Rates

Case	Nominal Rate at 4 Pa
1.27 L/s/m^2 at 50 Pa, per US ACE requirements	0.00679 m^3/s
1.67 L/s/m^2 at 75 Pa, per typical compartmentalized unit	0.00729 m^3/s
3.65 L/s/m^2 at 75 Pa, per average building (including older, leakier building stock)	0.0159 m^3/s
Constant 0.025 L/s/m^2, per energy modeling requirements.	0.004725 m^3/s

Design flow rates are then modified on an hourly basis within the energy model depending on wind patterns and velocity and temperature differential [20].

3.6 Modeling Internal Flow Short Circuits

Flow imbalances were modeled by modifying the supply air flow rate. Of importance to this study is a feature within *Energy Plus* which allows the user to create a simplified flow imbalance due to induced flows from duct leakage, unbalanced ERV flow rates or infiltration. This feature is designed for use in simplified, zonal ERV unit or other zonal mechanical system which lack the ability to model complex airflow networks. This allows these simple airflow inputs to be combined to produce a better representation of the airflows in the ERV unit, which may alter due to induced flows from imbalances or infiltration [20].

3.7 Summary

The purpose of chapter 3 was to provide an overview of the mechanical system in question, as well as to provide an overview of the modeling input and relevant modeling strategies important to the parametric analysis. A summary of important factors as they relate to the parametric analysis have been presented. To ensure the energy model has been developed according to real operating conditions, a validation exercise is undertaken prior to the parametric analysis. Validation involved the use of measured data points from an operation ERV unit in a residential building, and is presented below.

4.0 Validation

Before moving forward with the parametric analysis, a validation of the modeled ERV core is warranted. The validation exercise is undertaken to ensure that the modeled ERV unit, as described in Chapter 3, performs similarly in the energy model and under actual operating conditions. In this validation analysis, four main parameters related to ERV performance were considered to be of primary concern: winter sensible heat recovery, summer sensible heat recovery, winter latent heat recovery, and summer latent heat recovery. The purpose of this validation is to confirm that the inputs to the *Energy Plus* model as described above, including temperature set points and ERV control schemes, represent how the ERV core is controlled and how it responds under actual operation conditions.

To validate performance, an in-suite ERV currently installed in a residential suite in the GTA was outfitted with sensors to measure temperature (°C) and relative humidity (%) at four ports of the ERV. Measurement locations include: the supply air entering the ERV; the supply air leaving the ERV; the exhaust air entering the ERV; and, the exhaust air leaving the ERV. The supply and exhaust airflow were also measured, to determine whether or not the ERV is balanced. Measurements were taken at five minute intervals over the course of one heating and one cooling season. In addition, outdoor temperature (°C) and relative humidity (%), windspeed (km/hr), indoor temperature setpoints and system status (i.e. heating or cooling mode) were measured at all intervals.

The in-suite system is similar to the one represented by the energy model as described above. The in-suite ERV is ducted to an in-suite fancoil until which will cycle on and off to meet the heating or cooling loads set by the thermostat as required. In this scenario, the ERV is integrated within the fancoil unit, to minimize space needed for duct work. The ERV fans are provided in addition to the fancoil fan, allowing a minimum constant ventilation rate to be provided regardless of whether or not the fancoil is cycling on or off.

A schematic representation of the experimental setup appears in figure 1, and a photograph of the in suite ERV unit is shown in figure 3. Figure 3 shows the inside of the integrated ERV-fancoil unit, with the four temperature and humidity sensors shown in blue. The ERV core is located behind the panel at the top of the photograph. The main fancoil blower is shown at the bottom of the photograph.

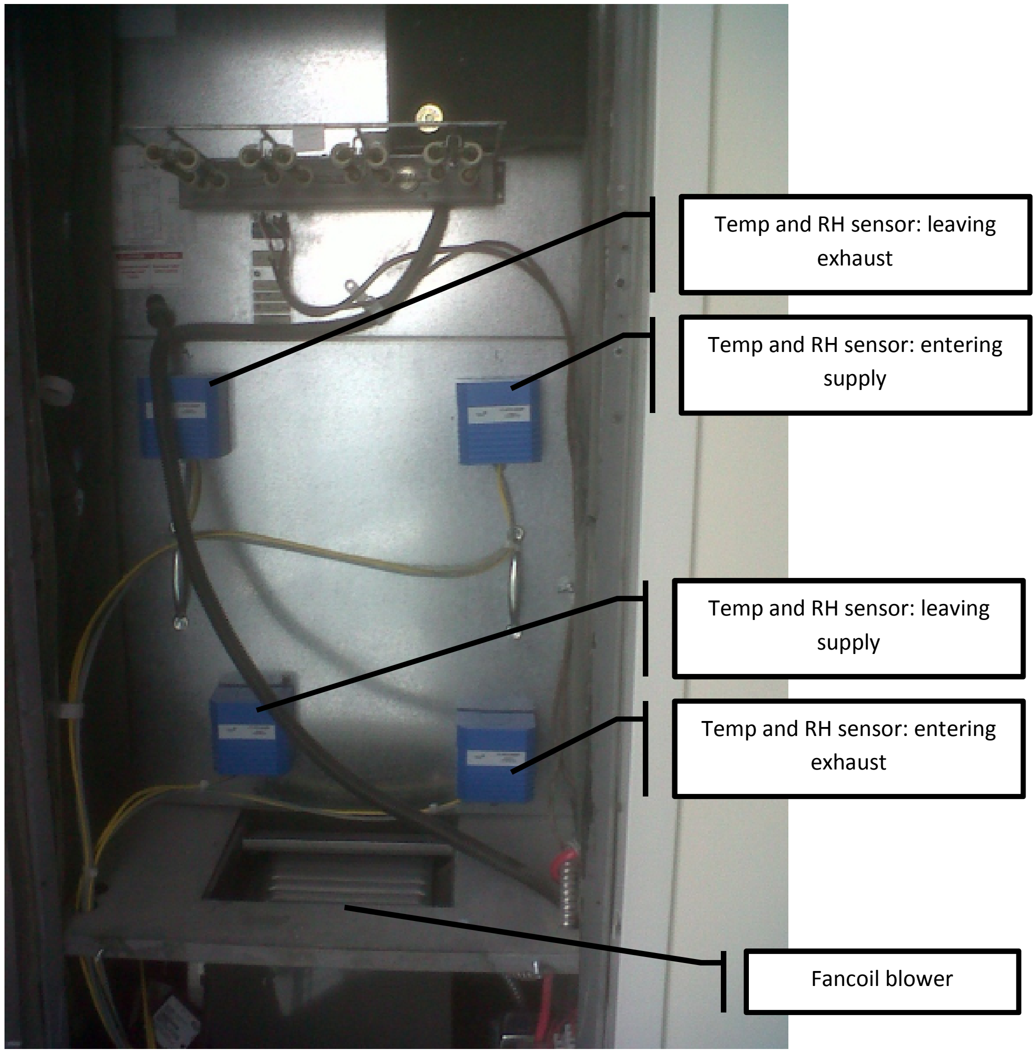

Figure 3 - Integrated fancoil unit, showing temperature and humidity sensors.

Data collection for the purposes of the validation analysis took place over a period of approximately 7 months, from December 17th, 2012 to July 17th, 2013. Outdoor dry bulb temperature ranged from -11°C to 35°C, and outdoor relative humidity ranged from 15% to 79%. This range of data is considered representative of a typical heating and cooling season in Toronto, and conditions in between.

Measurements took place over a period of time where the residential unit was occupied, and typical indoor temperature set points were maintained by the in-suite thermostat. Proper thermostat operation is important for validation, as otherwise indoor temperatures may float with the outdoor temperatures, reducing the temperature differential between indoors and outdoors, and therefore impacting ERV core performance. The thermostat allows the in suite fancoil to cycle on to meet either the heating or cooling load, to maintain reasonable temperature in suite, providing the ERV core with a temperature differential. Thermostats in-suite are capable of being programmed as 'away', 'asleep' or 'home'. In-suite temperatures ranged from 17.6°C in the winter to 24.7°C in the summer. The extremes of this range represent the thermostat in 'away' mode, where setbacks allow the tenant to reduce heating and cooling consumption respectively in the winter and summer. When only 'home' mode is considered, indoor temperature ranged from 19.9°C to 23.8°C. The range of temperature encountered during 'sleep' mode was 19.6°C and 24.4°C, indicating a slight setback in programming.

Indoor humidity levels ranged from 5% to 72% RH throughout the study. It should be noted that unlike the indoor temperature set point, indoor humidity is uncontrolled, in both the model and the experimental set up. A review of the measured data indicated that the in suite humidity levels essentially float with the outdoor levels, likely accounting for buffering due to occupant impact, infiltration rates, or other processes. An analysis of the literature indicates that uncontrolled indoor humidity levels are difficult to determine in residential buildings and that they may be largely dependent on the type of mechanical system [22] as well as the amount of air leakage in the building, number of occupants, and types of activities (for example, cooking or showering) [23].

Due to issues with installation and wiring, airflow measurement devices for the incoming supply and exhaust streams of the ERV were not operational during the course of data collection. Therefore, the core temperature performance of the ERV can only be validated here assuming a balanced flow. It is also important to note that as only two airstreams were measured during the data collection phase, the operating EATR and therefore the net effectiveness of the ERV core cannot be determined, as per equations 3 and 4. Therefore, validation analysis is limited to only the nominal, temperature based performance and operation of the ERV. Core flow is assumed to be balanced for the purposes of the validation analysis, and impacts from leakage and unbalanced flows are analyzed as part of the parametric analysis, as described in chapter 3.

The core sensible and latent effectiveness of the ERV unit can be derived from equations 1 and 2 above, respectively. These equations essentially highlight that the sensible effectiveness of an ERV is driven by a difference in dry bulb temperature, whereas the latent effectiveness of an ERV is driven by a difference in absolute humidity ratio. Considering a simple mass flow equation, the recovery rate of the installed ERV can also be estimated as follows:

$$Q_s = \dot{m}c(X_1 - X_2) \tag{6}$$

Where:

Q_s = Sensible recovery rate
$\dot{m}_s$ = supply air mass flow rate
c = specific heat of air
X_1 = dry bulb temperature of the supply air entering the heat exchanger
X_2 = dry bulb temperature of the supply air leaving the heat exchanger

And again for latent effectiveness:

$$Q_L = \dot{m}h_{we}(HR_1 - HR_2) \tag{7}$$

Where:

Q_L = Latent recovery rate
h_{we} = Latent heat of vaporization
HR_1 = dry bulb temperature of the supply air entering the heat exchanger
HR_2 = dry bulb temperature of the supply air leaving the heat exchanger

The *Energy Plus* software includes the capability to report hourly results, including the hourly sensible and latent energy recovery rates of the ERV core. By using equations 6 and 7, the latent and sensible recovery rates of the measured ERV and the modeled ERV can be compared. Comparison is focused on typical heating season and cooling season conditions, where the rates of recovery are more significant and more predictable in comparison to the shoulder seasons.

The condition of the air leaving the heat exchanger, as well as the mass flow rate, is a function of the ERV unit operation and the outdoor conditions. Considering this, the defining variable in equation 6 therefore becomes the incoming bulb temperature, X_1, which is impacted by the outdoor dry bulb temperature alone. In equation 7, this becomes incoming humidity ratio, HR_1. Therefore, when compared against the outdoor temperature and humidity ratio, similar trends in the modeled and measured ERV sensible and latent recovery rates should be observed if the modeled ERV core is operating similarly to the installed ERV.

4.1 Sensible energy recovery

Figure 4 and 5 below show sensible heat recovery in both the energy model and the measured data for a heating and cooling condition, respectively. The average energy recovery rate for a given outdoor air dry bulb temperature is presented and plotted against outdoor air temperature (°C). Average sensible recovery in winter is compared for outdoor temperatures of -11°C to 2°C, representing the range of temperatures during the heating season encountered both in the energy model and data collection period of the measured unit, During the summer, average sensible recovery is analyzed from 26°C to 31°C.

Figure 4 shows that as modeled dry bulb temperate decreases in the winter, a corresponding increase in recovery rate is seen in both the modeled and measured data. The average modeled and measured sensible recovery rates also respond similarly in terms of the rate of change in response to outdoor dry bulb temperature. Furthermore, the average recovery rate of the modeled and measured data displays significant overlap, averaging a difference of 7.1% at all temperature analyzed. The comparison therefore corroborates the importance of outdoor dry bulb temperature as a defining factor in overall recovery rate, given typical temperature set points and flow through the ERV is similar in both cases. Analysis therefore suggests that the modeled ERV is performing similarly to the installed unit in terms of winter sensible energy recovery.

Figure 5 shows that in summer this trend is flipped, where an increase in dry bulb temperature leads to a corresponding increase in sensible recovery. Again this is as expected as increasing outdoor dry bulb temperature represents an increase in the temperature difference between the outdoors and the indoor set point. Trends corroborates the findings in [3,8] which found an increase in ERV performance as temperature difference increases. Similar to figure 4, the average modeled and measured cooling energy recovery rates are also comparable in terms of overall recovery as a function on outdoor dry bulb temperature, with an average difference of 4.0% at the dry bulb temperatures analyzed. The rate of change in response to outdoor dry bulb temperature is comparable as well. Analysis therefore also suggests that the modeled ERV sensible cooling recovery performance is representative of the installed ERV.

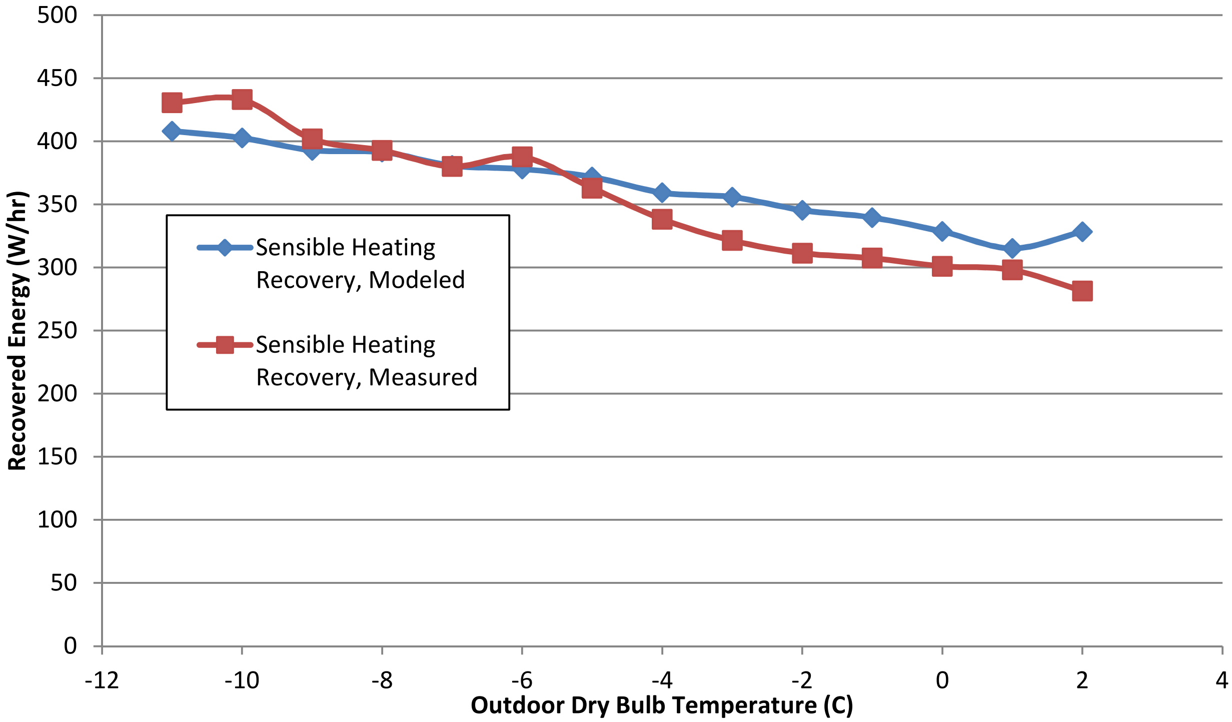

Figure 4 - Winter sensible recovery

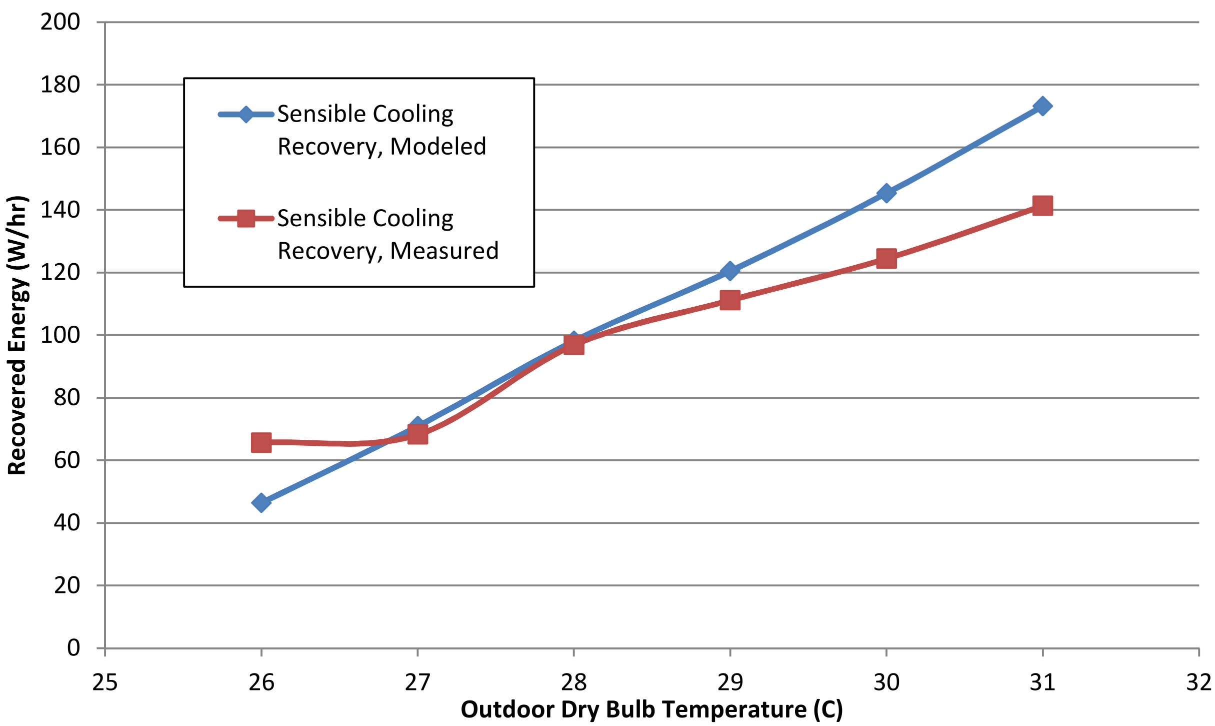

Figure 5 - Summer sensible recovery

The results of the sensible recovery validation are expected, given that the indoor temperature within both the modeled suite and the measured suite is governed by similar thermostat settings. Therefore, a similar temperature differential through the modeled and the measured ERV is expected at a given outdoor dry bulb temperature. As the mass flow rate through the ERV is assumed to be equal in both the measured and modeled analysis, the remaining variable becomes the outdoor dry bulb temperature. The sensible validation analysis therefore corroborates the importance of outdoor dry bulb temperature to sensible recovery rate. Both the winter and summer modeled sensible recovery rates correspond favourably to the measured ERV unit, and therefore the model can be considered validated in terms of the ERV unit's sensible performance.

