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Division of Energy Resources

Energy Recovery in Minnesota Commercial and Institutional Buildings: Expectations and Performance

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Executive Summary

Background

Energy recovery ventilation (ERV) systems exchange heat and/or moisture between the outgoing exhaust air and the incoming outdoor (ventilation) air. These air-to-air ERVs are incorporated into mechanical ventilation systems and have the ability to reduce the resulting heating and cooling loads. When operating according to design, it is possible for ERVs to use 10 to 100 times less energy than conventional heating and cooling systems, resulting in up to 80% energy savings on ventilation loads.

Despite their substantial energy efficiency potential, studies on as-operated energy recovery units are few and expectations have been tempered by real world observations – there is anecdotal evidence suggesting that as-operated performance of ERVs may not live up to expectations.

This project investigated the expectations and the operating performance of ERV units in Minnesota commercial and institutional buildings. The project team used available data to characterize commercial and institutional ERVs in Minnesota and then monitored the performance of representative ERV systems, identified and rectified problems that diminish ERV performance, and documented the energy use and costs associated with under-performing ERVs.

Methodology

This field investigation determined whether ERVs in commercial and institutional buildings are reaching their energy savings potential, documented the instances when they were not achieving expected savings, and resolved any issues that were preventing ERVs from performing at their full capacity. Basic demographic information about Minnesota ERVs was used to identify nine representative ERVs for long-term field assessment. Some existing data on the types of problems encountered with ERVs was consolidated to establish a field-based perspective on potential performance issues. The field work was organized to study and analyze representative ERVs, identify and resolve problems with ERV systems, and monitor post-resolution ERV performance. Measured field data were used to quantify existing unit energy recovery (the energy savings from ERVs), missed opportunities resulting from sub-optimal operation, and savings from recommissioned units.

The specific objectives were to:

1. Characterize ERVs in Minnesota commercial and institutional buildings
2. Study a representative sample ERVs in detail
3. Characterize and improve ERV performance

Results

Characterization

The research team analyzed data on 402 ERVs from 134 different buildings to understand basic system demographics. The analysis showed that the majority of buildings that have energy recovery units also have multiple air handling systems, multiple energy recovery systems, and several ERVs of the same type. However, only a fraction of ventilation air is typically served by energy recovery, particularly in institutional buildings. Additional results from the characterization phase can be found below.

Commercial versus institutional buildings

- Institutional buildings hold 69% of all ERVs while commercial buildings hold 31% of ERVs (n = 101).
- The majority of institutional buildings with ERVs are K-12 schools at 51%, followed by higher education at 22% and various state and municipal facilities making up the balance.
- In commercial buildings, ERVs are distributed among a variety of buildings types that have above average ventilation loads including casinos, manufacturing and auto shops, assisted living facilities, labs, and sports and gym facilities.

Sizing breakdown

- The ERVs sampled here represent approximately 3,575,700 cfm of ventilation flow.
- ERV units range in size (outside air flow) from 215 cfm to 60,000 cfm, with an average flow rate of 9,510 cfm and a median flow rate of 5,945 cfm.
- One quarter of all ERV units are below 3,240 cfm and deliver less than 5% of the total flow while another quarter of units are rated above 11,030 cfm and deliver over 63% of the total flow.
- Although smaller units account for 75% of all systems, the majority of energy recovery comes from larger units over 10,000 cfm.

ERV system types

- There are three types of ERV systems identified in these data: enthalpy wheels (80%), plate heat exchangers (13%), and membrane plates (7%).
- Enthalpy wheels span the entire flow range, plate heat exchangers span a slightly narrower range (1,800 to 37,000 cfm), and membrane plates are sized at less than 1,200 cfm (with two exceptions).
- Enthalpy wheels tend to have the highest effectiveness, followed by membrane plates and fixed plate heat exchangers (with average effectiveness of 0.73, 0.66, and 0.64, respectively).

In summary, these data suggest that the most common scenario for air-to-air exhaust energy recovery in Minnesota is total enthalpy wheels in institutional buildings, most likely K-12 schools. ERVs are found in a variety of commercial building types with high ventilation loads.

In both commercial and industrial buildings, the importance of large units to state-wide savings is striking – the top 25% of units are responsible for conditioning over 13 times the amount of ventilation air as the bottom quarter of units.

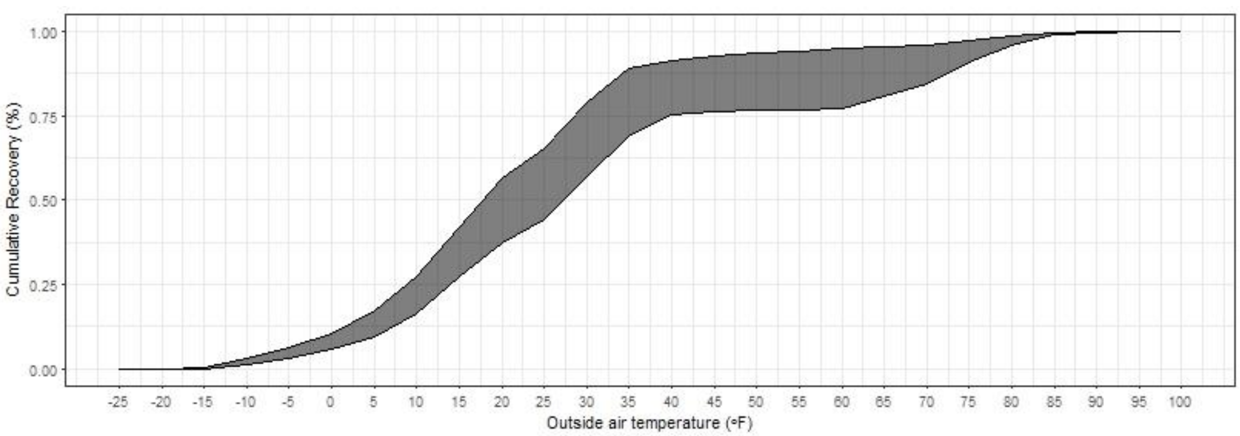
Expectations — Energy Recovery in Minnesota

There are several important performance observations with respect to energy savings and outside air temperature:

1. Half of all energy recovery in Minnesota occurs between about 12°F and 45°F
2. Less than 10% of energy recovery occurs below -5°F or above 85°F
3. Very little energy recovery takes place between 45°F and 65°F

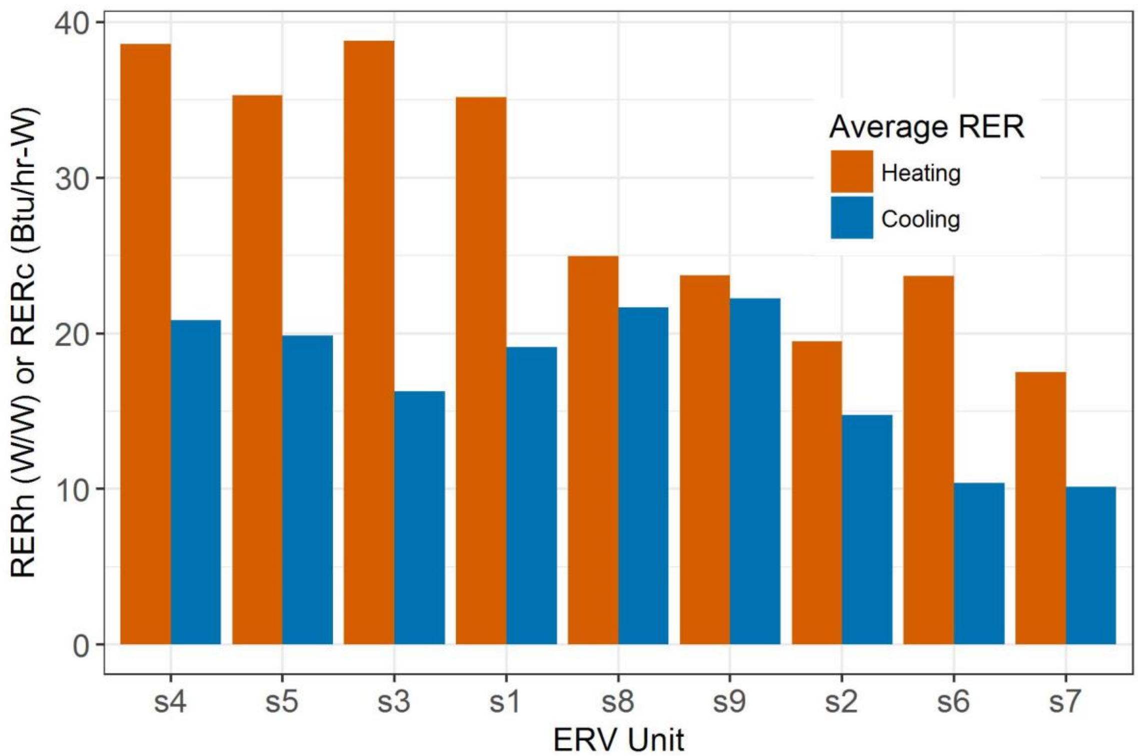
At a bare minimum, an ERV should be activated between 0°F and 45°F in order to realize between 60% and 80% of potential savings, and it should be activated above 80°F to achieve peak cooling load reduction. The cumulative energy recovery for the nine units in this study is plotted as a function of outside air temperature Figure 1. All ERVs fell within this range after recommissioning.