4.2 Latent energy recovery

As latent recovery rate is primarily dependent on differences in absolute humidity ratio, similarities should exist between the measured and modeled latent performance when compared to outdoor humidity ratio, as with sensible recovery and outdoor dry bulb temperature. Figures 6 and 7 were prepared to demonstrate this for the measured and modeled latent recovery rate, again for a typical winter and summer condition. During the heating season, the suite is theoretically more humid than the outdoor humidity condition due to internal process and latent gains, and the ERV is expected to recover some of this humidity from being lost. Therefore the average latent recovery rate of the modeled and measured data during winter is compared against outdoor conditions which are dry. Winter outdoor humidity ratio ranged from 0.0008 kg of moisture / kg of dry air to 0.0011 kg of moisture / kg of dry air during the validation analysis, representing dry winter conditions encountered in both the model and measured analysis for comparison. During the cooling season, the reverse trend should be expected and latent cooling recovery will act to remove moisture form the incoming air stream, based on the ostensibly drier indoor air condition. Therefore the average latent recovery rate of the modeled and measured data during summer is compared against outdoor conditions which have a higher moisture content. Summer outdoor humidity ratio ranged from 0.014kg of moisture / kg of dry air to 0.016 kg of moisture / kg of dry air representing moist summer conditions encountered in both the model and measured analysis for comparison.

Figure 6 present the winter latent recovery rate of the modeled and measured data in response to outdoor humidity ratio. In this comparison no clear trend in either the measured or modeled data presented can be determined, as recovery rates remain relatively stable in response to outdoor humidity ratio. The measured and modeled rates of latent recovery also do not display similar overall rates of recovery in response to the outdoor humidity ratio. Recovered latent heating is on average 45.5% less than modeled average latent heating at the plotted outdoor humidity ratios. However, the overall rate of latent recovery in the winter is in the range of 0 watts to 10 watts, compared to the sensible recovery rate which is in the range of 300 watts to 400 watts. Winter latent recovery therefore typically represents less than 5% of the overall recovered heating during winter in the Toronto climate, demonstrated both in the modeled results and the collected data. Similar conclusions were drawn in [18], which noted that the driving factors of ERV performance are latent recovery in summer and sensible recovery in winter for a cold, humid climate similar to Toronto. Given this, while less overlap is seen in figure 6 when compared to figure 4, the absolute difference in latent recovery remains small.

Figure 7, which demonstrates the comparison of latent recovery rates under summer conditions, displays a more clearly defined trend than the one seen in figure 6. In this comparison, both the modeled and measured average latent recovery rates increase in response to increasing outdoor humidity ratio. The modeled and measured recovery is also seen to respond at a similar rate of change. The similar trends seen in response to outdoor humidity ratio indicate that the modeled ERV and measured ERV react to the outdoor humidity during the summer. Specifically, an increase in outdoor humidity ratio will result in a corresponding increase in latent recovery. In summer this amounts to a drying effect on the humid incoming fresh air.

Overall rates of recovery do not compare when considering the average rate of recovery at a given outdoor humidity ratio in summer, with the measured recovery higher than the modeled recovery. In this scenario, modeled latent recovery rates are on average 47.0% less than measured recovery rates across the outdoor humidity ratios analyzed. Given that the rate of recovery is dependent on the differential in humidity ratio. Unlike an indoor thermostat to maintain dry bulb temperature, there is no in-suite equipment capable of regulating indoor humidity levels directly. Therefore, indoor humidity is dependent on numerous other processes which may impact latent heat gains, such as cooking, showering, use of a humidifier, or change in occupancy profiles and associated latent gains. These processes are not captured in the model, as variations in this type of activity are difficult to estimate, given the range of tenant behaviour possible, thus explaining the discrepancy between the modeled and measured latent summer recovery rate.

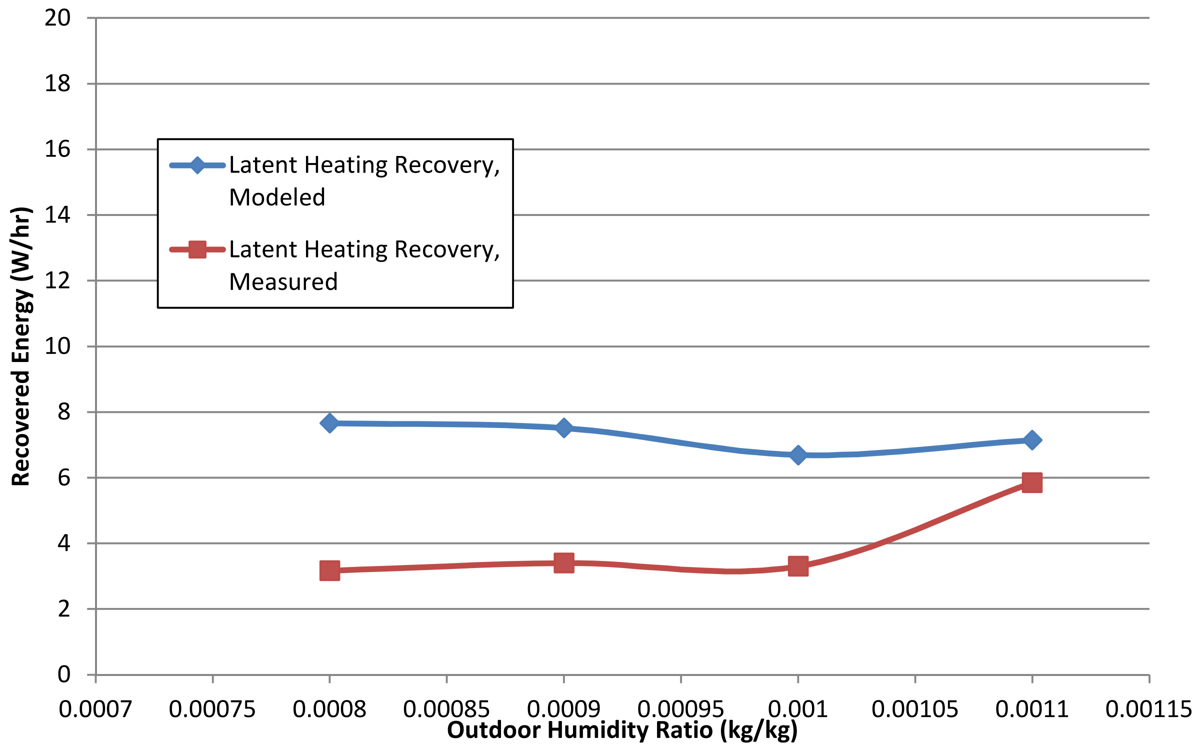

Figure 6 - Winter latent recovery

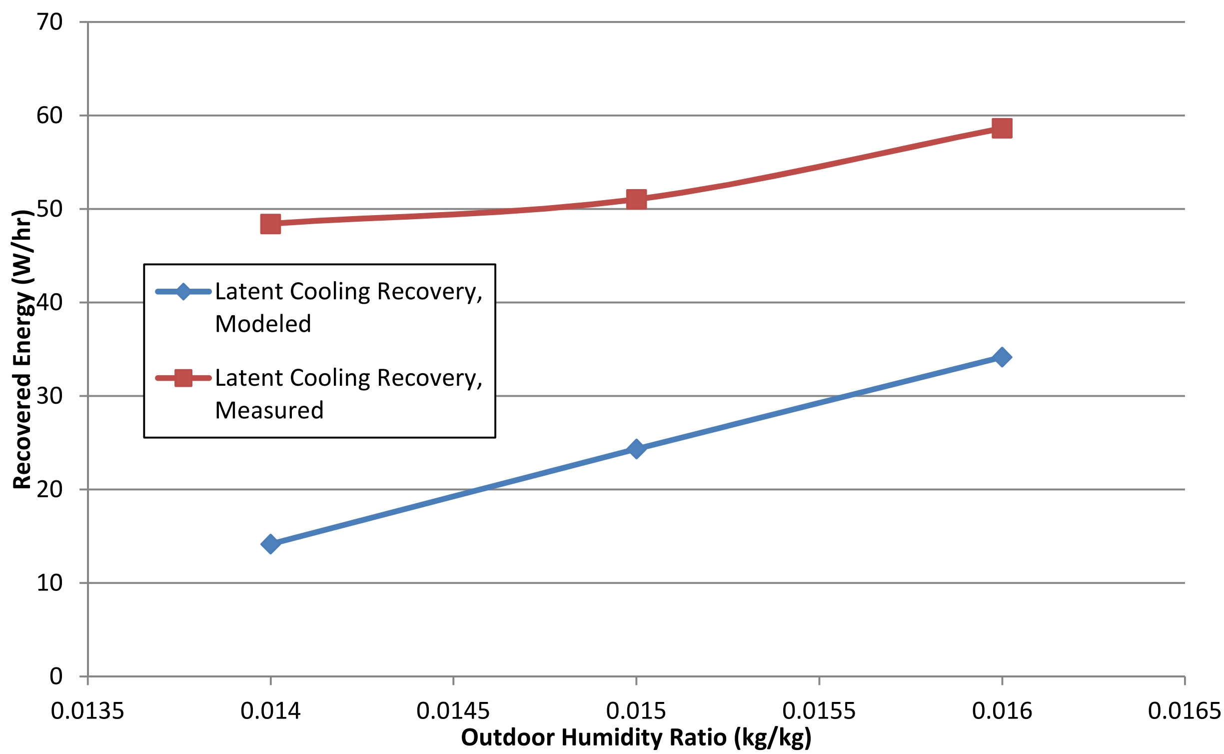

Figure 7 - Summer latent recovery

The fact that humidity is uncontrolled in suite may incidentally point to the overall lower rates of latent recovery reported in comparison to sensible recovery rates. During the winter months in figure 6, indoor conditions may also be fairly dry when compared to the outdoor conditions, as they are not necessarily maintained at a higher, more comfortable range via a suite humidistat. A smaller differential in humidity will follow, resulting in less latent recovery following equation 7.

The core sensible and latent performance of the modeled ERV unit has been validated against measured performance. In the case of sensible recovery, the measured data corresponds favourably to the modeled data in terms of response to outdoor cry bulb condition, as well as in terms of the overall rate of recovery. Given that a thermostat exists in suite to control the indoor condition, this result is expected as similar flow rates and a similar temperature differential is expected through the ERV at a given outdoor dry bulb temperature. In terms of latent recovery, winter recovery rates were seen to be much smaller when compared to winter sensible recovery, representing at most 5% of the overall winter heating recovery. At these relatively low rates overall recovery rates do not display as much overlap, however they are within a similar range, as absolute rates of latent recovery are less than 10 watts. IN comparison, sensible winter recovery ranged from 300 watts to 400 watts at the outdoor dry bulb temperature analyzed. The summer latent recovery comparison demonstrated a more defined trend, showing an increase in recovery when outdoor humidity increased, however also demonstrated a discrepancy in terms of overall latent recovery rate as a function of outdoor humidity ratio. The lack of humidity control in suite is identified as the reason for this discrepancy, impacting the humidity differential through the ERV.

Given that both the sensible and latent recovery analysis can be explained rationally when comparing modeled and measured performance, the modeled ERV core can be considered to be operating appropriately given the models defined inputs, and intent as a typical residential suite. Parametric analysis of the modeled ERV, to analyze the impacts of various factors described in chapter 3, is therefore justified.

5.0 Parametric Analysis – Results and Discussion

Energy Plus was used to carry out the parametric modeling analysis of the in-suite ERV by simulating the parametric runs described in Section 3.4. The parametric analysis is informed by a literature review, and focuses on four key aspects of the modeled suites which potentially impact ERV unit performance. Included in this analysis are an investigation into the impact of infiltration flows, an investigation into the impacts of leakage within the ERV unit, an investigation into the impact of temperature set points and an investigation of an economizer option to control the ERV. The economizer bypass works to circumvent the ERV when outdoor conditions are favourable to provide free cooling. Finally, the modeling assumptions for the typical residential suite are compared to the assumptions which would be made during the design stage energy modeling of a project. Results of the parametric analysis and a discussion of the findings follow below.

As with the validation analysis, sensible and latent heating and cooling recovery are analyzed in the parametric analysis. Considering a three day period during the heating season provides a snapshot of the heating sensible and latent recovery. Similarly, considering a three day period during the cooling season provides a snapshot of the cooling sensible and latent recovery.

To determine the impact of each parametric run, it is important to consider the amount of recovered heating and cooling provided by the ERV, as well as the resultant amount of heating and cooling energy required to maintain the temperature set points within the suite.

5.1 Baseline Modeled Energy Use

The baseline scenario, described as Run 1 of the parametric analysis, is built as per the characteristics in section 3.2, and represents a typical residential suite in terms of the parameters analyzed. A breakdown of the modeled energy use in the baseline run by end use is shown in Figure 8.

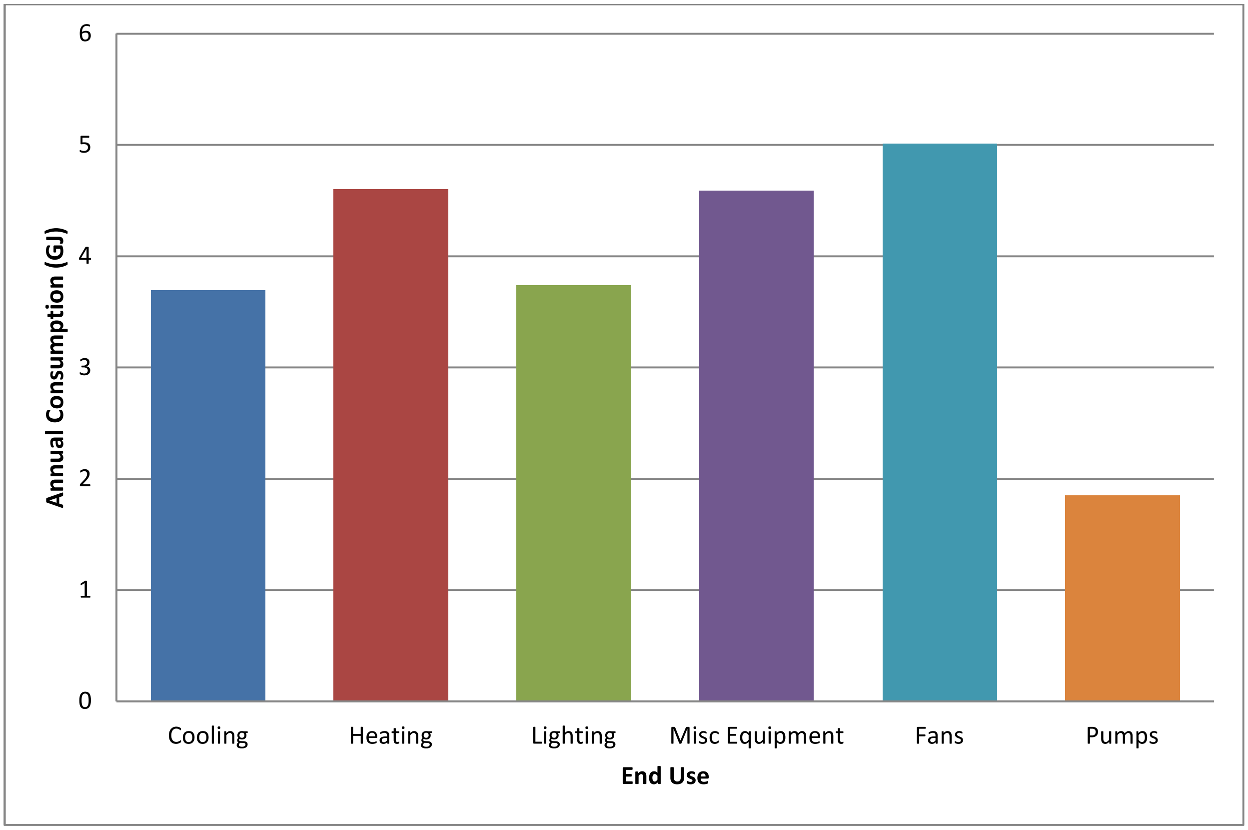

Figure 8 - Baseline suite energy consumption by end use

This demonstrates that even with energy recovery, heating remains one of the dominant energy uses in the suite, though the assumed fan consumption and electrical loads now surpass this. This is followed by lighting, cooling, and finally by pumping energy, which represents the upstream pumping energy required to supply the in suite fancoil with hot and chilled water to meet the suite loads. Heating and cooling are fairly similar in terms of overall consumption. The modeled suite is South facing, and therefore the suite experiences significant solar gains which reduces the heating required by the suite, while increasing the cooling required. Rotating the suite by 180 degrees leads to an increase in heating and decrease in cooling consumption. Heating is also reduced by the winter sensible heat recovery, described further below.

5.2 Infiltration Flow Impact

The impact of infiltration rates on ERV performance and annual suite heating a cooling consumption was modeled as part of the parametric analysis. When compared to the baseline infiltration rate, the parametric run which models the expected low infiltration rate resulted in a slight reduction in annual heating energy, from 4.60 GJ to 4.39 GJ. A corresponding increase in annual heat recovered from the modeled ERV unit, from 9.52 GJ to 9.54 GJ, is also seen. The impacts to the ERV itself in terms of recovered heat are fairly insignificant. However, the parametric run which modeled the expected high infiltration rate increased the annual heating consumption of the fan coil fairly significantly, to 8.61 GJ, while only reducing the annual heat recovered from the ERV unit to 9.121 GJ.

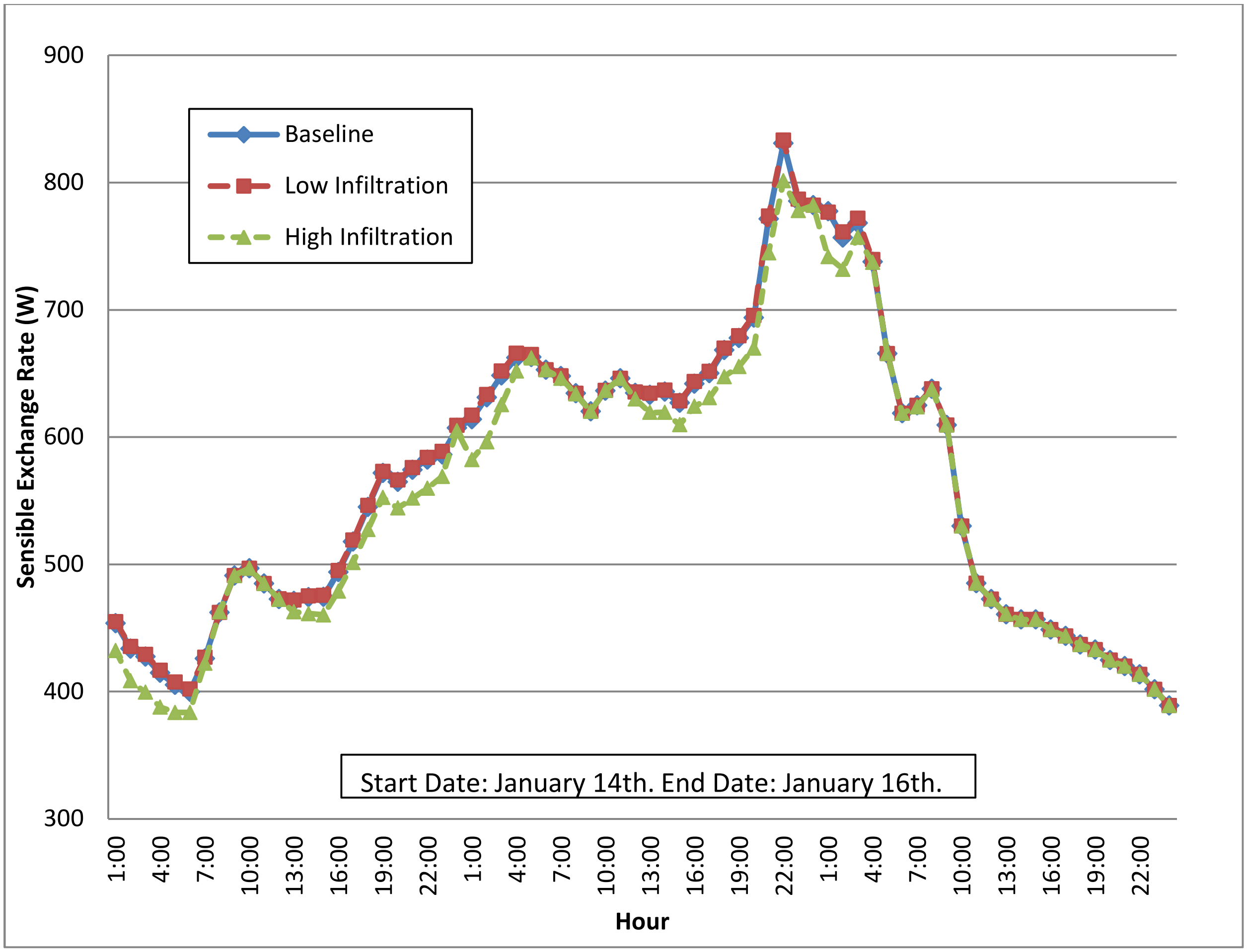

Figure 9 - Winter recovered sensible heating as a function of infiltration

Figure 9 compares the sensible heat recovery rate of the baseline scenario, as well as runs 2 and 3 with low and high infiltration rates, respectively. Figure 10 presents the comparison of latent heat recovery under the same scenario.

Figure 9 shows that little impact to the sensible recovery rate in the winter is noted over the period shown. These results suggest infiltration does not have a significant impact on sensible heat recovery during the winter. A more marked difference is shown in Figure 10, when considering latent heat recovery. Parametric run 3, which represents the high infiltration rate, exemplifies this. In this run, at times when the latent recovery is peaking, a more pronounced reduction in latent recovery energy can be seen compared to the baseline.

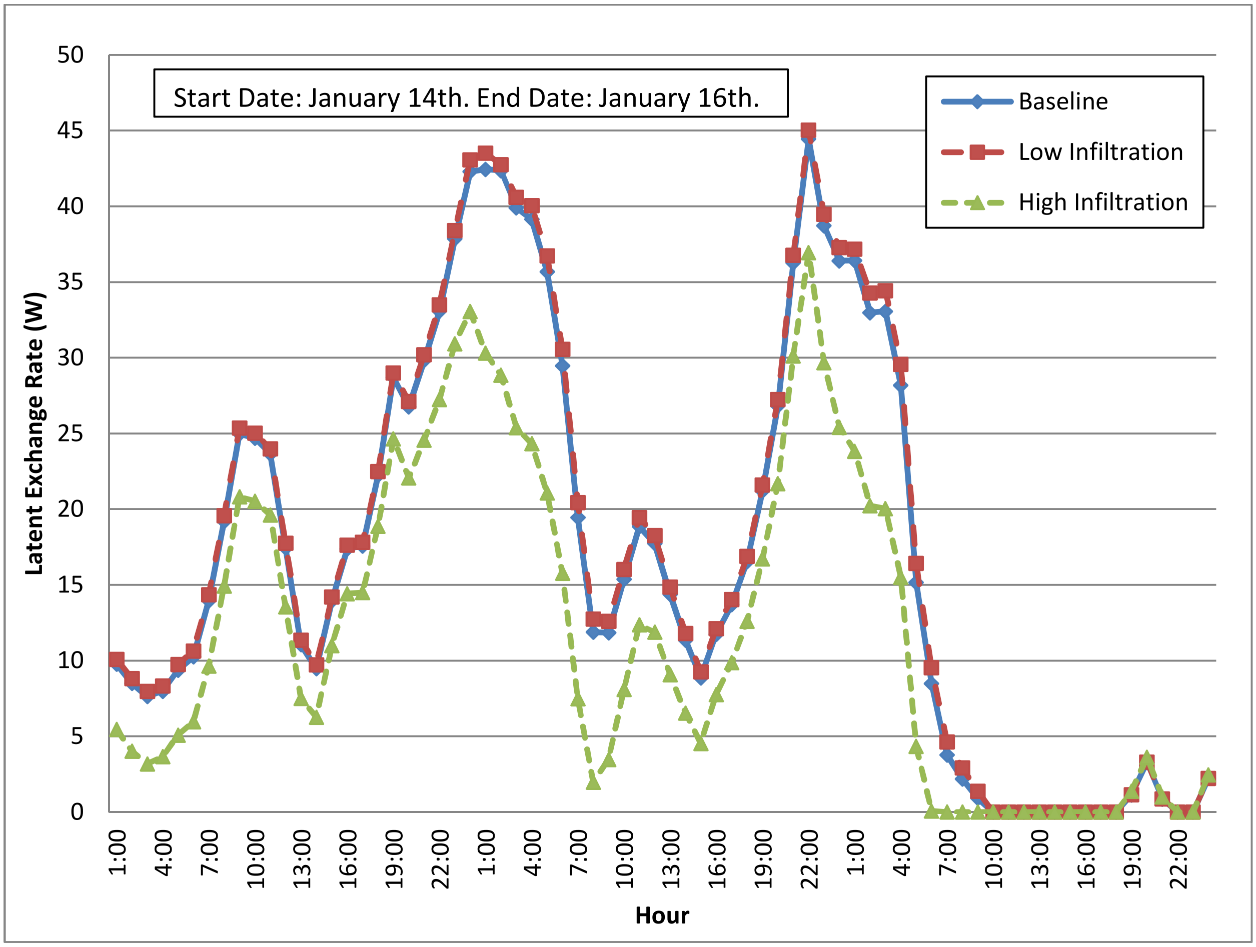

Figure 10 - Winter recovered latent heating as a function of infiltration

Impacts to ERV performance appear to be a function of modified sensible and latent loads due to infiltration, as well as modified indoor temperature and humidity due to the infiltration flow, which the exhaust side of the ERV encounters. In the case of sensible heating, this impact is reduced as any load or reduction in indoor temperature due to infiltration in the winter is remedied by the in suite fancoil providing more heat. When infiltration rates are increased, in Run 3, heating energy consumption increases significantly, as the suite fancoil must work harder and consume more energy in an attempt to maintain the set point. The small reduction in ERV sensible heat recovery noted in figure 9 can be attributed to those time steps which infiltration rate is higher. During these times the fancoil was not able to provide heating to the room quick enough to maintain the same indoor temperatures, and therefore the sensible recovery rate is reduced when compared to the baseline as the indoor-outdoor temperature differential is reduced.

In comparison, there is no process to humidify or dehumidify the suite. Therefore, a more significant impact to the latent recovery of the ERV from infiltration is noted in Figure 10. As the infiltration brings with it the humid outdoor conditions at higher rates, in the case with high infiltration, indoor humidity approaches outdoor conditions. As a result, the difference in moisture that the ERV encounters is reduced. Infiltration therefore has a more direct impact on latent ERV unit recovery rates during the heating season. However it is worth noting that overall rates of latent recovery and much less than sensible recovery rates, therefore overall impact to the ERV performance remains insignificant.

In both figures 9 and 10, a relatively small difference is seen between the improved infiltration rate and the baseline run. As discussed above, typical infiltration rates are much closer to the anticipated low infiltration rate, due to inherent benefits from suite compartmentalization. The high infiltration rate therefore represents a more pronounced difference in infiltration flows compared to the baseline. It follows that current construction practices regarding the quality of the air barriers is generally very good in relation to what levels of air tightness may be expected, highlighting the importance of compartmentalization.

When analyzing summer conditions, lower modeled infiltration corresponds with an increase in annual cooling energy, from 3.69 GJ to 3.74 GJ, while annual recovered cooling energy through the ERV unit remained constant at 0.1012 GJ. Modeled high infiltration conversely led to a decrease in annual cooling energy consumption, down to 3.13 GJ, and a very slight increase in recovered cooling energy through the ERV unit, to 0.1014 GJ. A very minimal change to recovered cooling when infiltration is modified in the model is therefore observed. Figures 11 and 12 corroborate this, demonstrating recovered sensible and latent cooling energy recovery based on infiltration during a weeklong period in a cooling condition. Both figures 11 and 12 indicate essentially no change to summer ERV performance.

The lack of a response to infiltration in the summer months is expected. Infiltration flows are reduced during the summer period, as the nominal infiltration flow is modified at each hour partially as a function of indoor-outdoor temperature difference. As this temperature difference is generally smaller in the summer months in Toronto, infiltration is therefore reduced. In figure 11, the sensible impact to the ERV is negligible. Figure 12 indicates a very slight impact to latent cooling energy recovery at certain times, suggesting periods of high outdoor humidity. In turn this registers as a slight increase to the humidity in suite at higher infiltration rates, and therefore a slight reduction in latent recovery.

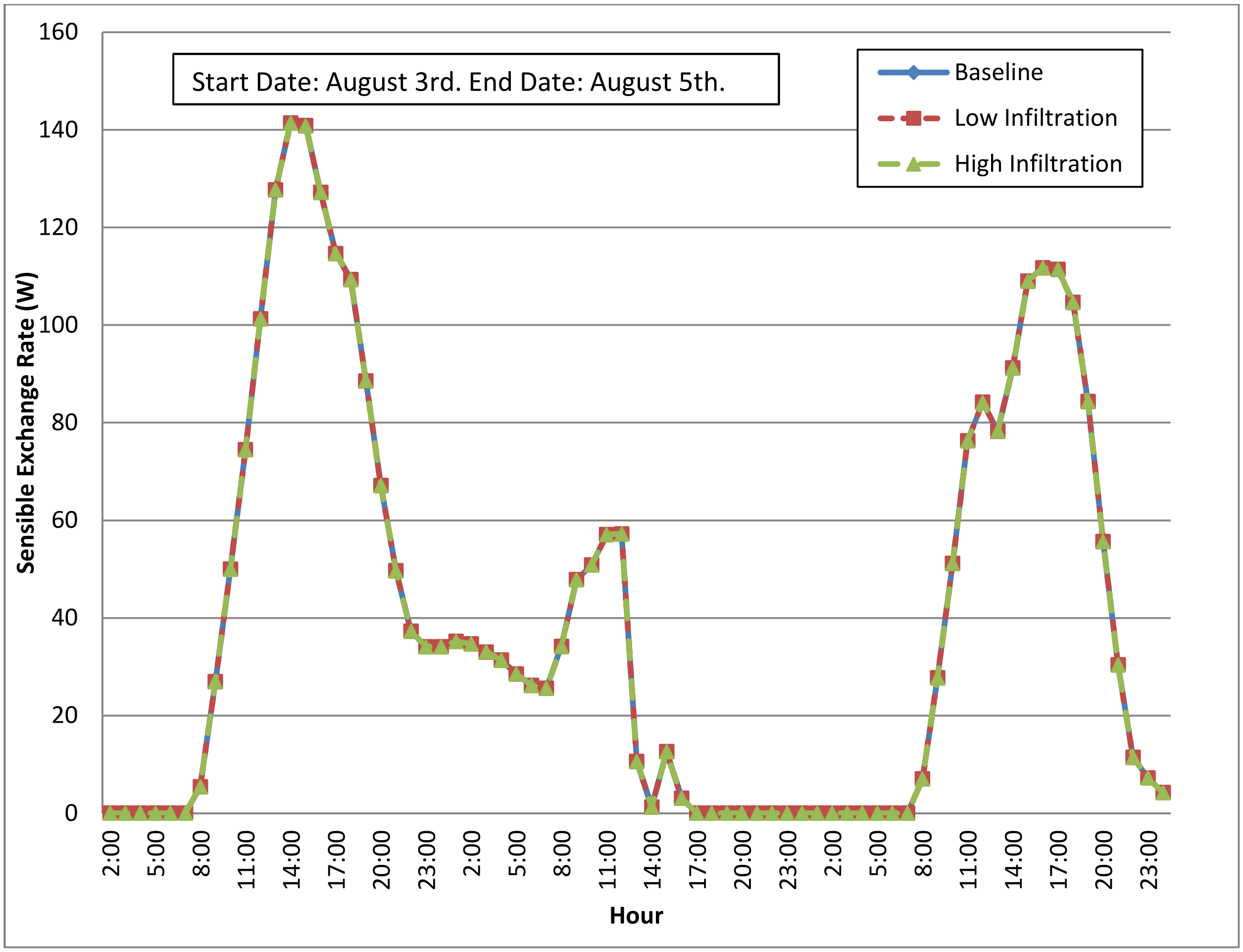

Figure 11 - Summer recovered sensible cooling as a function of infiltration

Contrary to winter performance, low infiltration in turn has a slightly negative impact to the suite on a whole, causing an increase in cooling energy consumption. Considering that lower infiltration essentially reduces any free cooling the suite may see from infiltration during summer periods, this response is expected. Increased cooling essentially represents the impact of opening or closing windows in the suite on a much smaller scale, which would result in higher cooling consumption if windows were not utilized as much throughout the cooling season.

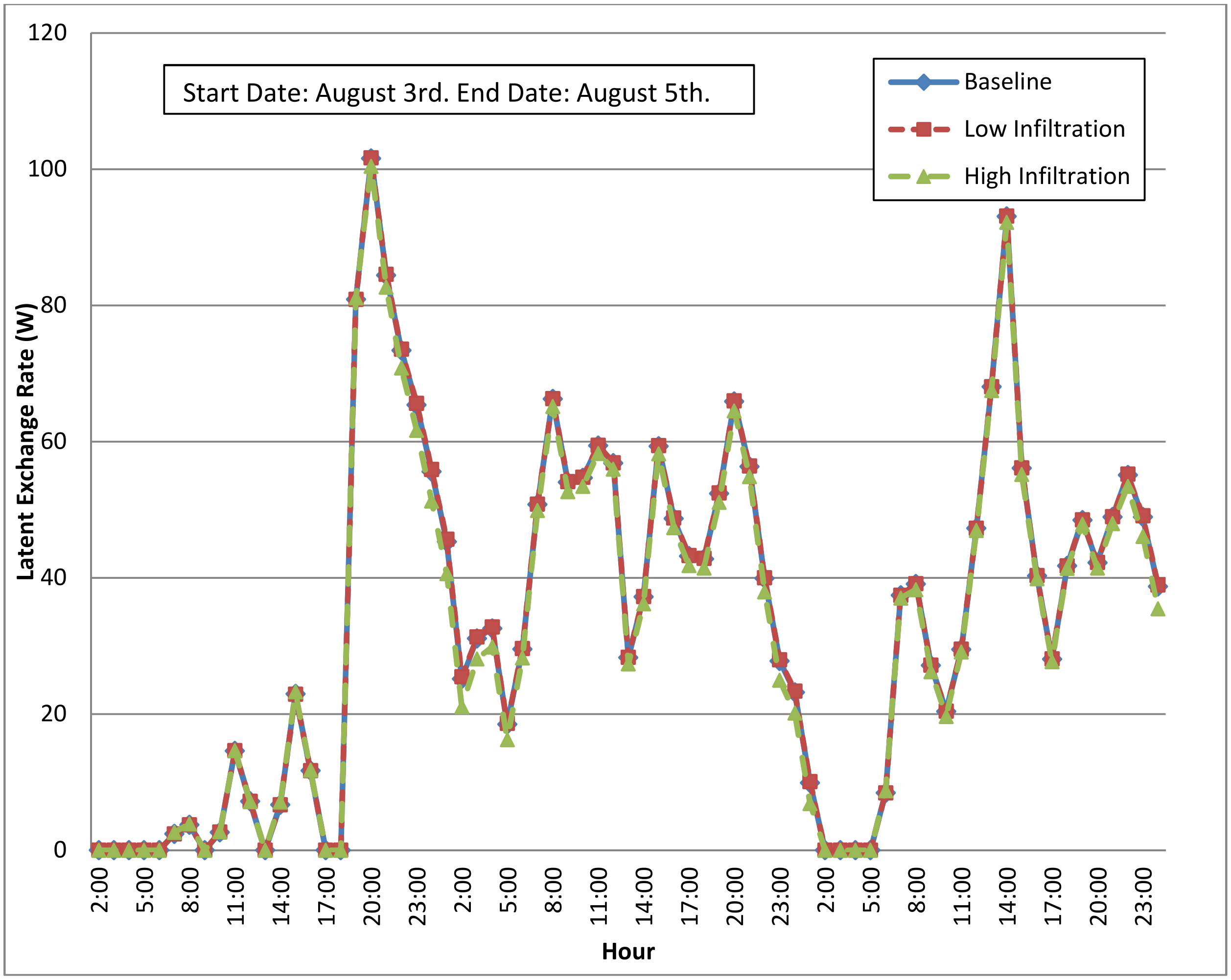

Figure 12 – Summer recovered latent cooling as a function of infiltration

Overall analysis of the infiltration parametrics indicates that expected infiltration rates in residential buildings are close to what can be considered as a best practice infiltration rate based on the more stringent air tightness standards currently available. When considering what is identified as the expected poor air tightness for a high rise residential building, a larger difference in recovery is seen. Results corroborate the importance of a compartmentalization strategy in MURBs with regards to air tightness, and consequently, ERV performance. Parametric analysis highlights the potential pitfalls of designing a less airtight building as it relates to ERV performance and energy consumption. Infiltration has been shown to have a positive impact on ERV performance in condo unit in past studies [12], when compared to standalone housing. With less exposed wall area by comparison, and therefore less infiltration per unit, typical construction is MURB buildings is inherently less leaky.

5.3 ERV Leakage Flow Impact

Modeled ERV leakage flows represent leakage ratios through the ERV as a result of poor construction of the ERV unit itself. When considering ERV leakage, parametric runs altering flow rates have a much more direct impact on the modeled ERV performance. The modeled low duct leakage flow rate resulted in a slight increase in annual heating energy consumption in the suite, from 4.60 GJ to 4.85 GJ. An increase in modeled annual heat recovered from the ERV, from 9.520 GJ to 10.748 GJ, is also observed. Conversely, the expected high duct leakage rate reduced modeled annual heating consumption to 4.29 GJ, while also reducing annual ERV heat recovery down to 7.981 GJ. An analysis of the change in sensible and latent heat recovery rate due to ERV leakage over a 3 day winter period is demonstrated in figures 13 and 14, respectively.