Figure 1: Cumulative energy recovery in of nine ERV units in a TMY3 Minnesota climate



Recommissioned ERV performance is summarized in Figure 2 using the average recovery energy ratio (RER) for heating and cooling operation. The RER is the ratio of recovered energy to expended energy. There is an energy cost to running an ERV because added fan power is needed to push air through the unit and a motor is sometimes used to spin the unit. The RER offers a performance perspective that allows for a comparison to conventional heating and cooling systems. The RER for conventional heating equipment (natural gas heat) is about 0.8 W/W to 0.9 W/W, consistent with the typical efficiency of the heating systems. The RER for conventional cooling equipment has a broader range from about 10 Btu/hr-W to 30 Btu/hr-W for air and water cooled systems, respectively.

Figure 2: Average Recovery energy ratio (RER) for units in study



Although heating RER_h for ERVs are very large at design temperatures (100+ W/W), they are substantially reduced at mild temperatures when there is less recovery. The average heating RER_h in this study ranged from 17 to 39 W/W, suggesting ERVs are about 20 to 45 times more efficient than gas heating. In this study, these heating RER_h correspond to heating ventilation load reductions between 34% and 90%.

The high cooling RER_c (130 Btu/W-hr) often cited for design conditions are also reduced by a decrease in recovery during mild weather. Average cooling RER_c for ERVs range from 10 Btu/W-hr to 22 Btu/W-hr, which is on par or better than many conventional air conditioning systems. Most ERVs in this study did not have bypass, which effectively cut the cooling RER_c in half because these ERVs required extra fan power even during economizer mode. These cooling RER_c correspond to about a 9% to 23% reduction in total cooling load. While cooling savings may be smaller than heating savings, these systems reduce peak cooling loads by up to 50% and thus provide a substantial benefit on top of the heating savings.

These performance metrics reinforce the notion that energy recovery in Minnesota's cold climate is a combination of heating energy savings and peak cooling load reduction.

Energy Savings from Recommissioning

Recommissioning the nine ERVs in this study resulted in savings of $17,168, or an increase in energy recovery of 42%. Eighty-three percent of the savings came from heating (gas) and 17% came from cooling (electric). Results varied greatly over the 9 units: 86% of the savings came from just two large units that were initially non-functional while two other units were already functioning such that no additional savings were found. The added savings summary from recommissioning the nine ERVs is shown in Table 1.

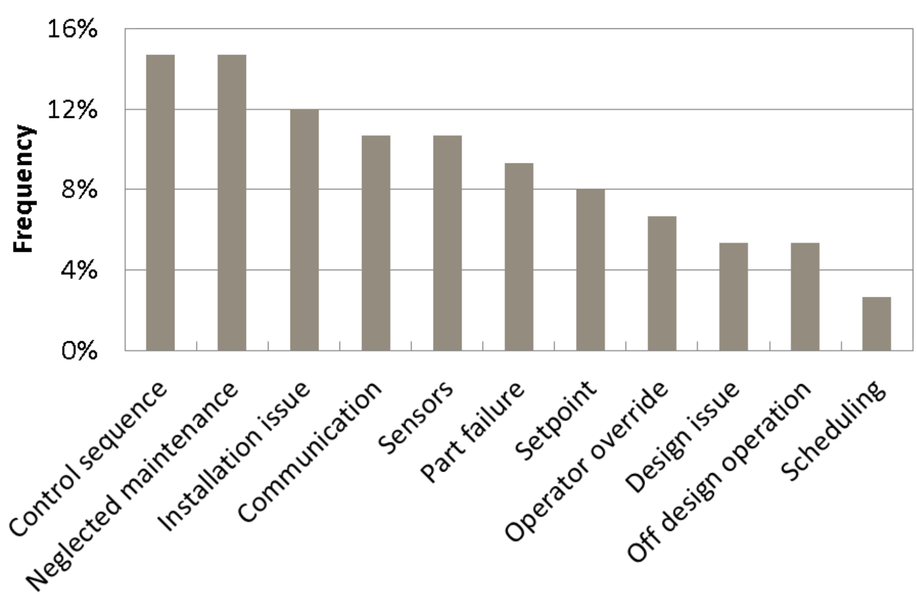
Table 1: Savings Summary

	New Gas Savings	New Gas Cost Savings	New Electric Savings	New Electric Cost Savings
	therms/yr	$/yr	kWh/yr	$/yr
Min	0	0	0	0
Max	4,721	5,852	2,805	2,234
Average	1,344	1,577	768	317
Median	772	631	511	25
Sum	12,099	14,197	6,916	2,853

Issues in ERV Systems

Through this field work, the project team identified and documented 75 different issues among the nine ERVs in the study. While the types of issues and their impact varied widely, they can be sorted into 11 different categories, as shown in Figure 3. About one third of the issues had major energy impacts, one third had only minor energy impacts, and about one third had no energy impact beyond diminishing the perception and expectations of ERVs.

Figure 3: Breakdown of 75 issues encountered



Issues in ERV Systems — Important Energy Penalties

About one third of the issues (24) were deemed to have significant energy impacts. Of those issues that did have an energy penalty, 21 reduced energy recovery during the heating season, increasing the ventilation load between 16 therms and 4,721 therms and increasing the gas costs between $13 and $3,857 annually. Sixteen issues increased the ventilation load during cooling season, which increased energy use between 67 kWh and 5,213 kWh and increased annual electrical costs between $7 and $584. Six issues relating to overrides, part failures, and installation prohibited energy recovery entirely. Several issues had very minor impacts and these included the adjustment of frost control sequences and the adoption of more aggressive frost control set points. Similar to frost control, economizer issues resulted in a lower energy impact than anticipated. The energy and cost penalties of the encountered issues are summarized in Table 2.

Table 2: Summary of energy and cost penalties of encountered issues

	Heating Penalty	Heating Cost Penalty	Cooling Penalty	Cooling Cost Penalty
	therms/yr	$/yr	kWh/yr	$/yr
Min	16	13	52	6
Max	4,721	3,857	5,213	584
Average	1,388	1,134	1,498	168
Median	698	571	813	91
Sum	27,756	22,676	23,963	2,684

CIP Recommendations

Commissioning New Systems

This project demonstrated a strong need for commissioning new energy recovery systems. The persistence of dysfunctional ERVs as part of normal operations indicates a need for system installations to be validated immediately. Fifty percent of the found savings discovered would have been identified during a robust initial commissioning process.

Some general commissioning guidelines include:

1. Large ERV systems (10,000 cfm+) must be fully-commissioned
2. Design flow rates (and subsequent savings estimates) need to be validated against as-operated flows.
3. Control sequences should follow ERV manufacturer recommendations and any deviations must be justified by project engineers.
4. Both control intent and detailed sequences need to be specified and as-implemented sequences verified by an accountable party.
5. Commissioning agents need to provide basic operator training to explain controls, warn about overriding controls, and offer guidance on when and how to verify ERV operation.

Improving Existing Systems

The majority of energy penalties that were found as a part of this project can be discovered and avoided if ERVs are touched by staff that are able to 1) identify when an ERV should be running and 2) assess whether an ERV is running. ERV problems often go unnoticed because there are usually no obvious operational implications, and thus it can be difficult to determine when an ERV is not operating. Validating an ERV system does not necessarily require a full recommissioning effort. For example, 60% to 80% of energy recovery occurs between 0°F and 45°F. Given this fact, a simple procedure to verify that an ERV is operational in this temperature range is an easy way to validate a majority of savings. Beyond basic operational validation, a dedicated recommissioning effort may be needed to achieve additional savings opportunities.

Targeted Recommendations

Design Engineers need to provide more rigorous specifications with regard to the control of energy recovery systems.

Mechanical and controls contractors need to follow engineer specifications and push-back against engineers that do not provide complete specification. Technicians are not responsible for making improvisational decisions on sensing and control.

Commissioning agents need to ensure knowledge transfer about system intent (including control) as well as design-based expectations for ERV performance. They have to validate sequencing and document instances where as-operated conditions differ significantly from design.

Owners need to provide resources for operators to understand systems they administer. Owners should establish protocols and ensure that operators are able to perform semi-annual operational checks on ERV systems.

Conclusion

Over the last 20 years, air-to-air exhaust energy recovery systems have become more common in Minnesota commercial and institutional buildings because of their potential for cost-effective energy efficiency benefits. While ERVs are in fact capable of achieving impressive savings of up to 80% of the ventilation air heating load, steps must be taken to ensure that units are installed and operated according to specification to reach performance expectations. Performance expectations should consider that practical implementation choices and performance under mild conditions will diminish savings with respect to design figures.