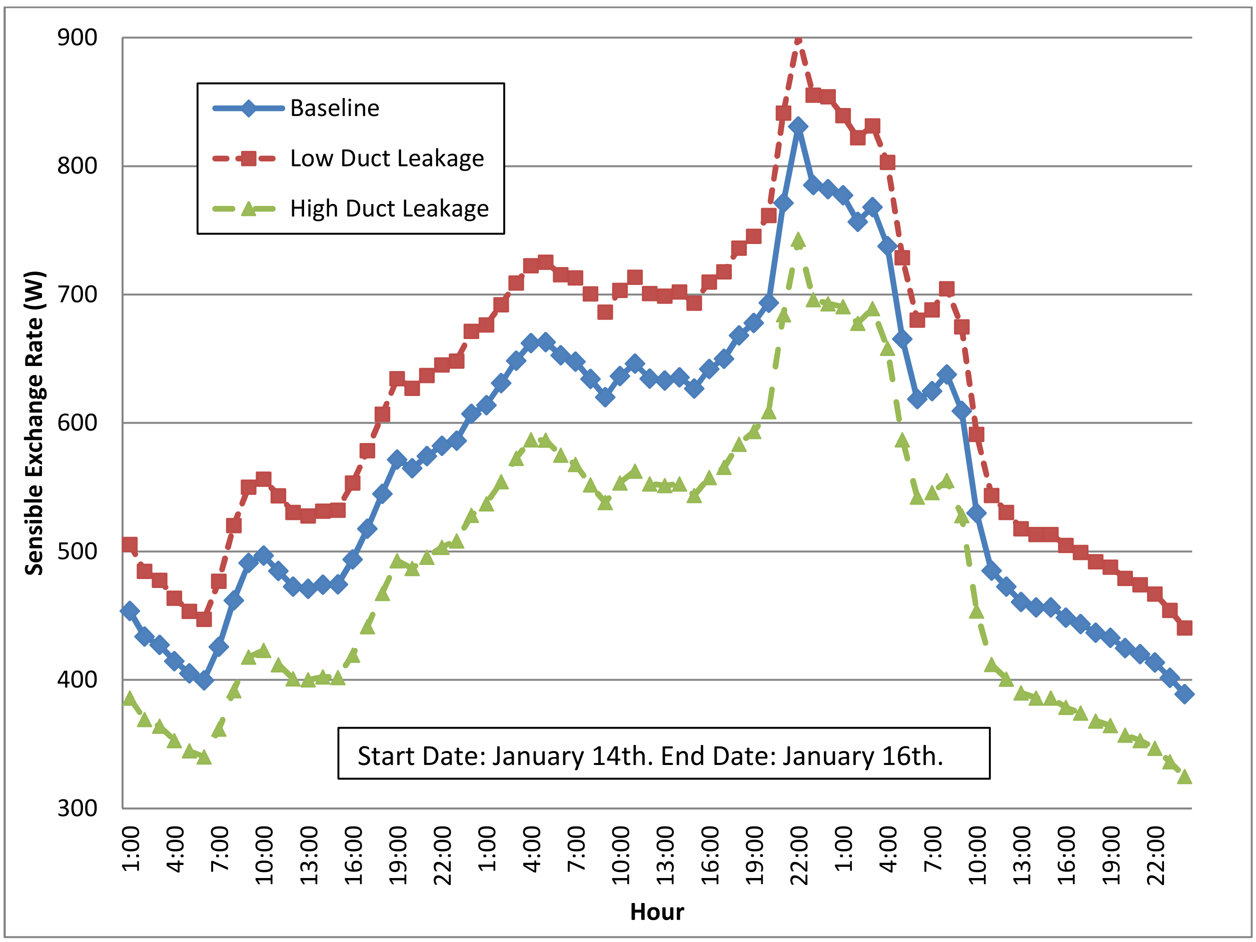

Figure 13 - Winter recovered sensible heating as a function of leakage flow

A much more direct impact to ERV performance is noted when compared to infiltration flows. In figure 13, as supply mass flow rates through the ERV supply side are reduced, in the case of high ERV leakage, recovery rates are reduced as well at all time steps. Conversely, recovery rates are increased as mass flow rates seen from the supply side of the ERV are increased due to lower leakage rates. A similar relationship can be seen with latent exchange in the winter, however it is less pronounced, as overall latent exchange rates are smaller overall when compared to sensible exchange rates.

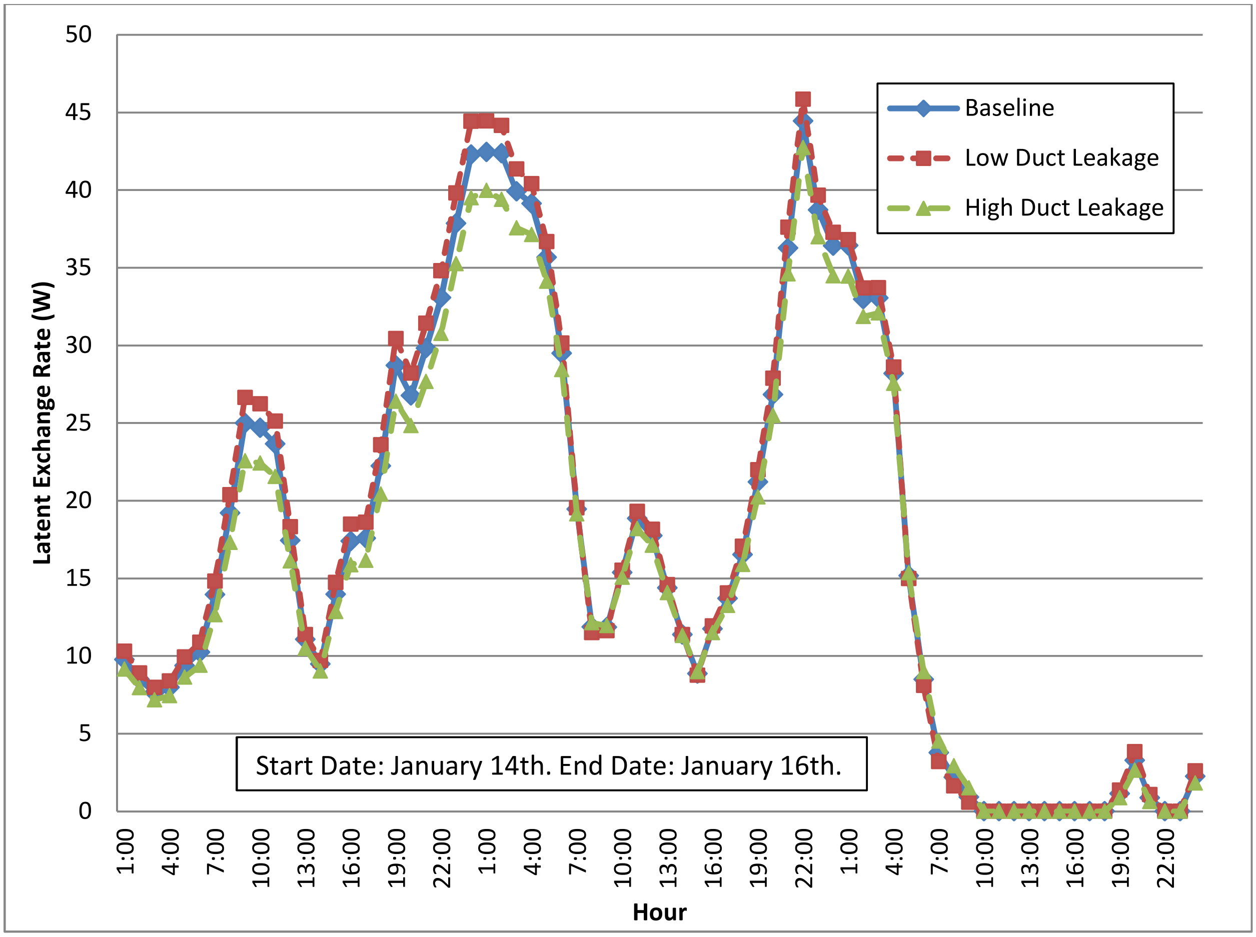

Figure 14 - Winter recovered latent heating as a function of leakage flow

While having a fairly significant impact on increasing overall recovery rates, the low ERV leakage parametric run shows a slight increase in overall heating consumption compared to the baseline case. Conversely, the high ERV leakage rate resulted in lower heating energy consumption. ERV leakage is modeled directly as an imbalance to the ERV supply and exhaust flows, with a reduction in supply flow analyzed here. Therefore, an overall increased amount of outdoor air enters the suite when ERV leakage is low, and more air makes its way through the ERV core and into the suites. The opposite scenario occurs with higher ERV leakage rates, where more supply air is lost to the exhaust stream before entering the space. Consequently, a larger ventilation heating load is seen by the in suite fancoil.

Results therefore suggest that high ERV duct leakage presents a potential issue with indoor air quality, as ventilation rates are less than designed. Reduced supply air volume is in addition to the indoor air quality problems associated with leakage of exhaust flows to incoming supply flows, discussed in the literature review in section 2.3.

When considering the summer condition, modeled cooling energy recovery responds similarly to the modeled heating recovery performance. Total annual cooling energy recovery through the ERV increases from 0.1012 GJ to 0.1164 GJ when ERV leakage is low, and is reduced to 0.0821 GJ when ERV leakage is high. Figures 15 and 16 demonstrate ERV cooling energy sensible and latent recovery rates. Fairly similar trends can be observed in these figures, as both sensible and latent recovery rates are reduced when leakage rates are high, and increased when leakage rates are low. Response to ERV leakage is most pronounced during peak periods of recovery. Following the same logic as the heating recovery response, as leakage rates are increased in the ERV unit the supply mass flow rate, and therefore recovery rate, is reduced.

Considering annual suite cooling energy consumption, the opposite trend is seen compared to annual heating consumption in response to ERV leakage. Modeled annual suite cooling energy shows a slight decrease when ERV leakage rates are low, from 3.69 GJ to 3.63 GJ, and a slight increase in response to high leakage rates, up to 3.76 GJ. As with heating, the response of annual suite cooling consumption is relatively small. An analysis of the fan coil cooling rates shows that differences in the cooling rate is limited to the shoulder seasons where a reduced requirement for cooling is seen, in response to relatively low temperature differentials. In this situation, the ERV and the fancoil act against each other. Improper operation is explored further with the parametric analysis of an economizer option.

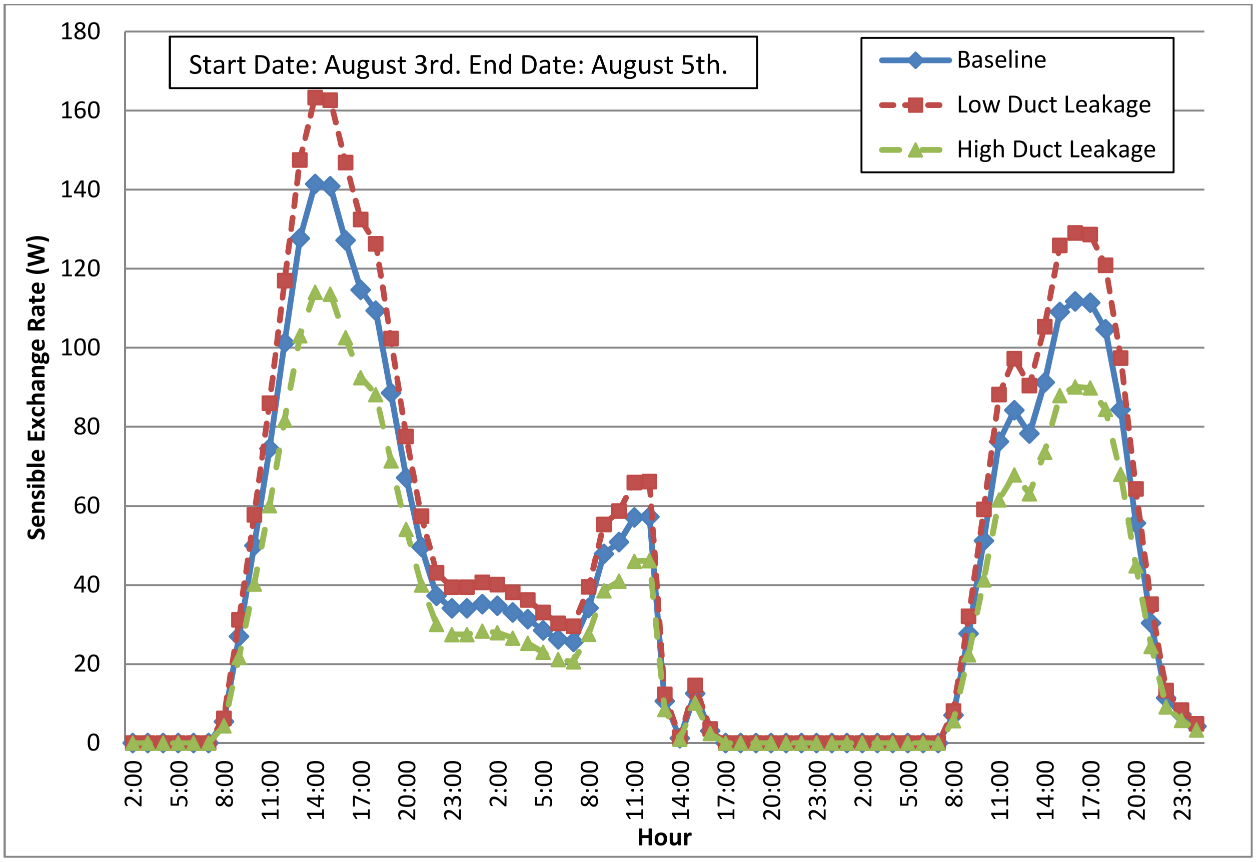

Figure 15 - Summer recovered sensible cooling as a function of leakage flow

ERV duct leakage is demonstrated as having a direct impact to the supply mass flow rates through the ERV, and therefore the recovery rates available. When comparing what the anticipated ERV leakage rates are under typical construction [6] to what should be able to achieved [11], the importance of ERV construction is demonstrated. Parametric analysis shows a not insignificant room for improvement when considering ERV heating and cooling energy recovery rates as a function of leakage. Leakage of supply flow also plays a role in indoor air quality as increased duct leakage reduces the amount of ventilation air seen by the suite, indicating additional issues in terms of tenant well-being. Figures 13 through 16 indicate that improvements can be made to the typical construction quality of the ERV units when considering duct leakage. It can be seen that in all cases a marked increase in actual recovery rates are viable with improved construction quality, and reduced leakage rates.

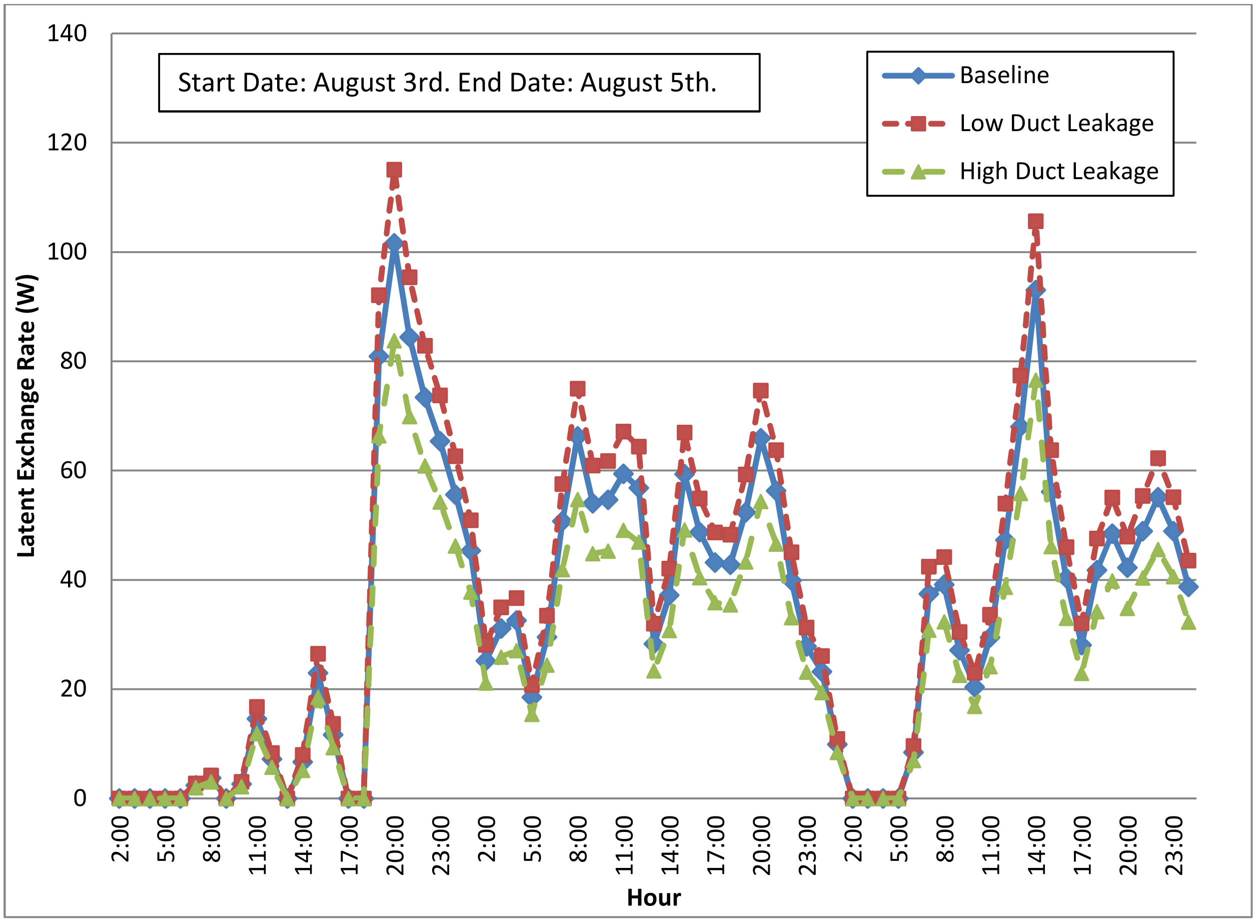

Figure 16 - Summer recovered latent cooling as a function of leakage flow

Results suggest that moving forward on improving the energy performance of MURBs partially relies on specifying ERV units with low leakage rates. The EATR should be considered just as carefully as the nominal recovery effectiveness, to help ensure ERV leakage is kept to a minimum. As demonstrated, this has implications to energy performance, but is also of importance regarding indoor air quality concerns, as overall ventilation flows are decreased. The adoption of the *Passiv Haus Institut* requirements for ERV leakage, represented in the low leakage rate, is therefore warranted.

5.4 Temperature Set point Impact

Indoor temperature set points were modeled as 24°C during the cooling season, and 22°C in the heating season, with an 18°C overnight setback during overnight periods. The two other conditions analyzed represented a tenant attempting to be conservative in their energy use, with a 26°C cooling set point, and 21°C heating set point, and a tenant less concerned with energy use, with a 23°C set point year round. When modeled, conservative and liberal behaviour resulted in decreased and increased cooling and heating consumption compared to the baseline modeled suite, respectively. Parametric analysis indicates that the suite fancoil responds as expected during the heating season, as annual suite heating consumption decreases with more conservative set point, from 4.60 GJ to 3.66 GJ, and increases with more a more liberal set point, to 6.66 GJ. A fairly significant impact to total suite consumption is therefore demonstrated. Annual heat recovered through the ERV increased in both scenarios, to 9.649 GJ and 9.86 GJ with conservative and liberal set points, respectively, compared to a baseline of 9.52 GJ.

Figures 17 and 18 indicate the sensible and latent response of the ERV to temperature set point during the heating season. An increase in recovery rate is seen when liberal (i.e. warmer) set points are modeled in suite. Increased recovery is a function of the increased temperature differential between the indoors and outdoors during peak periods. Contrary to the infiltration and ERV leakage parametric runs, this does not equate to a more optimal system as much more heating consumption is needed to maintain the more liberal temperature set point. Total heating consumption is close to double that of the heating energy required to maintain the more conservative set point.

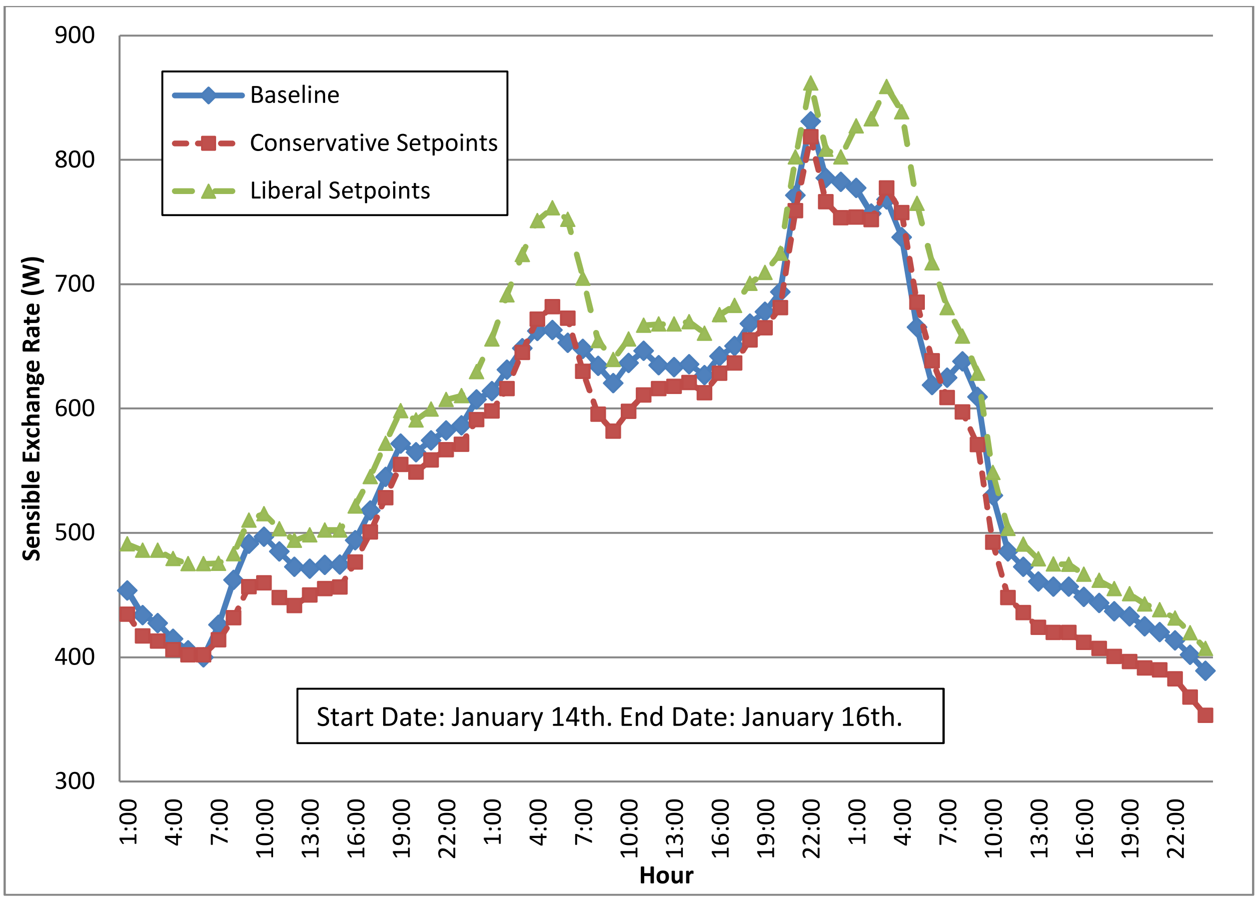

Figure 17 - Winter recovered sensible heating as a function of indoor set point

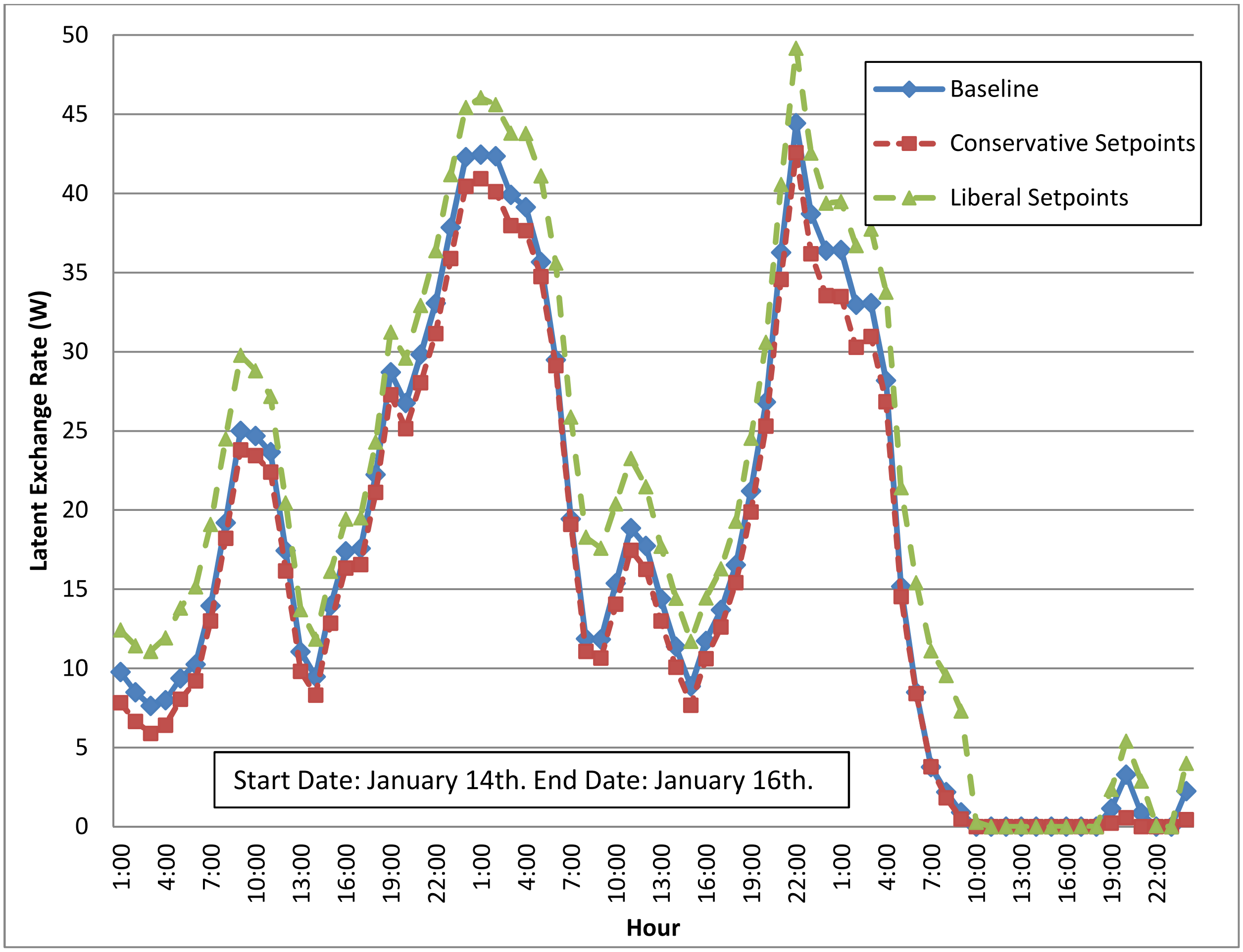

Figure 18 – Winter recovered latent heating as a function of indoor set point

A more conservative temperature set point lead to an expected reduction in heating energy consumption, however also lead to an increase in total recovered heat when compared to the baseline. Figures 17 and 18, however, show a reduction in sensible and latent heat recovery with conservative set points during the heating season, and a reduction in heat recovery is expected given a smaller indoor outdoor temperature differential. Therefore, to account for this increase in recovered heat, the summertime heating energy recovery is analyzed.

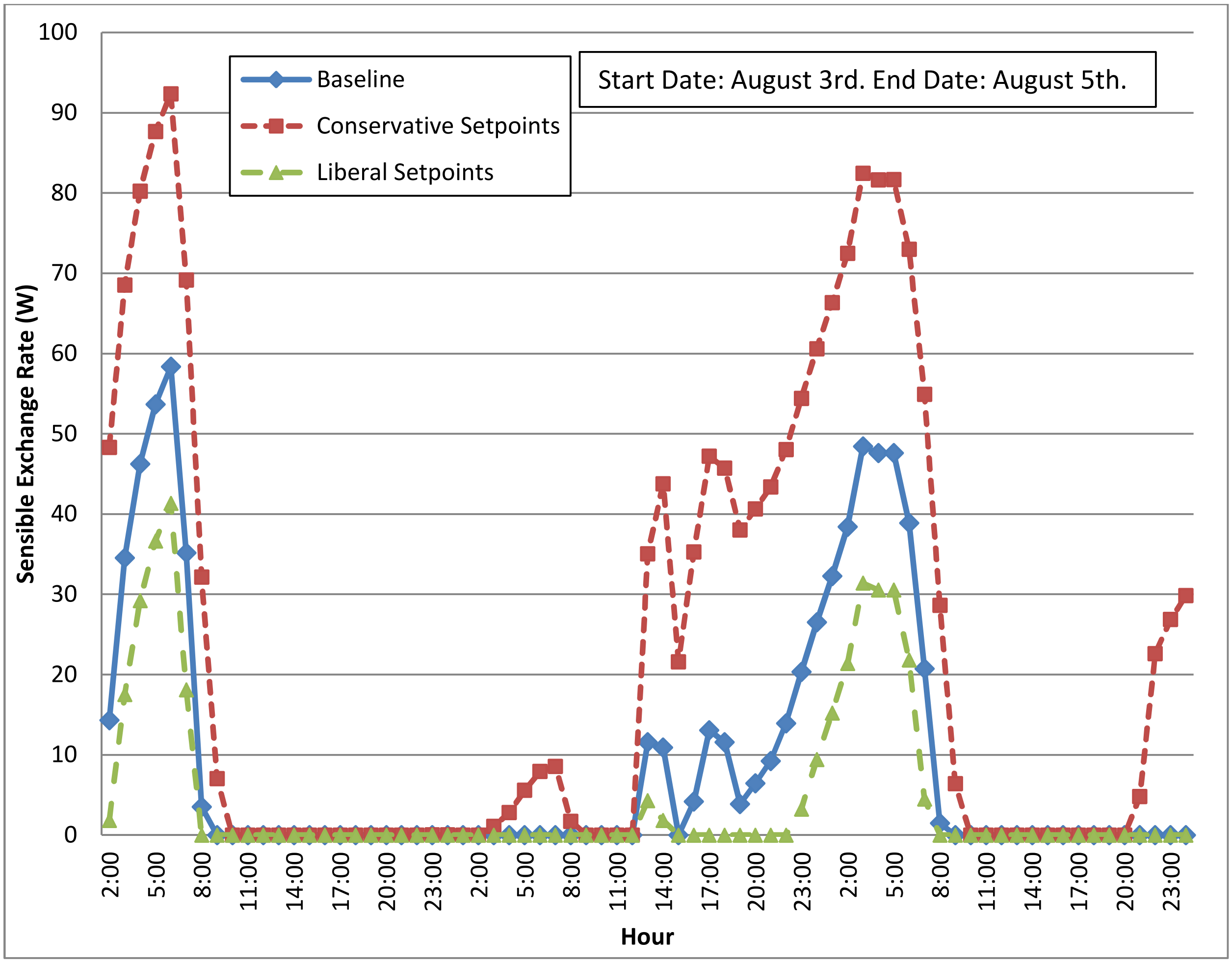

Figure 19 - Summer recovered sensible heating as a function of indoor set point

As shown in figures 19 and 20, more conservative temperature set points lead to an increase in the summertime heat recovery rate. Considering that the modeled conservative cooling set point is set higher in the cooling season, to 26°C, this leads to more hours throughout the cooling season where the outdoor temperature is lower than the indoor temperature. In this situation the ERV acts to heat the incoming air stream. Analysis of figures 19 and 20 shows that this response generally occurs overnight where outdoor temperatures drop. The overnight response would also feasibly occur throughout the shoulder season, where outdoor temperatures are also milder. Annual change to the recovered sensible and latent heat is fairly minimal, corroborating that this response occurs during period of relatively low temperature differential.

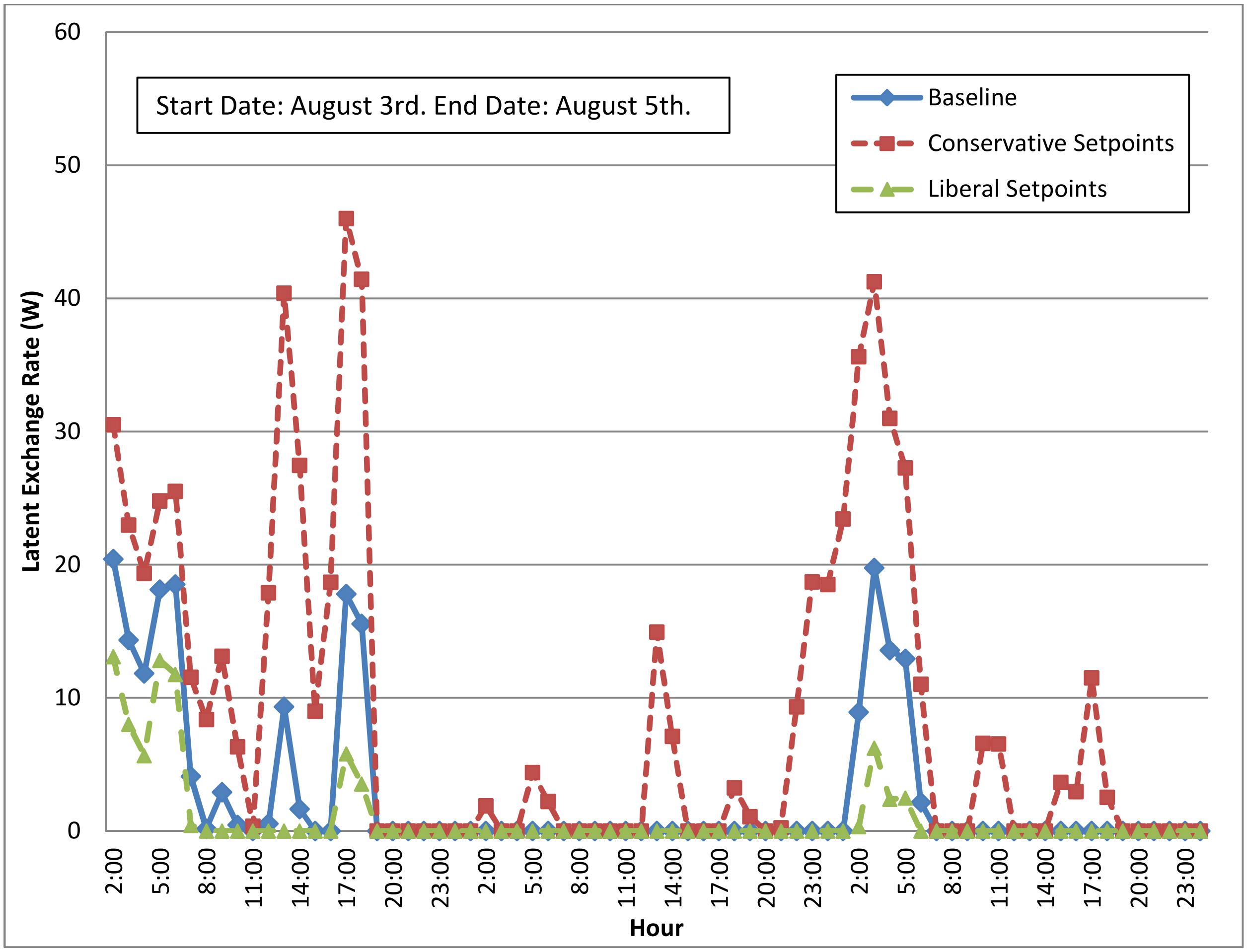

Figure 20 – Summer recovered latent heating as a function of indoor set point

The impact of temperature set point on cooling recovery is also analyzed. The modeled conservative temperature set point lead to a decrease in annual suite cooling energy consumption, from 3.69 GJ to 3.34 GJ, while the liberal set point increased annual cooling consumption to 4.29 GJ. The same intuitive relationship demonstrated in the response to heating consumption is observed. The response of the ERV to temperature set point is relatively more significant regarding the cooling energy recovered. Annual recovered cooling through the ERV decreased from 0.1012 GJ to 0.0352 GJ when more conservative temperature set points are modeled, and increased to 0.1560 GJ when more liberal set points are used. Figures 21 and 22 demonstrate the cooling sensible and latent recovery rate in the cooling season, in comparison to temperature set point.

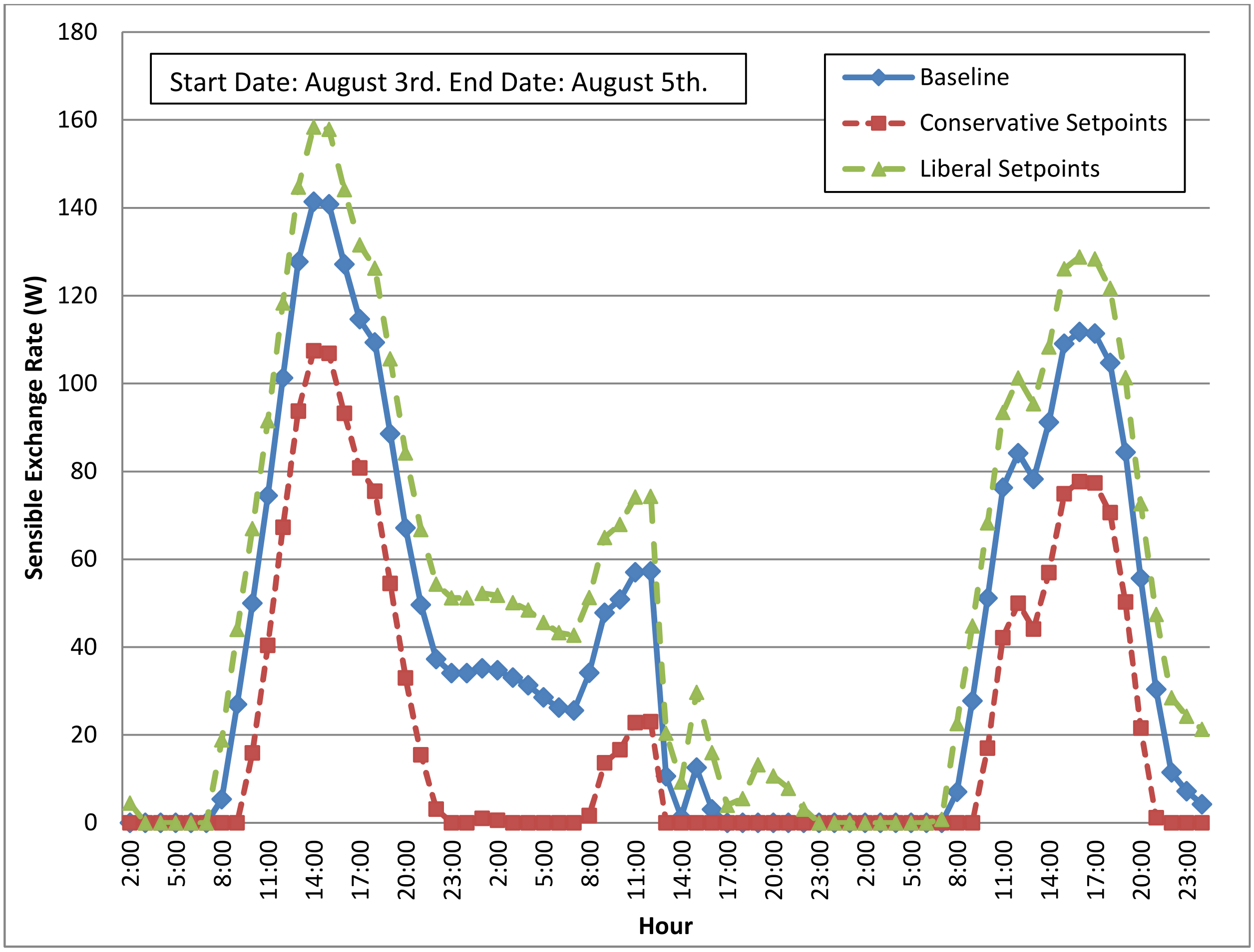

Figure 21 - Summer recovered sensible cooling as a function of temperature set point

Sensible and latent recovery rates again appear to respond fairly similarly in comparison to one another. Analysis indicates that more conservative temperature set points lead to reduced recovery rates during all time steps due to a reduced temperature differential. Modeled annual recovery rates through the ERV are conversely increased when set points are more liberal. Therefore the inverse of the unwanted heating effect produced when examining heating energy recovery is not seen when considering cooling recovery. Considering the Toronto climate, it is much less likely that the outdoor air temperature will increase during the heating season so much so that the ERV will respond by cooling the incoming air rather than heating it. An analysis of the cooling rate during the same 3 day period in the winter indicates that no cooling recovery takes place.