A general lack of understanding around ERV performance has led to bad experiences with ERVs and their associated systems, leading to negative perceptions and diminished expectations. However, these experiences and perceptions generally have little to do with the energy efficiency performance, but more so around the typical processes involved with implementing the technology.

Mistakes relating to part failures, operator overrides, and installation account for 75% of the lost energy recovery. These mistakes persist due to unfamiliarity among operations staff and controls technicians as well as the absence of system feedback from poorly functioning ERVs. Fortunately, these mistakes can be easily corrected by commissioning new units to ensure that they function properly from the start. Problems with existing ERV systems can be easily identified by staff that are trained to understand ERVs and assess their operation.

Introduction

Maintaining adequate ventilation in buildings is a core service of building mechanical systems. Ventilation reduces pollutants associated with occupants, processes, and building components that would otherwise reduce indoor air quality (IAQ) and affect occupant health and comfort. Ventilation systems in commercial and institutional buildings typically supply fresh air and exhaust stale air at approximately equal rates using mechanical systems. There is an energy cost to maintaining IAQ with fresh air ventilation because outside air must be conditioned to maintain comfortable indoor temperature and humidity levels.

Air-to-air exhaust energy recovery ventilation systems (ERVs) incorporated into mechanical ventilation systems offer the ability to transfer energy between the exhaust stream and the supply stream to reduce the energy necessary to condition the ventilation air. In essence, they recover wasted energy. These ERVs exchange heat and/or moisture between the outgoing general exhaust air and the incoming outdoor air to reduce the heating and cooling loads that are introduced by ventilation air and are otherwise met using heating and cooling equipment (e.g. boilers and chillers). At design conditions, up to 80% of the ventilation load can be met by a typical ERV, resulting in an equal reduction in energy requirements of heating and cooling equipment. ERVs can meet these loads while using 10 to 100 times less energy than conventional heating and cooling systems. By meeting part of the ventilation load, ERVs enable the downsizing of heating and cooling equipment and thus reduce capital equipment costs.

Despite their substantial energy efficiency potential, expectations must be tempered by real world observations. A 2010 Minnesota Market Assessment Report prepared for CenterPoint Energy noted mediocre customer satisfaction with 91 large ERV units installed between 2005 and 2007 (Hewett, 2010). Only 48% of the systems operated properly following installation. Taking a whole-building view, Roulet measured the performance of 13 ERV systems and found that the global efficiency of these systems was substantially reduced by air leakage, recirculation, and exfiltration (Roulet, 2001). In addition, the Center for Energy and Environment (CEE) identified 81 ERVs installed in Minnesota public buildings through screening visits for the Public Buildings Enhanced Energy Efficiency Program (PBEEEP). CEE found that while approximately one quarter of these systems were not performing optimally, none of facility operators has reported the units as underperforming.

There remain questions about the efficacy, reliability, and cost effectiveness of ERVs, given their relative immaturity with respect to conventional heating ventilation and air conditioning (HVAC) equipment such as boilers and chillers. According to the in the CenterPoint study, engineers surveyed in 2009 still viewed ERVs somewhat skeptically. At that time, design engineers still considered energy recovery systems to be specialty products that had not yet reached maturity. As a result, some design engineers may still be unfamiliar with the details of ERV operation and choices for specific controls and implementations. In this vacuum, rather than informing mechanical and controls contractors with complete specifications, design engineers may defer to manufacturers and by necessity require contractors to fill in implementation gaps during installation, programming, and start up. Engineers and controls technicians may also be overly reliant on generic or pre-existing sequences and controls that are not suitable for a particular implementation. Training for operations staff and building owners is not always provided or available, leading to additional inevitable gaps between the design and the operation and maintenance of ERVs. This study aims to investigate the space between the design potential and expectations of general exhaust energy recovery and real world implementations, particularly those systems showing symptoms consistent with common problems.

Study Objectives

The goal of this project is to investigate both the expectations and the operating performance of ERV units in Minnesota commercial and institutional buildings. It includes an updated characterization of commercial and institutional ERVs from available data. This study identifies common problems that diminish performance of ERVs in Minnesota buildings and documents the frequency and the effect that common operational problems have on ERV performance as well as the modifications necessary to improve performance. Problems are prioritized by their frequency and their energy impact. The study also attempts to identify the root cause of these problems and make broad recommendations for avoiding them in other systems. Finally, a practical guide and validation protocol are developed to identify these problems and estimate their impact.

The specific objectives of this study are as follows:

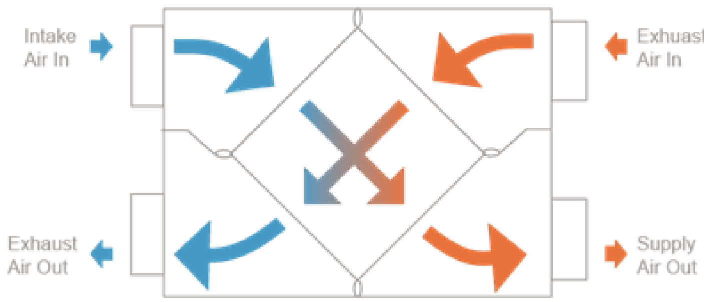
1. Characterize ERVs in Minnesota commercial and institutional buildings
    a. Including vintage, size, application
    b. Understand operational staff and building owner perception
    c. Examine available data on outstanding problems
2. Study representative (based on prior characterization) ERVs in detail including
    a. Long-term performance monitoring
    b. Short-term diagnostic testing
    c. Problems that diminish ERV performance
3. Improve ERV performance
    a. Make recommendations for resolving existing problems
    b. Facilitate implementation of recommended changes
    c. Monitor ERV units to measure performance gains
4. Develop tools for disseminating project knowledge including
    a. A guide to fill practical knowledge gaps that interfere with ERV expectations and performance
    b. A protocol for easily validating functioning ERVs and identifying non-functioning units.

Background

Basic Operation

Air-to-air exhaust energy recovery systems transfer energy between the exhaust stream and the supply stream to reduce the energy necessary to condition the ventilation air. Figure 4 shows a basic schematic to illustrate their operation. Exhaust and intake (outside) air streams pass through the ERV simultaneously. Heat and moisture are transferred between these airstreams without them mixing directly. Thus, heat and moisture can be transferred without transferring pollutants or odors from the exhaust air into the supply air.

Figure 4: Energy recovery ventilation (ERV) schematic



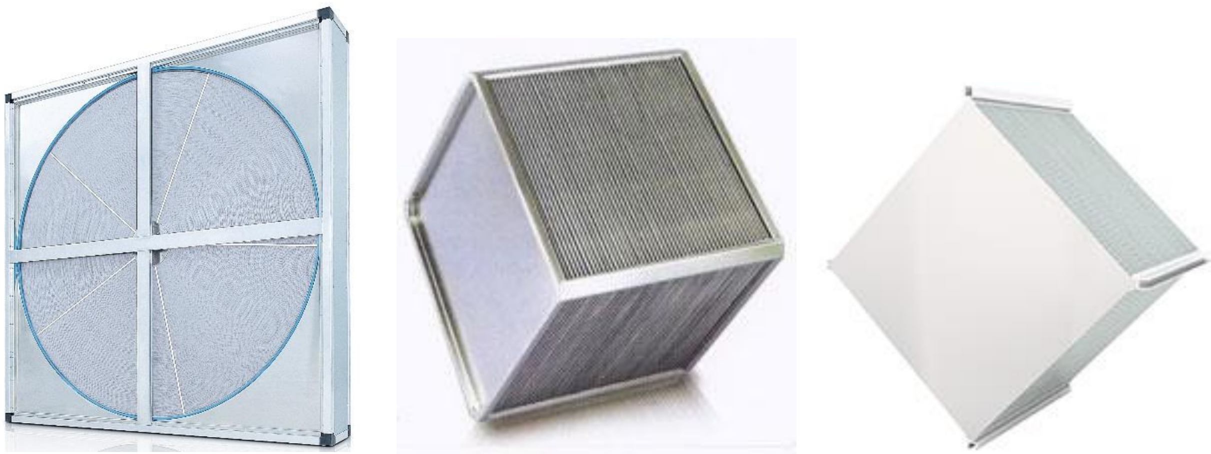
The systems operate according to basic transport principles: high moves to low. In other words, the hotter of the two air streams cools while the colder of the airstreams heats. This can be leveraged to reduce energy requirements in both heating and cooling seasons. In the summer, the outside air stream is warmer than the exhaust air. The exhaust air is warmed while the outside air is pre-cooled, which reduces the load on cooling equipment. In the winter, the outside air is heated as the exhaust air is cooled, which reduces the load on the heating equipment. Most energy recovery units also transfer moisture (humidity). In humid weather, moisture from the outside air is transferred into the exhaust air and the outside air is pre-dehumidified, which reduces the dehumidification load on the cooling equipment. In dry weather, moisture from the exhaust air is transferred into the outside air and the outside air is pre-humidified. In this last case, energy savings are only achieved if the building has active humidification. Without a humidification system, the primary benefit is increased comfort due to maintaining a higher indoor relative humidity during dry weather as opposed to a benefit from energy savings.