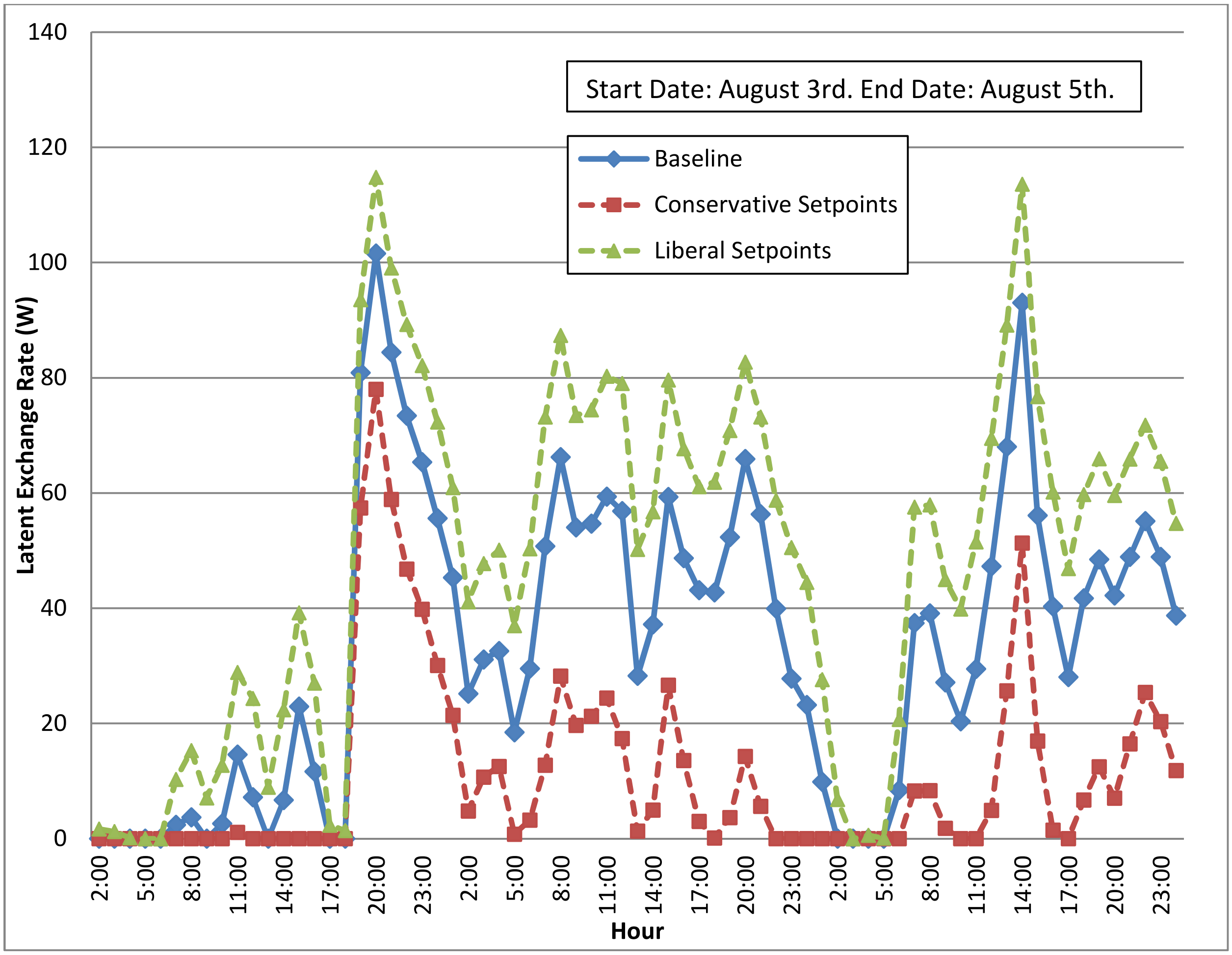

Figure 22 - Summer recovered latent cooling as a function of temperature set point

In summary, temperature set points play the biggest role of the parameters analyzed in terms of overall heating and cooling energy consumption, however a smaller impact to ERV recovery rates is demonstrated. Temperature set points share a direct relationship with the amount of heating or cooling called for by the in suite fancoil unit. By increasing the summer set point by 2°C and decreasing the winter set point by just 1°C, a significant reduction in both cooling and heating consumption of the parameters analyzed was shown. However, ERV performance was not optimized, as this also led to an overheating effect during the shoulder seasons and overnight in the summer. Findings therefore suggest there is potential to provide a more optimal control strategy of the ERV unit to optimize both heating and cooling season performance.

5.5 ERV Control Strategy Impact

Parametric analysis of indoor temperature set points highlight the fact that unwanted heating of the incoming air can occur during the cooling season. Overheating can occur overnight during the cooling season, as well as throughout the shoulder season, where outdoor temperatures fluctuate around the indoor temperature set point. The overheating impact is undesirable and can counteract the fancoil unit setting. To explore a way around this, an air side economizer mode for the in suite ERV is explored as a method of circumventing the ERV core when outdoor temperatures are favourable. The baseline operation, by comparison, is operated at a constant flow rate through the ERV unit.

The economizer by-pass parametric run results in little change in overall annual heating consumption, from 4.60 GJ to 4.61 GJ, while slightly reducing annual heat recovered through the ERV from 9.52 GJ down to 9.137 GJ. Annual suite cooling energy consumption is slightly reduced to 3.59 GJ from 3.69 GJ, while annual cooling recovered through the ERV is very slightly reduced from 0.1012 GJ to 0.1006 GJ. The lack of change to heating energy consumption is a function of the economizer operation, which only operates to provide a free cooling effect. The resulting decrease in heating energy recovery is therefore explained. Considering figures 23 and 24, the economizer has no impact on the sensible and latent heating energy recovery rates in the heating season, as it is not active.

The resultant decrease in recovered heating energy therefore must represent the decrease in the overheating effect of the ERV during the shoulder season and summer time. An analysis of heating energy recovery in late June, where mild outdoor temperatures may be expected, is demonstrated in figures 25 and 26.

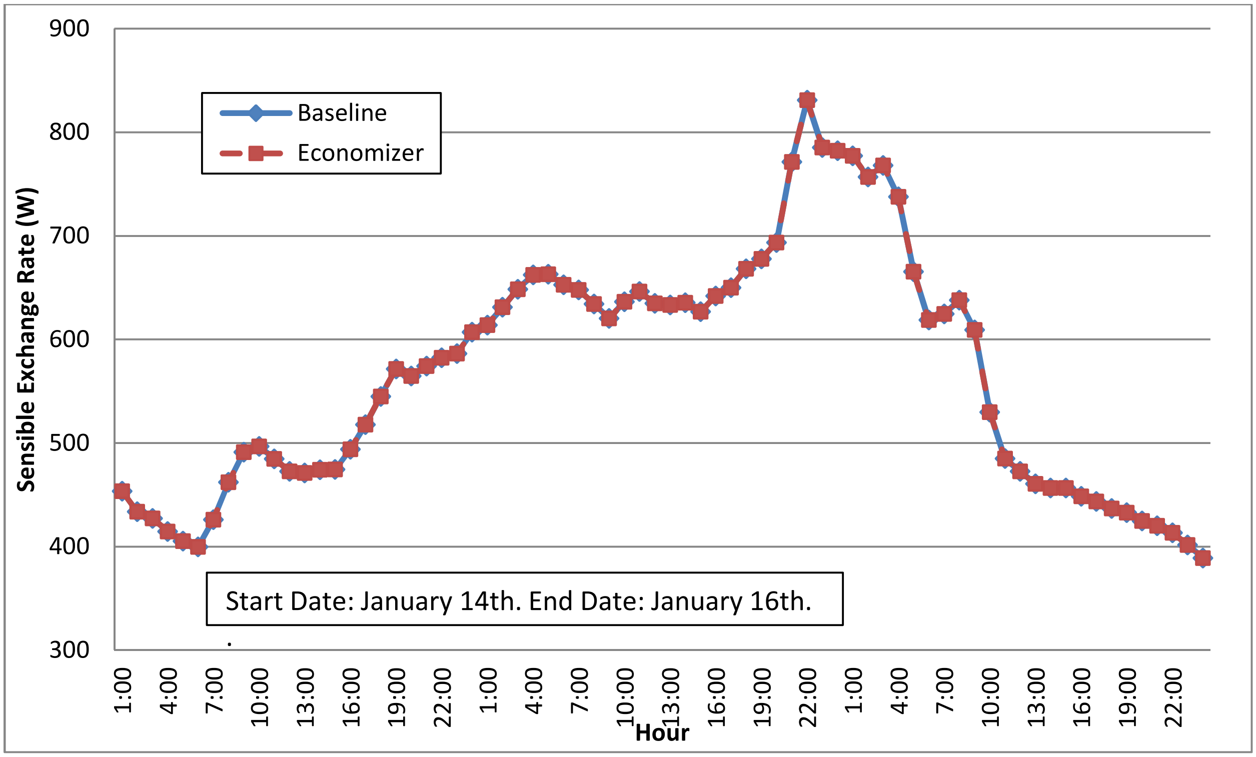

Figure 23 – Winter recovered sensible heating as a function of ERV control

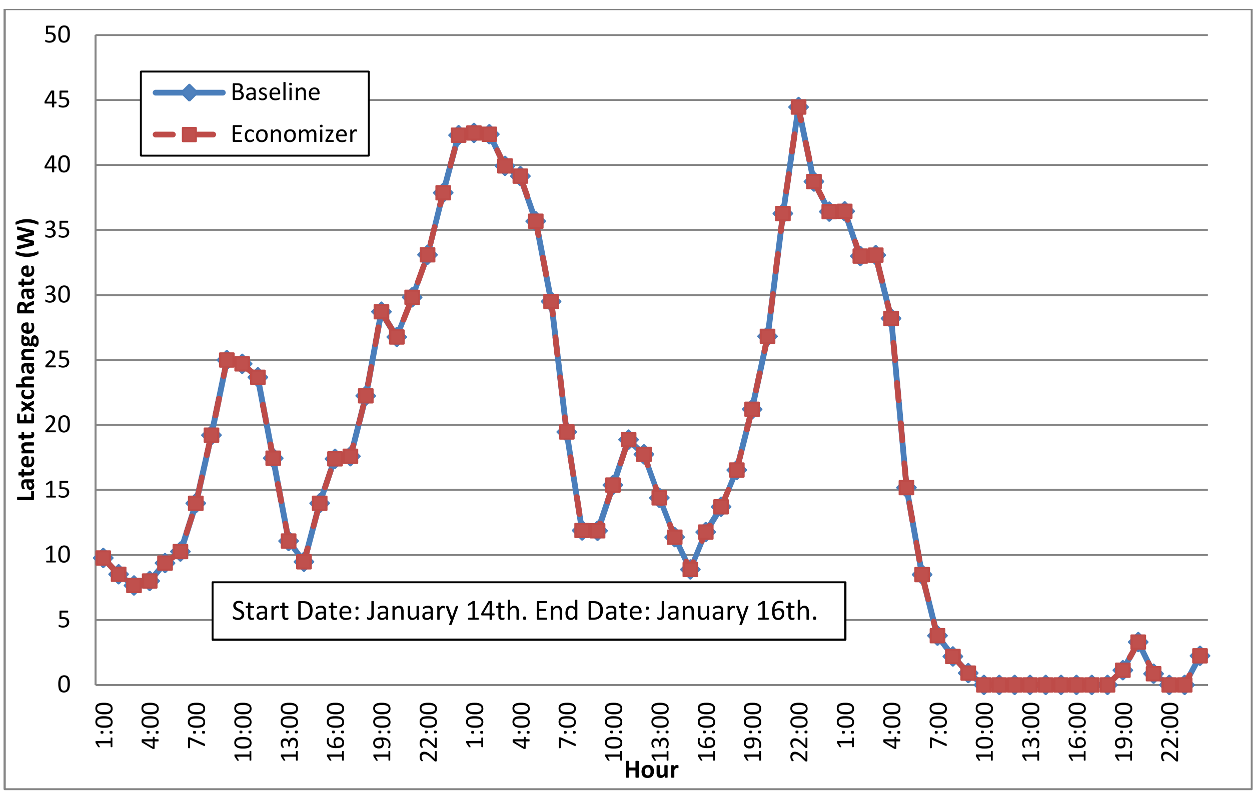

Figure 24 - Winter recovered latent heating as a function of ERV control

Figures 25 and 26 show that in the baseline, uncontrolled option, more heating energy is recovered by when compared to the economizer option. Shown in figure 25, the 'gaps' in the economizer heating recovery indicate periods of time when the outdoor conditions are within a favourable range for cooling, yet below the indoor temperature set point. At these times, the ERV core is bypassed, and the recovery rate correspondingly drop to zero. The periods where heating recovery remains on reflect conditions where outdoor air temperature is too low, and cooling is not desired. Figure 26 indicates a similar trend when considering latent recovery.

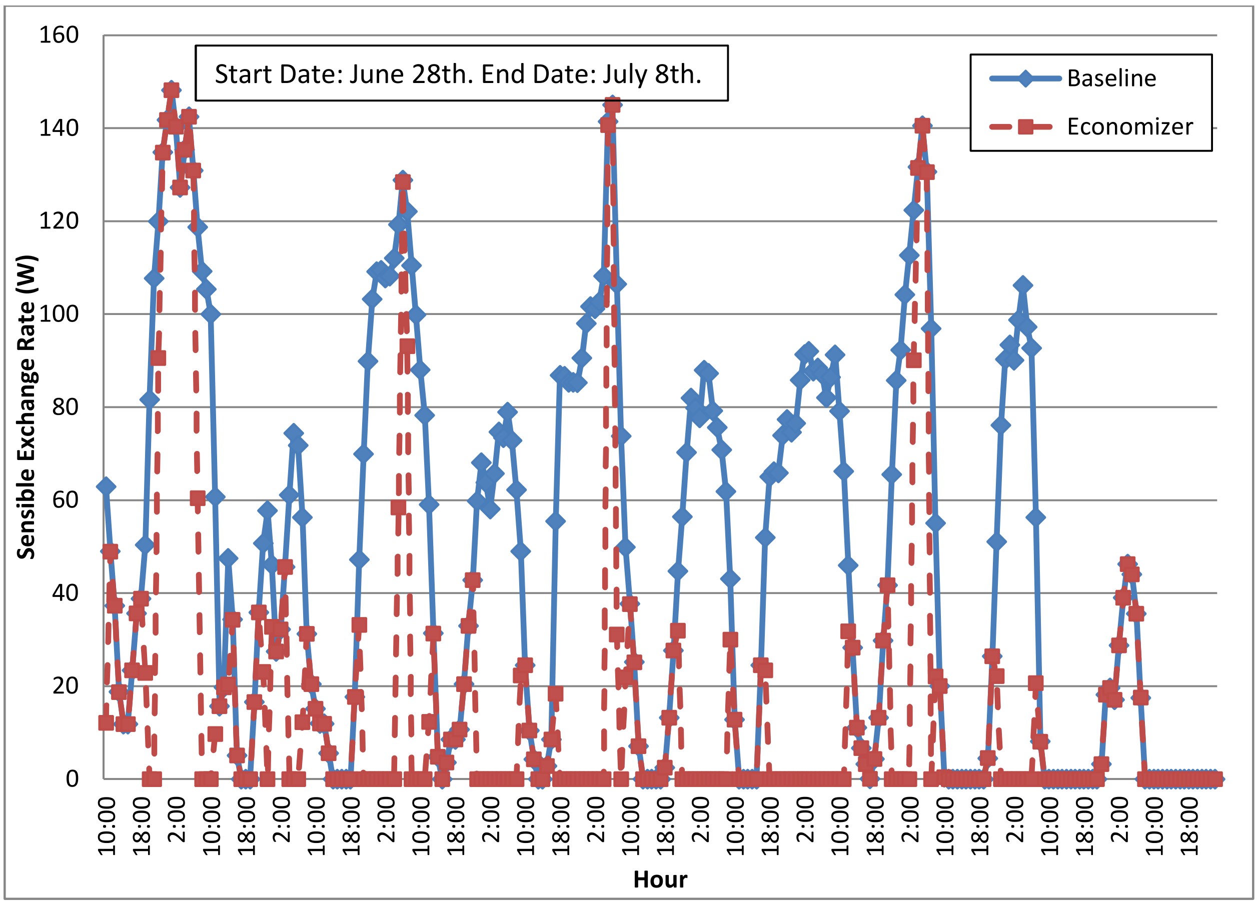

Figure 25 - Summer recovered sensible heating as a function of ERV control

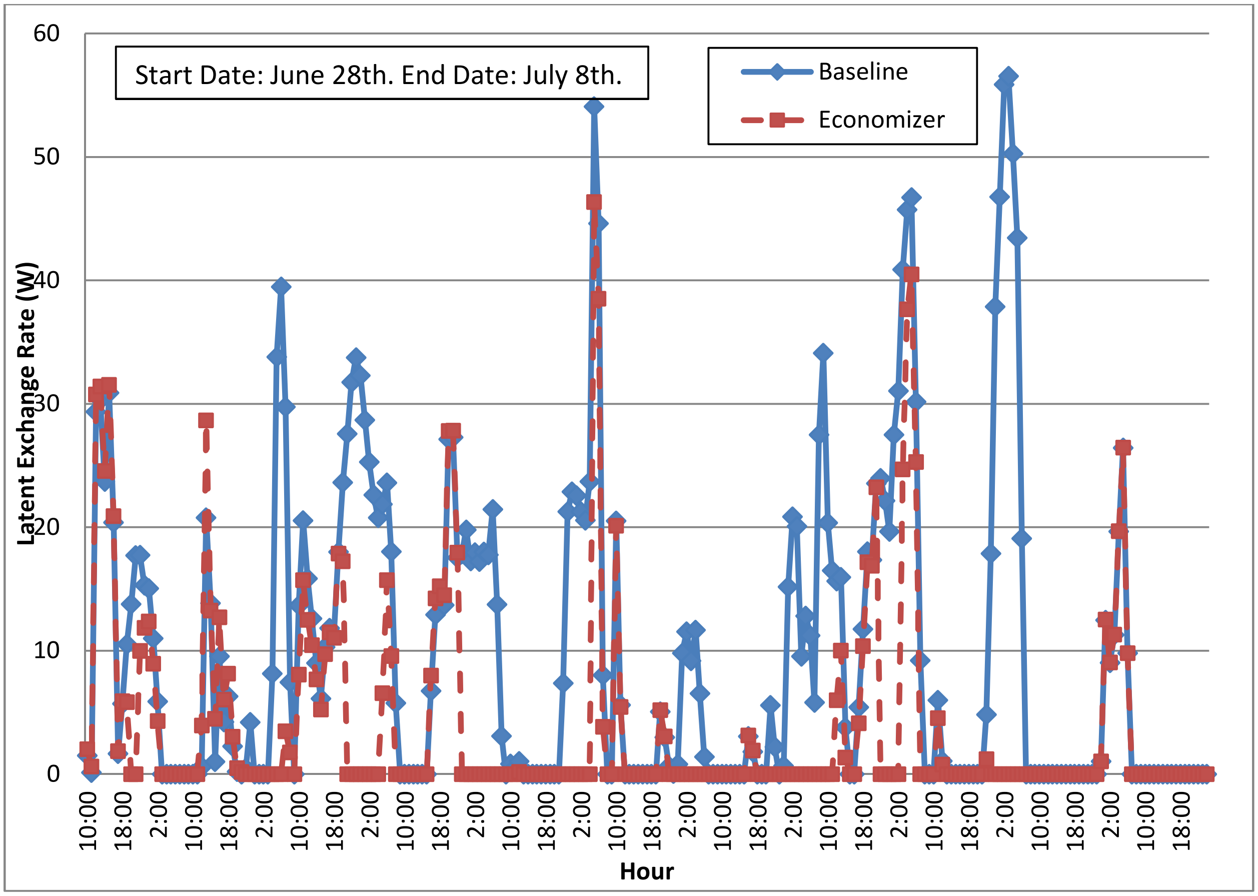

Figure 26 - Summer recovered latent heating rate as a function of ERV control

Summer time cooling operation of the economizer by-pass option results in a reduction of cooling energy consumed. However figures 27 and 28 indicate that, as with heating recovery, little to no response is seen in the ERV sensible and latent cooling rates during peak cooling periods. Decreased annual cooling consumption with use of the economizer by-pass is therefore a result of free cooling reducing the runtime of the fancoil required. Therefore while only a small impact to heating consumption is seen, an economizer can work to reduce overall cooling energy consumed, as well as avoid unwanted heat recovery, resulting in a ventilation system working more optimally.

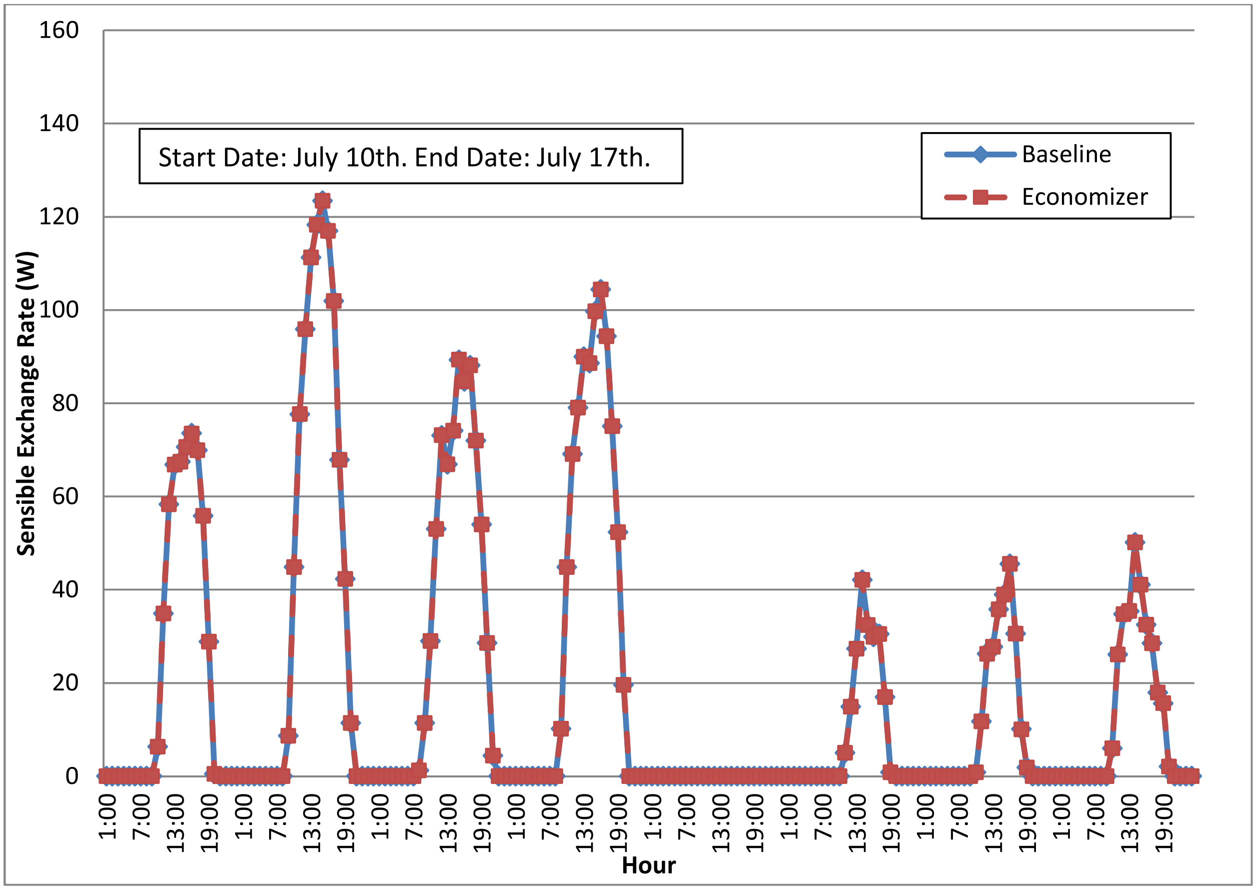

Figure 27 - Summer recovered sensible cooling as a function of ERV control

The economizer control strategy analyzed is fairly simple, however is often not used with small scale in-suite ERVs. A primary reason for this is restrictions from space constraints for mechanical equipment, as bulk head space is often limited in high rise construction. The units may also be simply too small to accommodate the bypass ductwork necessary for economizer operation. Alternatively, a control strategy may be proposed which makes use of the operable windows, which can be automated to open and close in response to outdoor temperatures, in conjunction with the ERV unit shutting down. Window automation would provide free cooing, reacting to the outdoor and indoor temperatures, and eliminate the need for by-pass ductwork within the ERV. An added benefit of this strategy is the reduction of fan run time, leading to additional energy savings not captured in the parametric analysis.

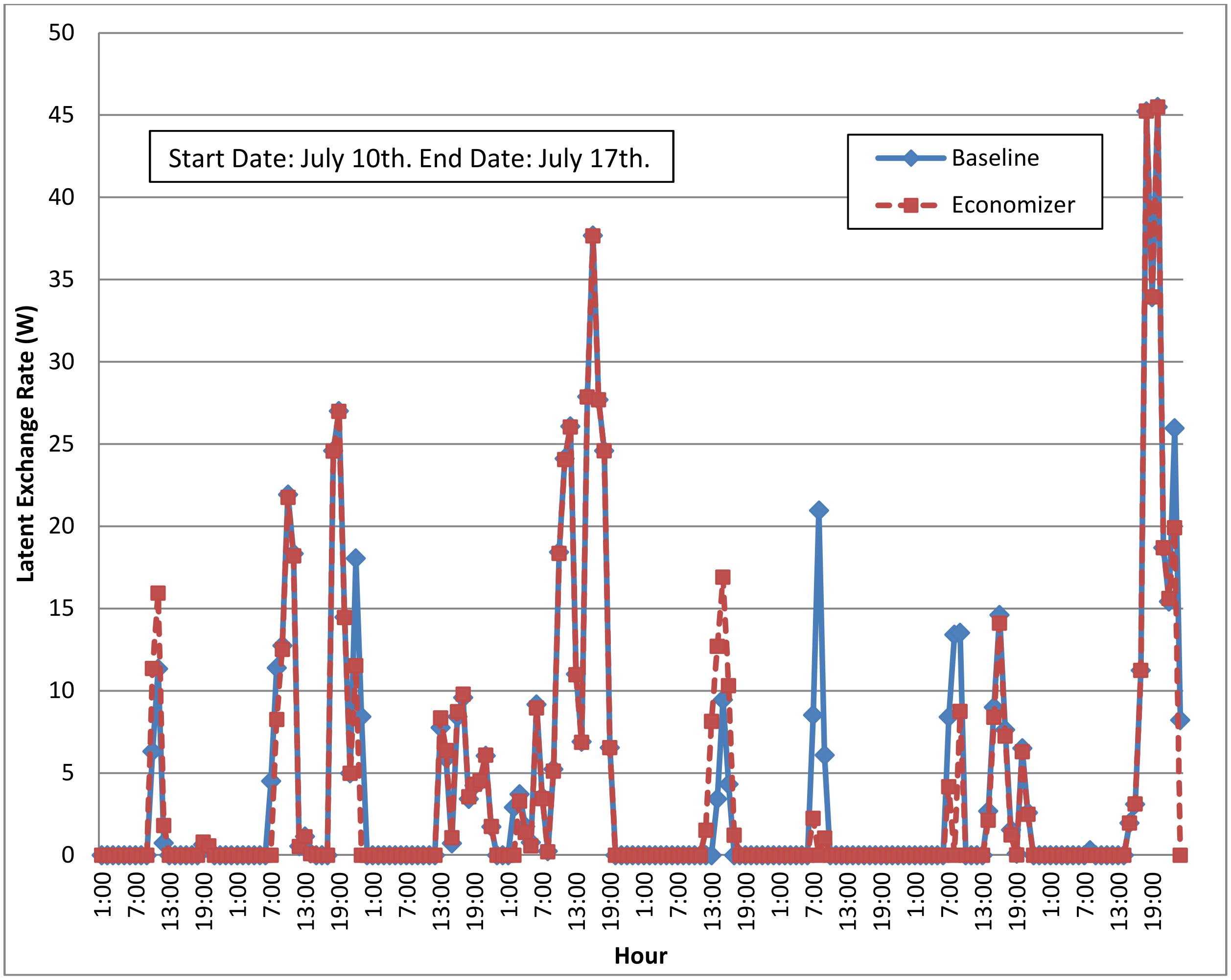

Figure 28 – Summer recovered latent cooling as a function of ERV control

Such a control strategy is however theoretical in a MURB building at this point, and many considerations would need to be taken into account. Of primary significance is individual occupant controllability, therefore a manual override is likely required to allow individual control if desired. Alternatively, property managers may focus on educating tenants regarding proper operation of their ERV, including its use in response to manual operable window adjustment. Education could highlight that to optimize operation, ERV units should ideally be turned off whenever windows are left open, and turned back on when they are closed, to maintain ventilation rates while avoiding unwanted recovery. An educational strategy is less likely to result in optimal performance, however is likely a more realistic option in the short term. Education can also be relied on for existing buildings with ERV units in operation.

5.6 Design Stage Energy Model Impact

The anticipated operation of in suite ERV unit is of significance to the design community when estimating energy savings for a design project. Particularly, energy modelers will simulate overall building performance for purposes of Building Code compliance, to determine *LEED® Energy and Atmosphere* points targets, and for various other green standard which can vary by jurisdiction in Ontario. Energy modeling at this stage often requires a number of assumptions related to the design and construction of a building, which often reflect an optimized operation of the building systems. The assumptions used to create the baseline performance of the in-suite ERV, described in section 3.2, were compared to the assumptions which are likely made at the design stage of the energy modeling process. Design stage, idealized assumptions include balanced flow through the ERV with no leakage, nominal infiltration rates of 0.25 $L/s/m^2$ of wall area, uncontrolled ERV operation and typical temperature set points.

Figures 29 and 30 represent the sensible and latent heating performance of the ERV during typical winter operation. Figures 31 and 32 represent sensible and latent cooling operation during summer periods. In all cases, modeled recovery rates through the ERV are increased compared to the baseline operation. Modeled annual heating and cooling energy recovered through the ERV represent the highest rates reported of all the parametric runs analyzed, at 11.217 GJ and 0.1191 GJ respectively. Annual suite heating consumption is reduced compared to the baseline, from 4.60 GJ to 3.81GJ, while annual cooling consumption is increased from 3.69 GJ to 3.85 GJ. The increase in peak sensible and latent recovery rates is primarily due to the elimination of leakage, which was demonstrated to have a comparatively large impact on ERV performance. The design community therefore must pay attention to leakage rates when specifying ERV units, or risk overstating performance.

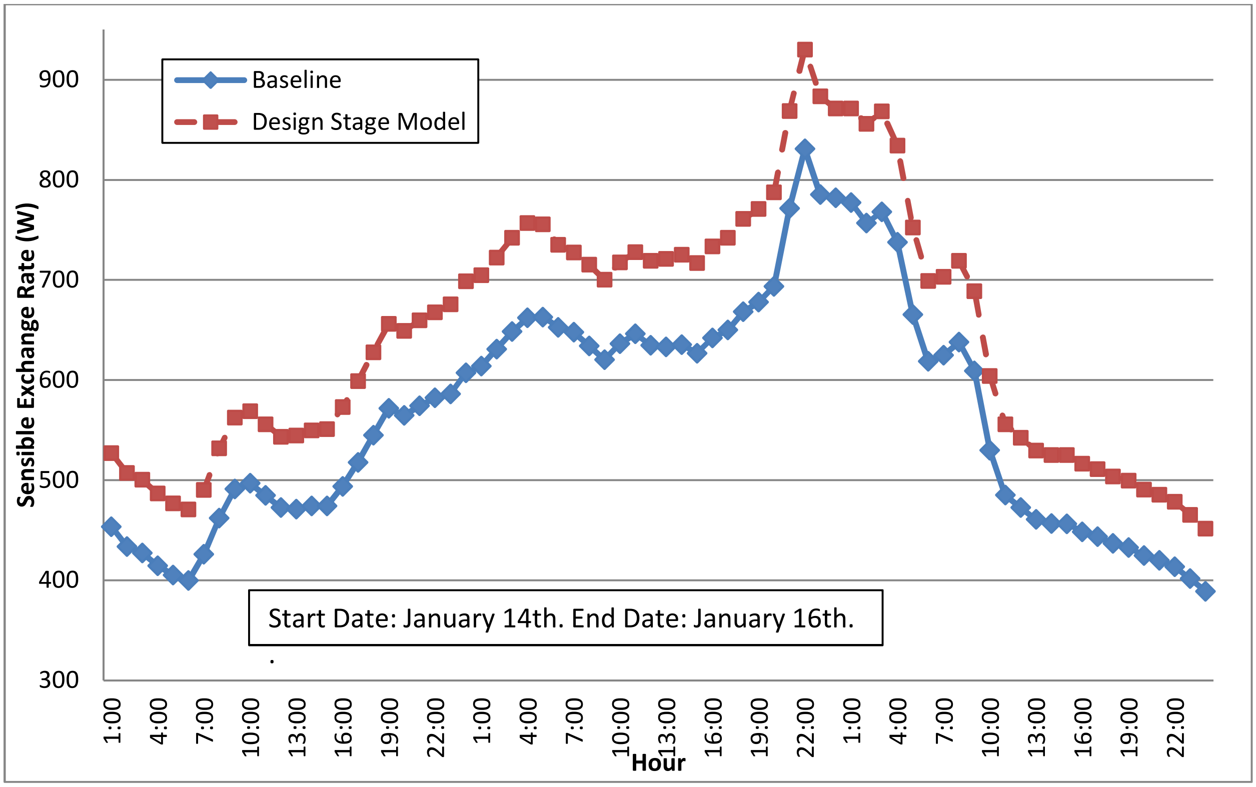

Figure 29 – Winter recovered sensible heating: baseline vs design stage assumptions

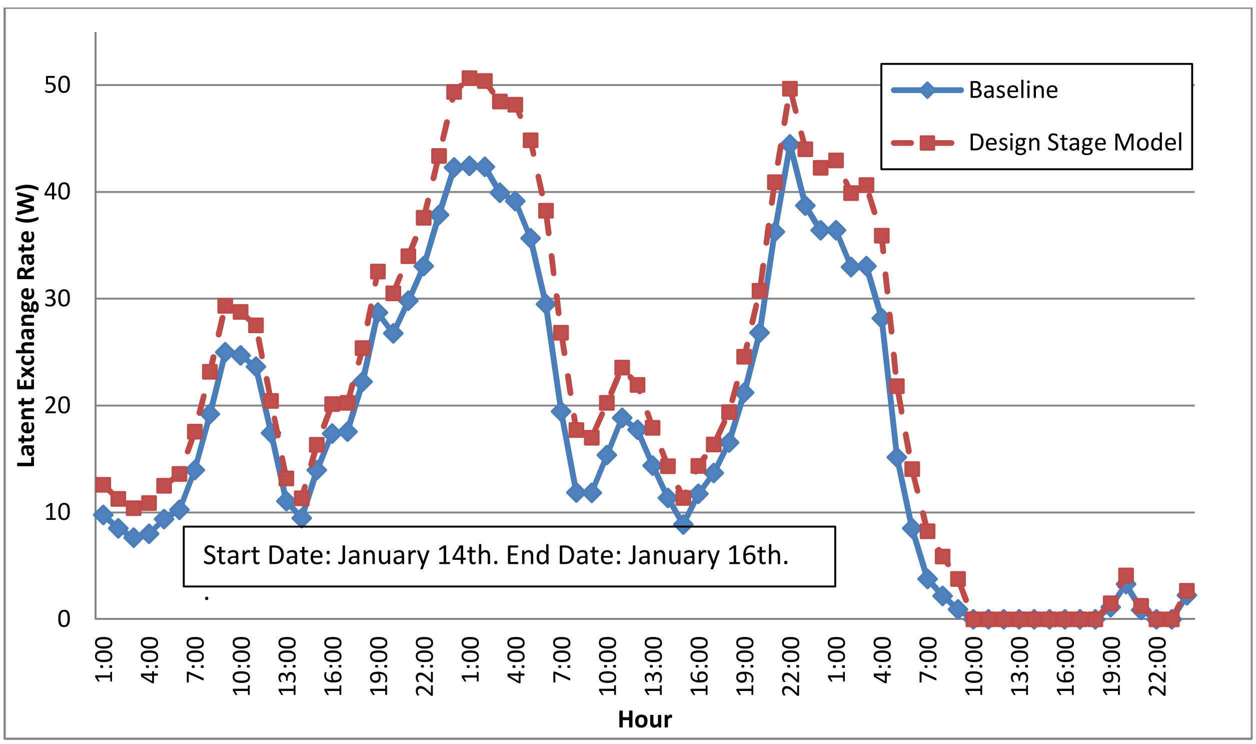

Figure 30 - Winter recovered latent heating: baseline vs design stage assumptions

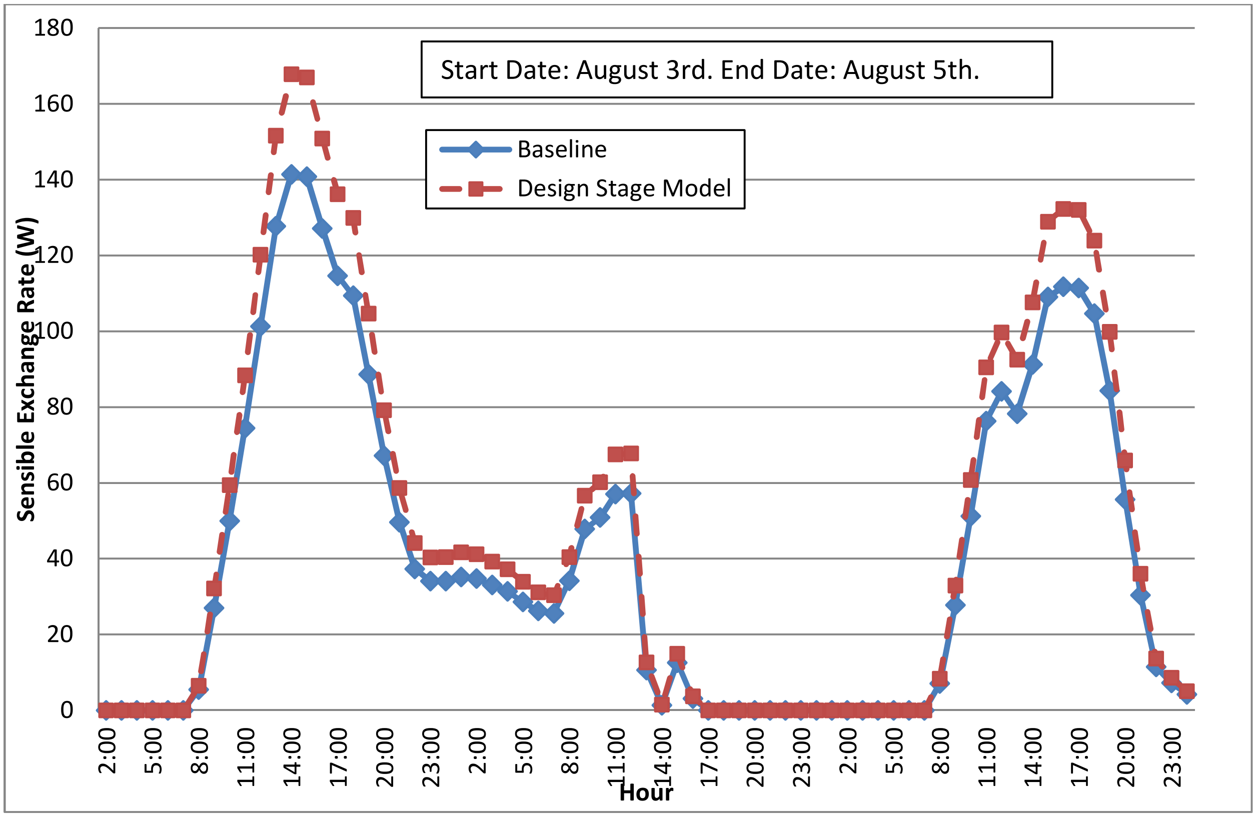

Figure 31 - Summer recovered sensible cooling: baseline vs design stage assumptions

Conversely, annual cooling consumption in the design stage model assumption is shown to increase slightly. The nominal infiltration rates assumed in the design stage model are less than even the low design infiltration rate expected. Therefore free cooling from infiltration is further reduced, causing the increase cooling energy. Specifically, that lower infiltration rates allow for reduced free cooling of the air to the suite during the summer and shoulder seasons. Design stage model assumptions in this case appear to favour a reduction in annual heating energy, and slightly overstate cooling energy compared to the anticipated real world scenario.