Types

While there are eight types of energy recovery devices presented and compared in ASHRAE HVAC Applications (ASHRAE, 2016), only three types are considered here because data show they comprise the large majority of installed units. These are given in Figure 5 and include sensible and total energy recovery wheels and sensible and membrane plate heat exchangers. Energy recovery wheels (ERW) are rotary devices that rotate the heat/moisture exchange media between the exhaust and outside air streams. The effectiveness of these devices can be manipulated by varying the rotational speed (typically 0 – 30rpm) or with the use of bypass ducting and a face/bypass damper set. Most ERWs are total enthalpy wheels. Energy recovery wheels are favored for their compactness, large operating range, high effectiveness, and competitive costs. While there are a variety of considerations that influence the selection of exhaust air energy recovery systems, the cost and performance of total enthalpy wheels have lead them to dominate the market, particularly with large units found in institutional and commercial buildings.

The other predominate type of ERV is a fixed plate device, which come in two varieties, plates and membranes. Plate energy recovery systems typically have low pressure drop and no moving parts. Plate heat exchangers are regular air-to-air heat exchangers. They only transfer heat between exhaust and supply air flows, impacting only temperature. Membrane plate devices permit the transfer of both heat and moisture across their surface, which changes the temperature and humidity of these air streams. The effectiveness of these devices is controlled through the use of bypass ducting and a face/bypass damper set. A more complete comparison as well as the other air-to-air energy recovery devices can be found in the ASHRAE HVAC Applications and Systems (ASHRAE, 2016).

Figure 5: Common types of energy recovery systems: (a) total enthalpy wheel, (b) plate heat exchanger, and (c) membrane heat exchanger.

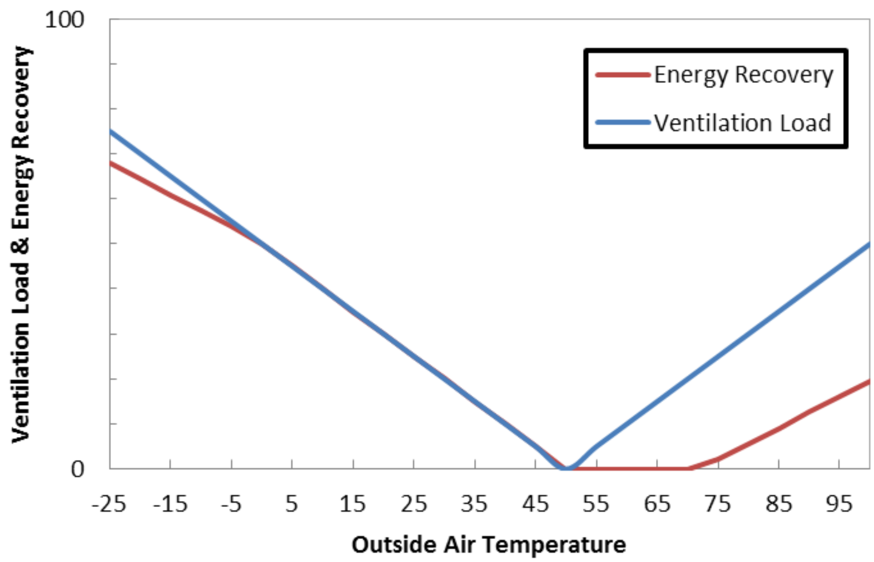


(a) (b) (c)

Practical Operation

In practice, ERVs should operate year-round to reduce ventilation loads, which are roughly proportional to the difference between the inside and outside temperature as shown in Figure 6. In Minnesota the greatest ventilation load occurs at winter design conditions (-12°F to -26 °F). This condition is also the greatest opportunity for energy recovery. In some cases, frost control or frost prevention methods may reduce energy recovery during the coldest conditions. At milder conditions during heating season (15°F to 50°F) the ventilation load is smaller and energy recovery can potentially meet the entire ventilation load. The ventilation load is the smallest around the balance point temperature. Above this temperature, the ventilation is a cooling and dehumidification load. However, between the balance point temperature and the approximate desired indoor conditions (55°F to 72°F) ventilation air can be used for cooling directly, typically called economizer functionality. In this case, the energy recovery system is either not used or is used minimally. As outside air temperature and humidity increase beyond the indoor conditions, the ventilation load must be met by the mechanical system. In this case energy recovery is again desirable. At summer design conditions (84°F to 91°F) the cooling ventilation load is largest and an ERV can meet around 25% to 50% of the cooling load.

Figure 6: Example sensible ventilation load and energy recovery potential as a function of outside air temperature

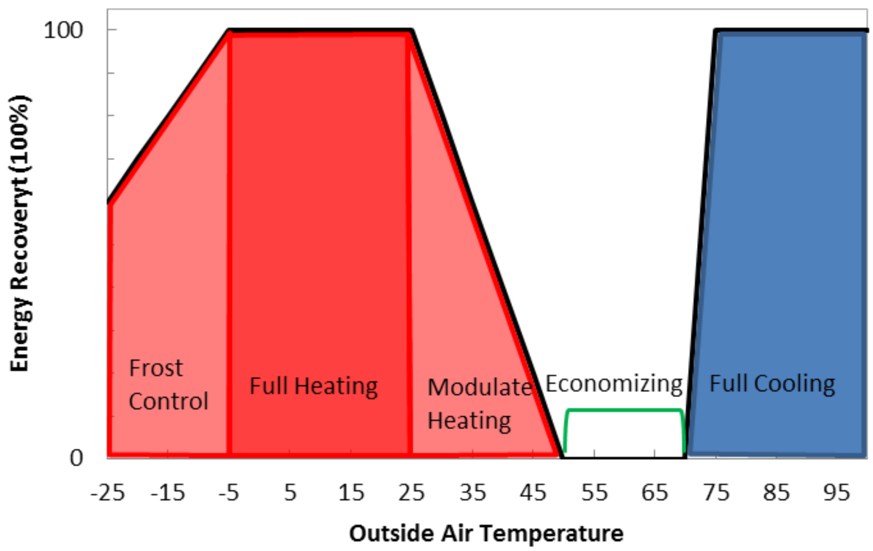


The different roles ERVs play throughout the year require modulating the amount of energy recovery, and control of energy recovery systems should reflect these requirements. This is illustrated approximately in Figure 7. Energy recovery operations can be divided into approximately five different periods depending on outside conditions:

1. Frost control
2. Full heating
3. Modulated heating
4. Economizing
5. Full Cooling

The exact conditions under which ERVs should vary their operation depend on the specific unit, control sequences, sensor locations, and building characteristics. At the coldest conditions some type of frost prevention or frost control strategy is necessary to prevent counterproductive or harmful frost build up on the ERV. During this period, either energy is used or energy recovery is lessened to decrease or prevent frost. At cold to moderately-cold temperatures, ERVs run in full heating mode. At these temperatures ERVs operate for maximum energy recovery and displace a majority of the heating load. They typically cannot meet the entire heating load and heating systems function in an auxiliary fashion to meet discharge temperature requirements. At moderately-cold to mild outdoor temperatures, energy recovery is reduced to prevent overheating the building. This is distinct from economizing mode because the ERV is still heating outside air to meet the heating load. Between the balance point and indoor conditions, energy recovery should be disabled in favor of economizer mode to provide free cooling. As outside air temperatures exceed indoor conditions, mechanical cooling is required and maximum energy recovery is used to displace demand on the cooling system. Alternatively, ERVs may incorporate enthalpy based controls to change the amount of recovery based on enthalpy differences, but the same principles apply.

Figure 7: Energy recovery in practice



Performance

In Guideline V, the Air Conditioning, Heating and Refrigeration Institute (AHRI) presents three performance metrics for ERV systems: the effectiveness (ε), Recovery Energy Ratio (RER), and the Confined Efficiency (CEF) (AHRI, 2011). ERV performance is typically presented and discussed in terms of effectiveness. Effectiveness is a parameter from heat transfer science that considers the actual amount of energy transferred by a heat exchanger compared to the physical maximum amount of energy that can be transferred.

A definition for effectiveness is provided by AHRI Standard 1060-IP 2013, Performance Rating of Air-to-Air Exchangers for Energy Recovery Ventilation Equipment (AHRI, 2013):

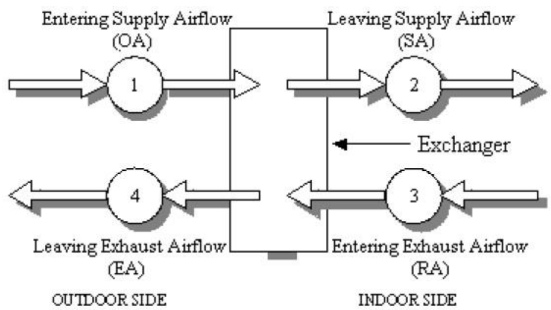
> *A ratio of the actual energy transfer (sensible, latent, or total) to the product of the minimum energy capacity rate and the maximum difference in temperature, humidity ratio, or enthalpy.*

Effectiveness can be defined for different energy transfers including sensible (temperature transfer), latent (humidity transfer), and the total energy (enthalpy transfer). The concept of energy transfer is the same for each type, allowing a generic effectiveness parameter to each, as done by AHRI:

$$\varepsilon = \frac{c_2(X_1 - X_2)}{c_{min}(X_1 - X_3)}$$

Where c_2 is capacity rate of the supply airstream and c_{min} is the capacity rate of the smaller of the supply or exhaust air streams. The property value is given by X where subscripts refer to the location with respect to the ERV as shown in given in Figure 8.