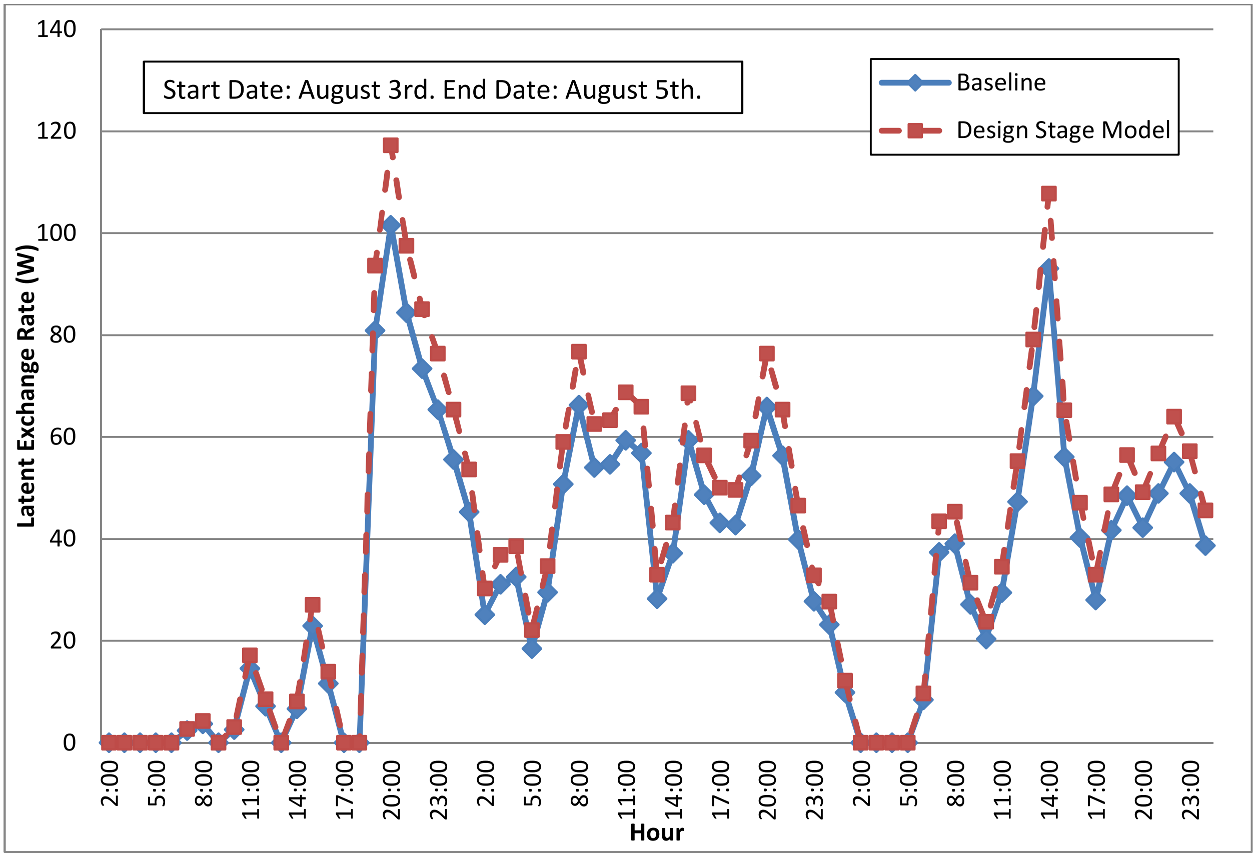

Figure 32 – Summer recovered latent cooling: baseline vs design stage assumptions

5.7 Results Summary

Table 5 summarizes the results of the parametric analysis, as described in sections 5.2 through 5.6. The modeled annual heating and cooling consumption in the suite, as well as the annual recovered heating and cooling energy, are presented in gigajoules (GJ). Total annual suite energy consumption in GJ and energy use intensity (EUI) in MJ/m^2 is also presented, which represent all energy end uses experienced by the suite, including heating, cooling, lighting, electrical loads and HVAC electrical consumption. All parametric runs are presented. For comparison, a scenario in which no ERV device is installed is also presented.

Figures 33 and 34 demonstrate a comparison of annual heating energy compared to recovered heating energy, and annual cooling energy compared to recovered cooling energy, respectively, for each parametric run.

Table 4 – Parametric Analysis Results Summary

	Parametric Run	Annual Total Energy Use (GJ)	Total Energy Use Intensity (MJ/m2)	Annual Heating Energy (GJ)	Annual Cooling Energy (GJ)	Annual Recovered Heating (GJ)	Annual Recovered Cooling (GJ)
-	No ERV device	34.73	467.43	17.67	2.03	0	0
1	Baseline scenario, with inputs as defined in Table 1.	23.51	316.42	4.60	3.69	9.520	0.1012
2	Expected low infiltration rate.	23.34	314.13	4.39	3.74	9.554	0.1012
3	Expected high infiltration rate.	26.89	361.91	8.61	3.13	9.121	0.1014
4	Expected low duct leakage/imbalance rate.	23.72	319.25	4.85	3.63	10.748	0.1164
5	Expected high duct leakage/imbalance rate.	23.2	312.25	4.29	3.76	7.981	0.0821
6	Expected ‘conservative’ temperature set points.	22.12	297.71	3.66	3.34	9.649	0.0352
7	Expected ‘liberal’ temperature set points.	26.58	357.74	6.66	4.29	9.836	0.1560
8	Economizer by-pass option.	23.38	314.67	4.61	3.59	9.137	0.1006
9	Design stage energy model	22.95	308.88	3.81	3.85	11.217	0.1191

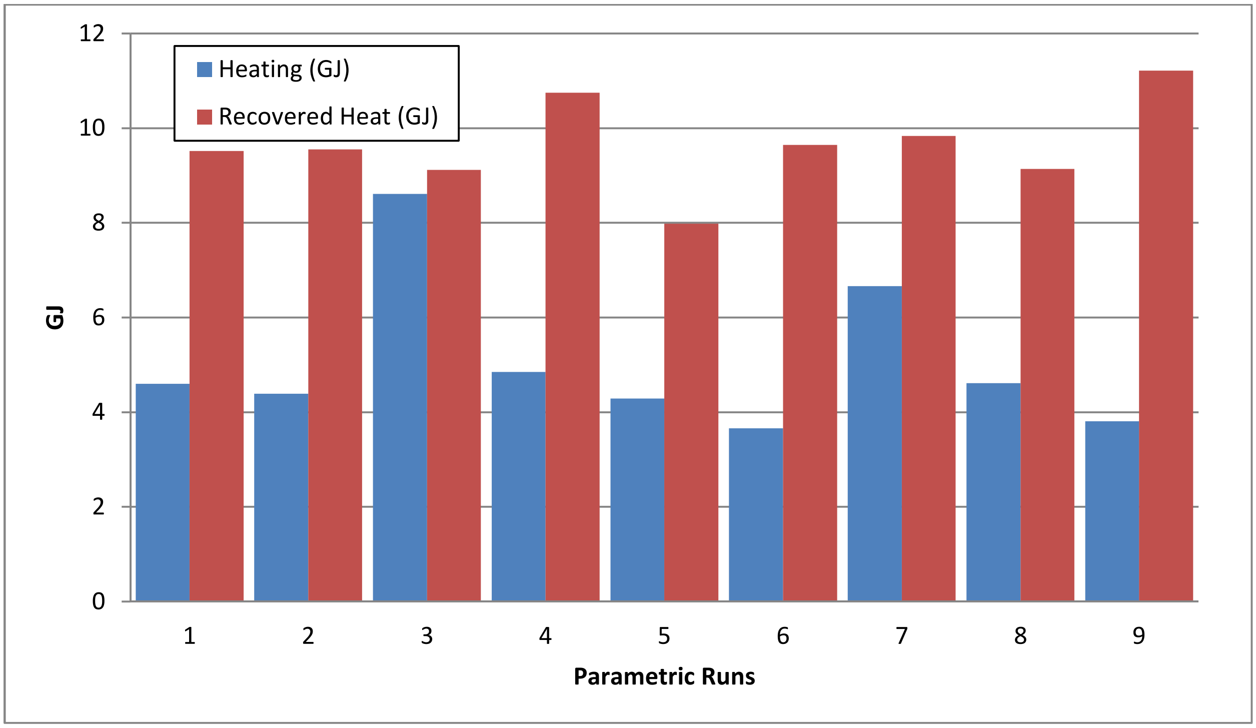

Figure 33 - Comparison of annual heating to recovered heating energy

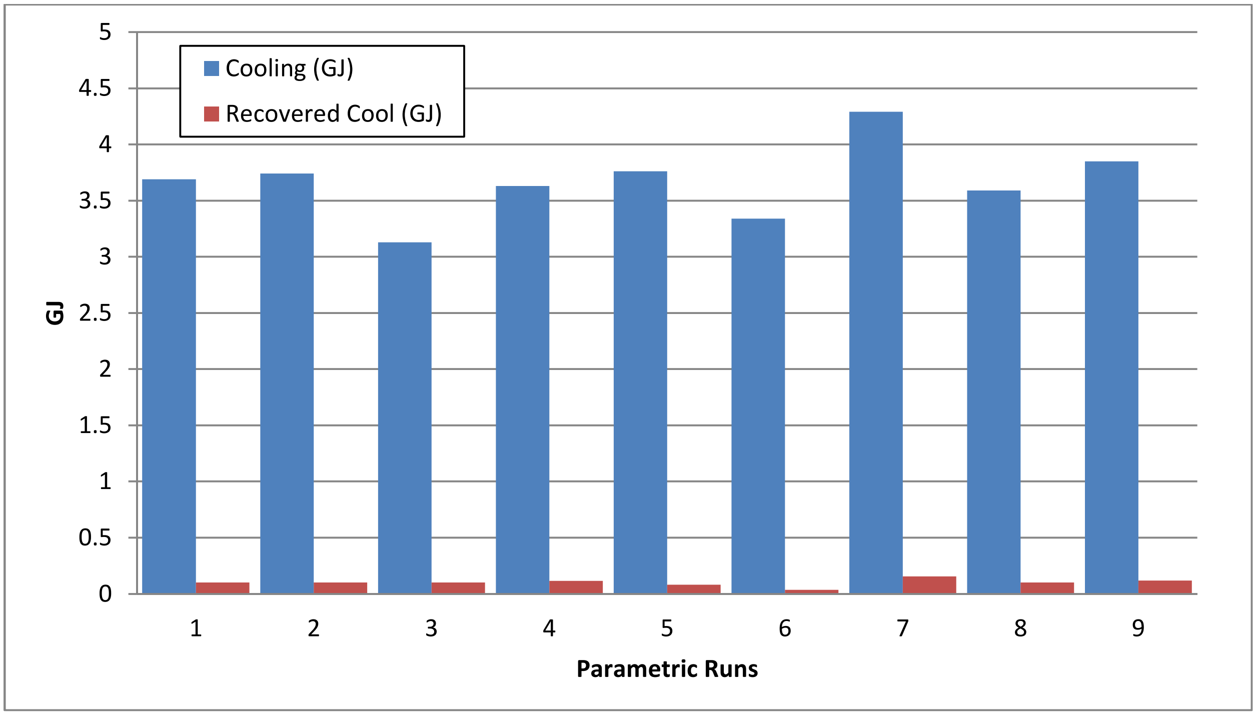

Figure 34 - Comparison of annual cooling to recovered cooling energy

Figures 33 and 34, as well as Table 5, indicate that overall the vast majority of the recovered energy can be attribute to heating. In all parametric runs, recovered heating energy exceeded the annual heating used. As mentioned in section 5.1, the South facing window in the suite results in significant solar gains to the model, bringing down the heating consumption relative to the suite consumption in all parametric runs. The solar gains allows the amount of heat captured through the ERV annually to exceed the primary heating needed to maintain the models set point, as with a south facing window a large portion of the heat within the suite is generated from solar gains, as well as other internal gains. This heat is not reflected in the primary heating consumption value presented. Cooling energy recovery, on the other hand, is only able to recover a small fraction of the annual cooling energy required for the suite in all cases. Again this can be attributed to the solar gains increasing the amount of heat in the suite, keeping the suite warm throughout the summer months, and reducing the temperature differential through the ERV.

Overall energy use intensity of the baseline case is 316.42 MJ/m^2. This value is low for a typical residential suite, however is partially due to the reduced heating load from solar gains. Furthermore, in comparison to the case where no ERV is modeled a significant reduction in heating is seen, from 17.67 GJ down to 4.6 GJ, suggesting that the ERV device itself is also responsible for a significant portion of this reduced energy use. Considering that the suite modeled is a simplified case with one exterior exposure, which is south facing, it follows that the heating load of the modeled suite is primarily dependent on the ventilation load. As the ventilation is tempered by the ERV, the inclusion of this equipment has a significant impact to the suites energy use.

Of note as well when considering the sensible and latent recovery rates is the overall amplitude of the exchange rates. As shown in the preceding sections, sensible recovery in the winter remains in the range of about 400 W to 900 W during the period analyzed, whereas latent heating recovery only accounts for recovery rates on the scale of 0 W to 50 W. The amplitude of the exchange rates suggest that sensible heat recovery in the winter is of much more significance than latent recovery, which is likely due to the high temperature differentials between the indoors and outdoors during the heating season. This was further corroborated by the validation analysis in section 4. Latent recovery plays a much larger role during the summer as sensible and latent exchange rates are much closer in scale, in the range of at 0 W to 160W and 0 W to 120 W, respectively.

6.0 Conclusions

ERV units are relied on to achieve savings in heating and cooling consumption in newer, high performance multi-unit residential buildings. Ventilation recovery goes hand in hand with the compartmentalized approach to high rise condo unit construction. Proper unit specification, and a proper understanding of the real world performance is therefore of importance to the design and construction community.

The impacts of several parameters to in-suite ERV performance in high rise residential buildings in Toronto were analyzed and discussed. The parametric analysis was informed by the current literature regarding impacts to real world ERV performance. Several key parameters were identified. Space infiltration rates, and resultant sensible and latent loads to the space, have the potential to alter indoor conditions, which the ERV unit encounters at the exhaust stream. Leakage rates from the supply to the exhaust side of the ERV reduce the supply rate of the ERV, and therefore the energy recovered. Changes to room temperature set points alter the temperature differential between indoors and outdoors, impacting potential recovery rates. Finally, modifying the control of the ERV unit has the potential to optimize performance. To ensure a proper context, attention was paid to the amplitude of the factors analyzed in the parametric analysis. The range of values analyzed, for example the anticipated tight and loose infiltration rates, therefore reflect what may be encountered under real world operating conditions.

Expected infiltration rates ranged from 1.27 L/s/m^2 of exterior wall area to 3.65 L/s/m^2 of exterior wall area at 75 Pa pressure difference, while typical conditions for a compartmentalized suite were estimated at 1.67 L/s/m^2 at 75 Pa. Parametric analysis indicates that typical construction practices are close to optimizing ERV performance when infiltration is considered, as typical infiltration flows are close to the expected optimal flows. The cause of this is suite compartmentalization, and the associated weather-stripping and air sealing required. Performance of ERV units can be expected to demonstrate a marked decrease in performance if high infiltration rates, resulting from poor construction practice, are encountered.

Leakage of supply flows to the exhaust side of the ERV, which can result in a flow imbalance and therefore induced supply flows, ranged from 3% of the nominal flow, as required by *Passiv Haus*, to 34% of the nominal flow. Typical leakage rates were determined to be 17% as per the literature [6]. Parametric analysis indicates room for improvement regarding ERV leakage, as a marked improvement in ERV performance was noted when considering the low leakage rates which can be expected. Analysis also indicated that leakage rates have the largest impact to ERV unit performance of the parametrics analyzed. The *Passiv Haus* requirements for flow leakage are recommended as an appropriate benchmark for acceptable leakage rates.

Typical temperature set points were considered to be 24°C during cooling, and 22°C during heating, with an 18°C overnight setback. A conservative tenant who wishes to conserve energy was estimated to set temperatures at 26°C during cooling, and 21°C during heating, with the same 18°C setback. A tenant less concerned with energy consumption and more concerned with thermal comfort was anticipated to set a year round 23°C temperature set point, preferring warmer winter and cooler summer indoor temperatures. Indoor temperature set points have a large impact to annual heating and cooling consumption, as they play a direct role in the operation of the in-suite fancoil unit, which cycles to provide heating and cooling. Impact to ERV performance is less pronounced during peak periods but is shown to decrease with reduced indoor outdoor temperature differentials, and vice versa. The exception to this is heating recovery when conservative temperature set points are used: in this case an increase in heating recovery is also seen. Recovery in this case was found to take place primarily during the summer overnight periods and shoulder season, and represents undesired heating from the ERV unit. While overall impact to the suite energy performance remained positive when more conservative set points are used, analysis therefore points to a less than optimal control strategy during summer operation.

A simple economizer option was simulated, which attempts to optimize summer operation of the ERV unit. The economizer bypass was controlled to operate when outdoor temperatures are less than 24°C and cooling is required. Economizer operation resulted in reduced annual cooling energy consumption, as well as reduced annual heating energy recovery. Both results are attributed to elimination of some of the unwanted summertime heat recovery. Heating energy consumption was shown to remain constant. Such a control strategy therefore is beneficial as it works to optimize ERV operation during summertime, while not impacting winter operation. However, the practical implementation of a by-pass in small in-suite ERVs may be a limiting factor due to space restrictions. It is recommended that building operators communicate to tenants in a clear manner how they should operate their ERV unit in conjunction with free cooling via the use of operable windows. Education regarding ERV operation would have the added benefit of reducing fan run time and associated electrical energy.

A comparison to the modeling assumptions of in suite ERVs which may be utilized at the design stage of a building project is also presented. Analysis highlights that modelers risk overestimating the heating energy reduction due to ERV operation, while underestimating the cooling energy consumption. Overestimation of heating recovery is primarily due to the elimination of ERV leakage often assumed at this stage. Assumed infiltration rates were even lower than the lowest values anticipated in this scenario, leading to the relative increase in cooling energy.

In suite energy recovery represents an important step toward reducing energy consumption in high rise residential buildings. Energy recovery reduces heating and cooling consumption, while increasing user controllability. To further optimize this system, analysis suggests that efforts should focus on minimizing leakage within the ERV unit itself, to optimize both ERV performance, as well as maintain adequate indoor air quality levels. An economizer by pass can further increase optimized performance. Pending the feasibility of this strategy, communication to tenants regarding the proper operation of the in suite ERV unit during the summer and shoulder seasons, to avoid unnecessary operation, can be prioritized.

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