Figure 8: AHRI Standard 1060 energy recovery stations (AHRI, 2013)



These capacities depend on the type of energy transfer considered. This discussion continues here with sensible (heating/cooling) energy for brevity. The sensible effectiveness is given as

$$\varepsilon = \frac{(\dot{m}c_p)_2(T_1 - T_2)}{(\dot{m}c_p)_{min}(T_1 - T_3)}$$

The sensible energy capacity rate, c_2, is equal to $\dot{m}c_p$, the mass flow of air (lbm/min) times the specific heat of air (Btu/lbm°F). The transferred property in this case is the dry bulb temperature, T. ERVs that transfer humidity (latent energy) in addition to sensible energy have a separate latent effectiveness and the transferred property is the absolute humidity (lbm-H_2O/lbm-air). Latent effectiveness is usually similar, but is less than sensible effectiveness. The total effectiveness is the combination of the latent and sensible effectiveness and the transported property is the total enthalpy of the air (Btu/lbm).

Effectiveness is not adjusted to account for any leakage air that may directly enter the supply stream. The *Net Effectiveness*, as defined by AHRI, adjusts the effectiveness for this leakage via a quantity called the exhaust air transfer ratio (EATR). While more elaborate formulations for effectiveness consider broader effects such as recirculation (i.e. stale exhaust air entrained by fresh intake air) and losses via exfiltration (i.e. air not available for energy recovery), these are infrequently used when discussing ERV performance.

The effectiveness is reasonably constant over the normal range of temperature and humidity, and hence effectiveness figures given at design conditions are suitable for use throughout the operating range. However, effectiveness is sensitive to flow rate. Heat and mass transfer, and therefore effectiveness, depend on the velocity of each air stream through the ERV unit. Effectiveness decreases as the velocity increases. A typical situation is the case of unbalanced flow between the exhaust and outside air flows. In practice, ERVs are usually sized at the larger of the two flows, and effectiveness increases as, for example, the exhaust flow is lowered. However, the total recovered energy is proportional to the flow rates. A common situation is that effectiveness of an unbalanced unit increases while total recovered energy decreases, thus exposing the main weakness of effectiveness as the defining performance parameter.

The Recovery Energy Ratio (RER) is a less cited ERV performance metric. According to AHRI Guideline V (ARHI, 2011) it is defined as

Recovery Efficiency Ratio (RER). The efficiency of the energy recovery component in recovering energy from the exhaust airstream is defined as the energy recovered divided by the energy expended in the recovery process.

Units vary according to the application; for cooling the RER_c is expressed in Btu/(W·h) and for heating the RER_h is expressed in W/W. The RER is an expression of the ratio between the energy recovered and the energy required to move air through the pressure drop across the ERV and rotate the ERV media, where necessary. It has the convenient property that it can be compared to similar calculations of conventional heating and cooling systems. A general formula for the total (enthalpy based) RER is given below:

$$RER_{total} = \frac{\varepsilon_{net\ total}\, \dot{m}_{min}(h_1 - h_3)}{Pwr_{blwr} + Pwr_{comp}}$$

Where Pwr_{blwr} and Pwr_{comp} are the additional fan power introduced by the ERV and the power input to spin rotating media, respectively.

A third parameter characterizing ERV performance is Combined Efficiency (CEF), which evaluates the performance of the combined ERV and HVAC systems. Contributions from energy recovery to CEF are equivalent to the RER, which will remain the focus here.

Alternatively, there are more practical measures of ERV performance including total recovered energy (Btu), energy recovery rate (Btu/hr), energy savings (Btu), energy cost savings ($), and heating/cooling ventilation load reduction (%). As will be shown later, there is some nuance in understanding ERV performance that cannot be accomplished with a single metric.

Building Code

Air-to-air energy recovery systems have gradually become a standard component of commercial and institutional HVAC systems over the last 20 years in order to meet more demanding energy efficiency goals. Energy recovery code requirements have been evolving in tandem with this growing familiarity. Current energy Minnesota Commercial Energy Code (2015) (based on ASHERAE 90.1-2010/IECC-2012) specifies energy recovery requirements by climate zone and percent outdoor air at design flow rate (ASHRAE, 2010). The requirements for ERVs for Minnesota climate zones are shown in Table 3.

Table 3: Air-to-air exhaust energy recovery ventilation requirements for Minnesota

Climate Zone	% Outside air at design flow					
	(30% - 40%)	(40% - 50%)	(50% - 60%)	(60% - 70%)	(70% - 80%)	(80%+)
6A	≥5500	≥4500	≥3500	≥2000	≥1000	≥0
7	≥2500	≥1000	≥0	≥0	≥0	≥0

The current code additionally specified performance requirements that

"Energy recovery systems … shall have at least 50% energy recovery effectiveness… mean(ing) a change in the enthalpy of the outdoor air supply equal to 50% of the difference between the outdoor air and return air enthalpies at design conditions."

In ASHRAE 189.1: Standard for the Design of High-Performance Green Buildings, this minimum energy recovery effectiveness is increased to 60% (ASHRAE, 2011).

ASHRAE 90.1-2007 specified energy recovery for all climate zones if design flow was 5,000 cfm or greater and minimum outside air fractions were 70% or greater (ASHRAE, 2007). The same minimum performance requirement was present. Future energy codes are likely to increase energy recovery requirements. For example, ASHRAE 90.1-2013 adds energy recovery requirements for outside air fractions as low as 10% and for ventilation systems that operate more than 8,000 hours per year (ASHRAE, 2013). It is reasonable to expect than exhaust air energy recovery technology will continue to proliferate through stricter code requirements.

Prior Work

There is an extensive academic and practical literature on energy recovery systems. The literature establishes that energy recovery systems reduce the heating and cooling loads associated with ventilation air. A variety of case studies suggest exhaust air energy recovery is a cost-effective HVAC strategy in most climates and in many cases even reduces first costs.

Design and application specific energy recovery guidance is readily available. The ASHRAE Handbook: HVAC Systems & Equipment Chapter 26 provides a comprehensive background on exhaust air energy recovery systems. This chapter comprehensively describes the theory, performance, control, testing, types, applications, comparisons, economic considerations, and sample engineering calculations for energy recovery systems (ASHRAE, 2016). Additional efforts have consolidated key information into more accessible and practical formats for design engineers. These include: (Besant & Simonson, 2000), (Rabbia & Dowse, 2000), (McQuay, 2001), (Stanke et al., 2000), and (Moffitt et al., 2012).

While specific application literature for ERV systems is available, it tends to focus on cooling system operation (Turner, 2005), (Dieckmann 2008). Energy recovery in lab environments (Barnet, 2013) is a special case as air classification and potential contamination concerns are more significant than in more typical commercial and institutional buildings that typically cycle stale ventilation air (class 1).

There is also robust literature on potential, modeled, and assumed savings from energy recovery systems. However, data are sparse with respect to in-situ performance. The field work in this area emphasizes these difficulties. For example, Zhai et al. note the difficulty of applying ASHRAE Standard 84 to field testing due to heat and moisture transfer with surroundings, air leakage to/from surroundings, non-uniform conditions, and leakage between air streams (Zhai 2006). They also found that the manufacturer-placed sensors in the total enthalpy wheel in their study were not representative of outlet conditions. They were however able to place additional sensors to accurately capture the energy balance within -9 to +3%. They were also able to show that effectiveness is constant regardless of outside air temperature. While their measured effectiveness of 77% was less than laboratory derived estimate of 83%, it was within the margin of error.

Shang and Besant detail these non-uniformities in their attempt to characterize and reduce field measurement uncertainty. For enthalpy wheel systems, they found very large radial and angular non-uniformities of up to 11°F and 15% RH caused by surface variations and wheel rotation (Shang, 2001a). They make measurement recommendations for estimating effectiveness and uncertainty with respect to ASHRAE Standard 84. In further work, they outline detailed recommendations for in-situ field testing of energy wheels (Shang, 2001b). These recommendations allow, through some additional testing and correction, the estimation of enthalpy wheel performance from single measurements at one location 90° from the diameter seal line. However, there are still limitations posed for accurate long-term performance monitoring in that their method recommends manipulating flow rates to equalize supply and exhaust stream pressures.

Roulet et al. did extensive airflow and leakage field measurements on 13 energy recovery units in Western Europe (Roulet, 2001). They found a very large spread of performance, effectively from high-performance units with global heat recovery efficiency between 60% and 70% to low performance units with global heat recovery efficiency at 10%. They found that in practice, rated effectiveness was decreased by leakage flows, recirculation, and exfiltration. Their results compelled the authors to cast doubt as to the economic viability of energy recovery, particularly small units.

Longstanding testing and certification standards that document energy recovery performance leave little doubt as to the laboratory and potential performance and savings of air-to-air energy recovery systems. Consequently, properly instrumented, installed, and controlled units should approach expected performance and provide anticipated savings. Nonetheless, in the best case, field verification of this performance is difficult. In the worst case, instrumentation, installation, and control problems may reduce energy recovery, but the extent to which is not clear. Experience from recent work by CEE suggests that these are the types of commonly encountered problems. A CEE market assessment report noted mediocre customer satisfaction with 91 units, with only 48% of the systems operating properly immediately after installation (Hewett, 2010). Furthermore, the PBEEEP assessment found that approximately one quarter of 81 ERVs installed in Minnesota public buildings were not performing optimally. Nonetheless, there appears to be little useful documentation as to the consequences and performance impacts of these issues, perhaps excluding specific recommissioning results.

Thus, there is an opportunity to investigate the real-world problems that prevent commercial and institutional energy recovery systems from satisfying building owners and reaching their energy savings potential. This work is aimed at finding these problems, exploring their cause, determining their impact, and identifying solutions for avoiding these problems on both new and existing air-to-air exhaust energy recovery systems.

Methodology

This study is primarily a field investigation to determine whether energy recovery ventilation systems (ERVs) systems in commercial and institutional buildings are reaching their energy savings potential in practice and, when they are not, to document and remedy issues that prevent them from achieving their expected performance. Basic demographic information about ERVs found in buildings in Minnesota and a follow up screening process were used to identify representative ERVs for long-term field assessment. Some existing data on problems was consolidated to establish a field-based perspective on potential performance issues. The field work was organized to study and analyze representative ERVs, identify and resolve problems with ERV systems, and monitor post-resolution ERV performance. Measured field data were used to quantify energy recovery (energy savings) from existing systems, the missed opportunities due to sub-optimal operation, and the savings from recommissioned units.

Characterization and Site Selection

This study used data on ERV units from three sources to characterize ERV units in Minnesota C&I buildings:

1. A prior public building recommissioning program, Public Building Enhanced Energy Efficiency Program (PBEEEP);
2. An ERV Market Characterization Study (MCS) (Hewett, 2010); and
3. A limited set of recently rebated ERVs.

These data included limited information about problems with ERVs from the perspective of building owners, project engineers, and recommissioning engineers. These problems were categorized to frame expectations for this study. Screening criteria were developed from this characterization to identify representative ERVs for long term study.

After analyzing the available data, the following primary characteristics were used to select representative systems:

- Recovery unit type (e.g. enthalpy wheel, plate heat exchanger)
- Outside air flow rate (i.e. unit size)
- Operational issues (i.e. problems uncovered during screening or preliminary interviews)

The following secondary criteria were also considered where possible in order to maximize the diversity of results. Essentially, an effort was made to vary the following criteria where possible, as long as the building had met the primary characteristics.

- Manufacturer
- Project engineer
- Building owner
- Age
- Space use

Operational Problems and Their Frequency

Data collected by CEE through the PBEEEP screening visits and an ERV market study were used to generate the initial scope of operational issues afflicting ERV systems. These data were collected through a combination of recommissioning efforts, interviews and surveys targeting project engineers, building owners, and site operators.

Ninety-seven problems were reported from all sources. They were divided into three main categories. These categories (given in Table 4) are Operation & Maintenance, Controls, and Design & Install.

Table 4: Categories for classifying problems with ERV systems

Category	Description
Operation & Maintenance	Routine maintenance, part failures, neglect, operator training, system modifications
Controls	Communications, integration, schedules, wheel speed control, set points, economizer mode, frost control
Design & Install	Excessive exhaust or supply air leakage, insufficient supply airflow, poor humidity control, building pressure control, other design or installation flaws

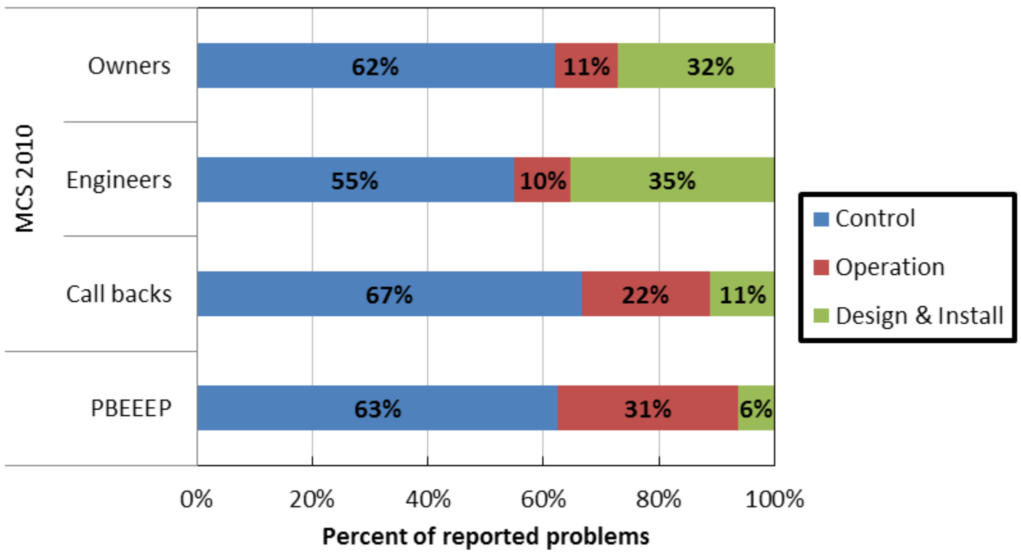
Responses and findings from the data are grouped by data source and sorted into the categories in Figure 9. From MCS2010, owners and project engineers were asked to report problems regarding 21 specific ERV projects. Separately, project engineers were asked to document only the initial problems (call backs). The PBEEEP grouping includes ERV-specific problems identified during building recommissioning completed through the PBEEEP program.

All sources indicated that the majority of the problems (55% to 63%) were controls-related. The bulk of these problems were related to wheel schedules, frost control, and economizer mode. The variety of controls packages, special modes, and integration with other building systems increases the likelihood of controls-related issues. Additionally, the interviews suggested a lack of familiarity with ERV systems by all stakeholders, which likely increases the prevalence of issues.

The frequency of operation problems varied slightly more among sources, from 10% to 31% of reported problems. Part failures were predominant, especially in the PBEEEP data, which featured older units. On average, project engineers expect increased maintenance and difficulty of operation of ERV units compared to typical air handling units, but the data from these sources are unable to confirm this expectation.

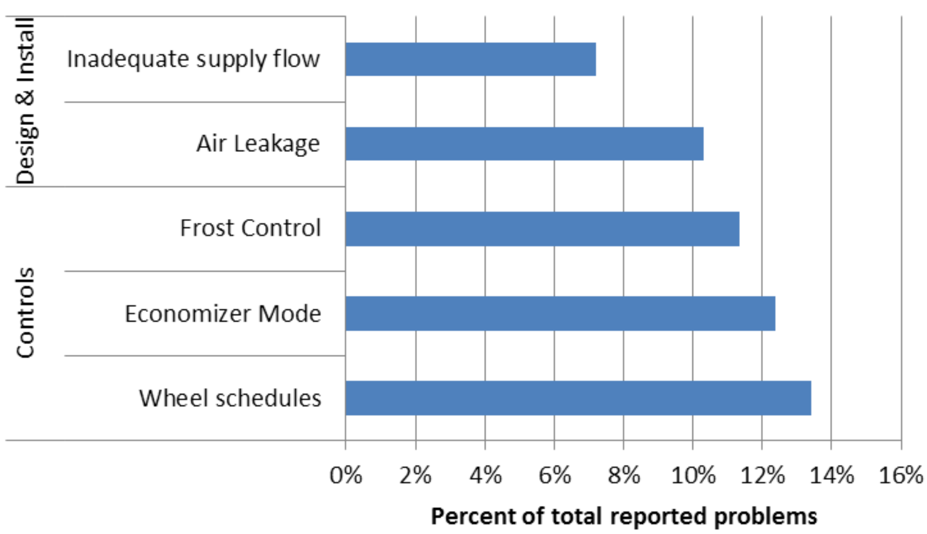
The Design & Install category represented between 6% and 34% of the reported problems. In this category, the most frequently reported problems were air leakage and insufficient supply air flow.

Figure 9: Frequency of problem types encountered in ERV systems



The top five problems are identified in Figure 10. These problems account for over half (55%) of all reported issues, suggesting control-related issues are the most likely cause of ERV operational issues. The major caveat with these data is that they were recorded by various engineers and processes and no real context is available for evaluating their consequences on energy efficiency. Nonetheless these data guided the approach for this study and informed unit selection regarding representative problems.

Figure 10: The prevalence of the top five problems



Fieldwork

Fieldwork on this project included site screening and physical inspections, long-term performance monitoring, and short-term characterization measurements.

Screening

Through existing data, prior research recipients, business contacts, and existing relationships, CEE identified 37 units for potential inclusion in this study. These 37 ERVs were screened according to a two-step screening process, from which nine units were selected to represent commercial and institutional ERV systems. Unanticipated operations staff turnover at the site prevented the inclusion of a tenth ERV into the study.

In the first step, a phone interview was conducted to:

1) Verify the existence of the selected ERV system(s) at the site location
2) Introduce the study, its benefits, outcomes, and participation requirements
3) Assess interest in study participation
4) Collect any readily available information that would disqualify the unit
5) Schedule a screening visit and operator interview

Following the phone interview, a screening visit was scheduled to collect information about the ERV systems, associated mechanical equipment, and the building. The ERVs were also subject to a visual inspection to document their initial state.

A sample screening form is included in Appendix B. The main information collected was:

1) Energy recovery system information including, associated air handling, heating, and cooling equipment
2) Control system details
3) Building operations and schedules
4) Projects, contractors, operators, engineers, and firms associated with implementing, maintaining, controlling, or operating the ERV
5) General building characteristics

An interview with the primary operator was also completed at the time of the sample screening to discuss their interaction, expectation, and opinion about the energy recovery equipment.

Long-term Monitoring

Long-term operational data were collected from two sources: each site's building automation system (BAS) and a CEE-installed data acquisition and sensor package. Each is discussed below.

Data from the BAS were collected at each site. While all monitored ERVs had automation systems, the quantity and frequency of data varied depending on the automation system capabilities.

Where possible the following data were collected:

- Equipment status (ERV, fans, heating, cooling)
- Flow rates (outside, supply, return, exhaust air)
- Temperature and relative humidity (outside, supply, exhaust, return, mixed, discharge air)
- Damper positions (outside, face/bypass, mixed air)
- Speed/positions (Fans, wheel, heating and cooling valves)

In addition to BAS monitoring, each monitored ERV was outfitted with an instrumentation package to measure conditions at the inlet and outlet of each ERV, independent of available automation system measurements. Temperature, relative humidity, and static pressure were each measured at four locations to characterize the outside air, supply air, return air, and exhaust air conditions on each monitored ERV. Duct-mounted Vaisala HMD83 sensors were used for temperature and relative humidity with ±0.5 °F and ±3% RH accuracy respectively. These sensor readings were digitized and logged using a Campbell Scientific CR3000 data logger. Static pressure probes at each location were plumbed to an automated performance testing system (APT) pressure transducer (accuracy is ±1% of reading for 0-800Pa range and ±2% for 800-1000Pa range) from The Energy Conservatory (TEC). The data from both the APTs and the Vaisala sensors were averaged and logged to a local laptop at one minute intervals. The CEE sensors ensured accurate, calibrated operational data from the ERVs. The sensors were also used to validate BAS sensors where both types are co-located as shown in Figure 11. Short term measurements were used to compare permanent probe placement with respect to non-uniformities in outlet distributions (Figure 12).

Figure 11: Supply T/RH sensor and static pressure sensor co-located with automation system sensors

Figure 12: Measuring radial variations in outlet temperature distribution with respect to controlling sensors

Data from automation system and the CEE instrumentation package were remotely gathered where possible and incorporated into a validation routine (Figure 13). This workflow included flagging missing data, outlier data, and invalid (malfunctioning sensor) data. The intent of this workflow was to identify and quickly remedy problems with sensors and recognize aberrant ERV behavior.

Figure 13: Logging equipment left on site for recording and transmitting measurements

Airflow Measurements

Where reliable airflow data were not available, airflow measurements of supply air and return air were taken using a CO_2- based tracer gas technique. Pure carbon dioxide (CO_2) was injected into the supply or return air duct at a fixed injection pressure, and the concentration was measured downstream using a CO_2 gas analyzer. The average airflow rate for the measurement period was calculated from the average CO_2 concentration and the total mass of injected CO_2. The injection and sampling locations spanned an air handler fan to ensure large scale turbulence and rapid mixing. The measurement period lasted 60 to 100 seconds. Each supply and return air streams were measured three to four times to reduce measurement uncertainty. The supply and return fan speeds were fixed for the test, and either fan speed or VFD frequencies were recorded for each measurement in order to estimate flow rates at different operating conditions.

Figure 14: A CO2-based tracer gas system was used to measure flow rates and air leakage between air streams where necessary

Some airflow leakage was measured using a similar technique except with additional sampling points located at each of the outside, supply, return, and exhaust airflows. Sampling between these locations was controlled with an array of solenoid valves. Each valve was cycled open during a constant rate of injection of CO_2 into either the return or supply airflow streams. The sampling time per measurement varied between 30 and 60 seconds, and each sequence of four measurements was repeated for three to six cycles depending on the steadiness of the samples. Owing to the use of CO_2 as a tracer gas and the maximum rate of injection, both airflow techniques were limited to measurements less than about 23,000 cfm.

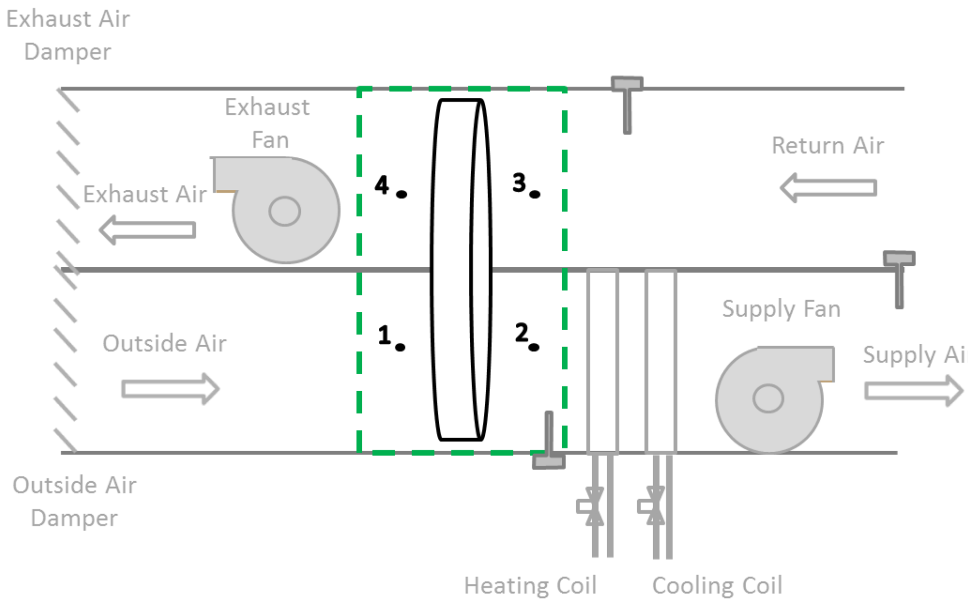
Analysis Method

To analyze energy recovery performance, the ERV is isolated as a component. Energy and mass balances were constructed about a control volume containing each unit to understand the relationships between the inflows, outflows, and leakage between them. One advantage of this approach is that it avoids complexities that typically take place in an around energy recovery units due to leakage, heat and mass transfer, and fan heat. However, it does introduce uncertainties, particularly those associated with non-uniform conditions on the ERV outflows (exhaust and supply airflow). Ancillary to the ERV control volume exist impacts from mixed air, heating and cooling coils, and fan heat, which all interact with energy recovery and were treated separately in the analysis.

In most cases, the measured data were used directly to identify performance and operational issues and validate their correction. For reporting the results, data were consolidated and calculated according to the following methodology. Calculations follow AHRI Guideline V for Calculating the Efficiency of Energy Recovery Ventilation and its Effect on Efficiency and Sizing of Building HVAC Systems (AHRI, 2011)."

Energy and mass flows into and out of the ERV unit were measured or estimated from measurements located at stations defined by AHRI as shown in Figure 15.

Figure 15: Generic energy recovery system shown with control volume defined for this study



Energy and mass conservation between the supply and exhaust flow were enforced to evaluate measurement quality and, where necessary, adjunct measurements were used to estimate mean bulk properties. Total errors were typically less than 10% at design conditions.

Depending on available data, flow rates were estimated through some combination of air flow station data, fan speeds, ERV pressure measurements, damper positions, and tracer gas measurements.

Air leakage estimates based on the measured static pressures were used to interpolate outside air correction factor (OACF) and exhaust air transfer ratio (EATR) from AHRI certification data. These values were validated where possible using a tracer gas measurement. Depending on the location of the airflow measurement, the supply air and exhaust air flow rates were corrected for these values where necessary. EATR and OACF estimates for ERV s8 are shown in Figure 17 and Figure 18 as an example. These were among the most widely varying in the study due to a large range of operating flows (fan speeds). Even in this case, the total variations are small at less than 2%. However, as is typical on the design documents, purge, pressure differential, EATR, and OACF are not specified so comparison to design is not possible.

Figure 16: Exhaust air transfer ratio estimate from measured pressures and AHRI data

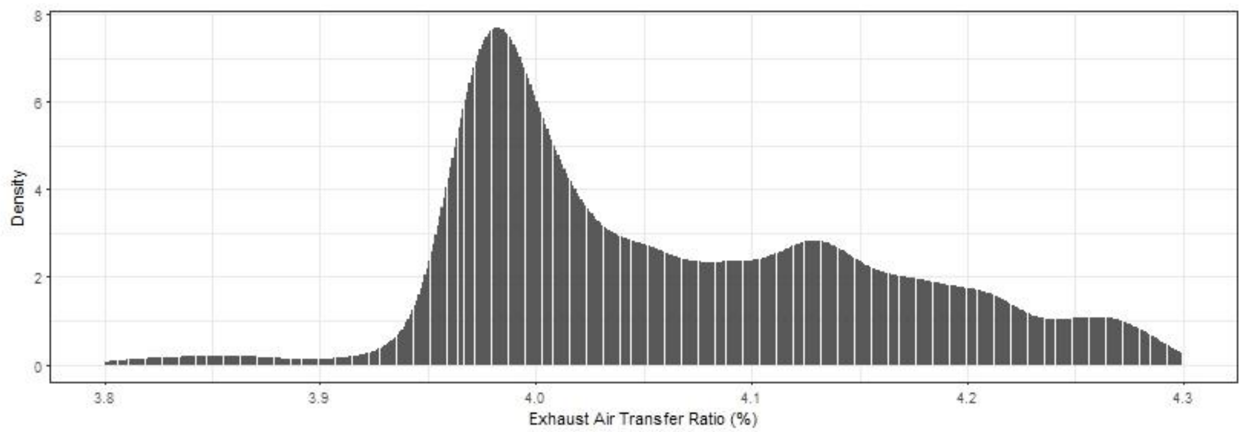
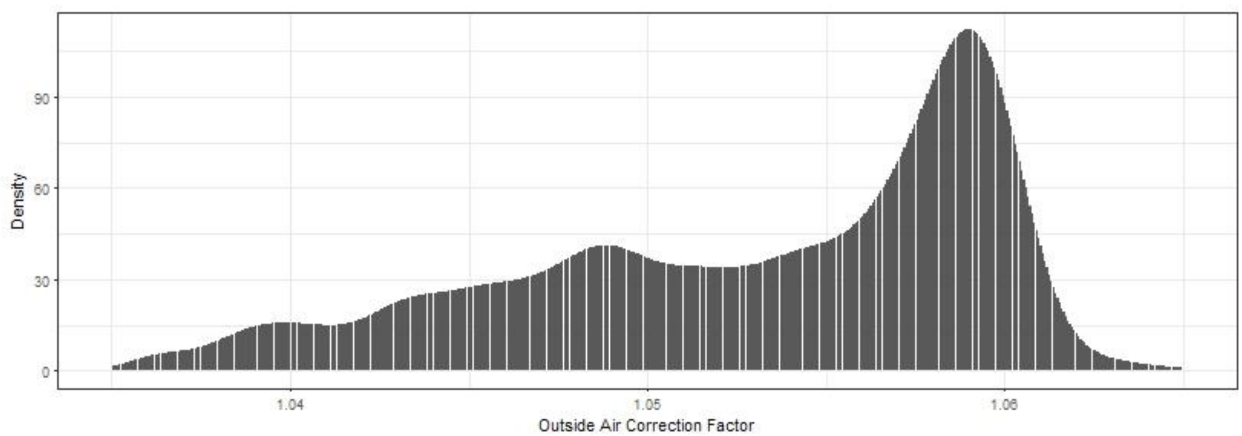
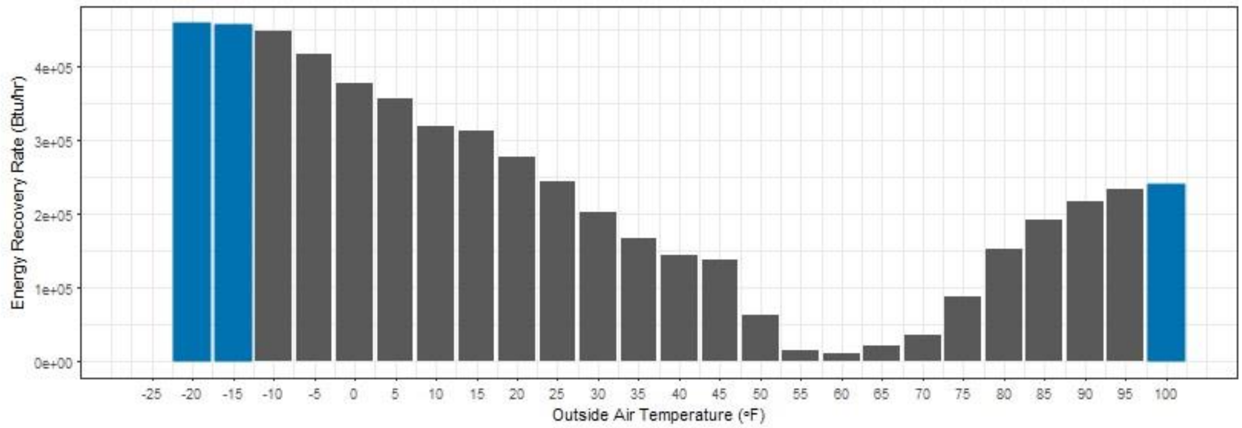


Figure 17: Outside air correction factor estimate from measured pressures



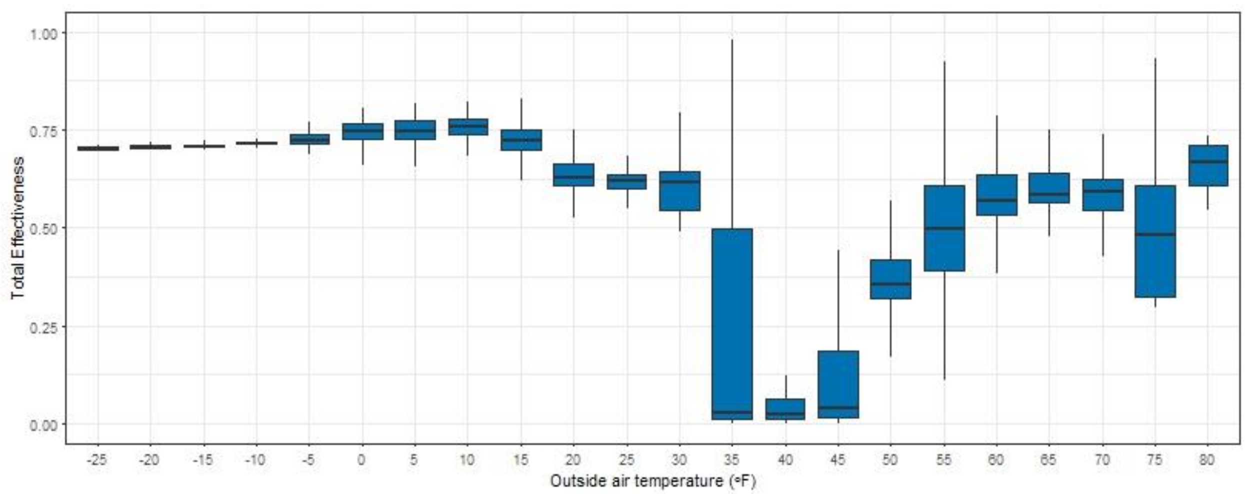
These measured data were consolidated using a bin analysis based on outside air temperature from the nearest National Oceanic and Atmospheric Administration (NOAA) station. Bins of 5°F were selected to get sufficient energy recovery data set across the operating range of -20°F to 100°F. The idea behind the bin analysis was to estimate performance over a wide variety of weather conditions and use that estimate to determine the total energy savings according to the frequency of those weather conditions. For example, Figure 18 shows the average energy recovery rate, or the change of energy in the outside air flow, as it passes through the ERV to become the supply flow. The rate of energy recovery rate is proportional to the ventilation load. Outside air conditions highlighted in blue were rarely or never encountered during the study and values were estimated based on measured effectiveness.

Figure 18: Average measured energy recovery rate (Btu/hr) modeled data highlighted.



Performance was also assessed using this bin analysis. For example, a sample distribution of effectiveness measured within each outside air temperature bin is shown in Figure 19. Effectiveness is approximately constant and near design values over regions of full speed operation. Larger variations are seen as the wheel speed is modulated to maintain a discharge temperature or for economizer operation. The relatively large uncertainty in effectiveness can be approximately assessed from these data as well. Consistent with prior work, in the best case effectiveness can be measured best at very cold temperatures. Under mild temperatures and larger variations exist, especially with significant latent contributions.

Figure 19: Distribution of total effectiveness by outside air temperature bin.



Results were standardized by subjecting all units to a standard schedule (6A-6P, M-F) under normalized weather conditions using TMY3 data (Wilcox & Marion, 2008). The measurements were taken over a two year period. The weather over this period varied significantly, and each year varied with respect to TMY3 data as seen in Figure 20 and Figure 21.

Figure 20: Operating condition distribution for all hours in year 1, year 2, and TMY3

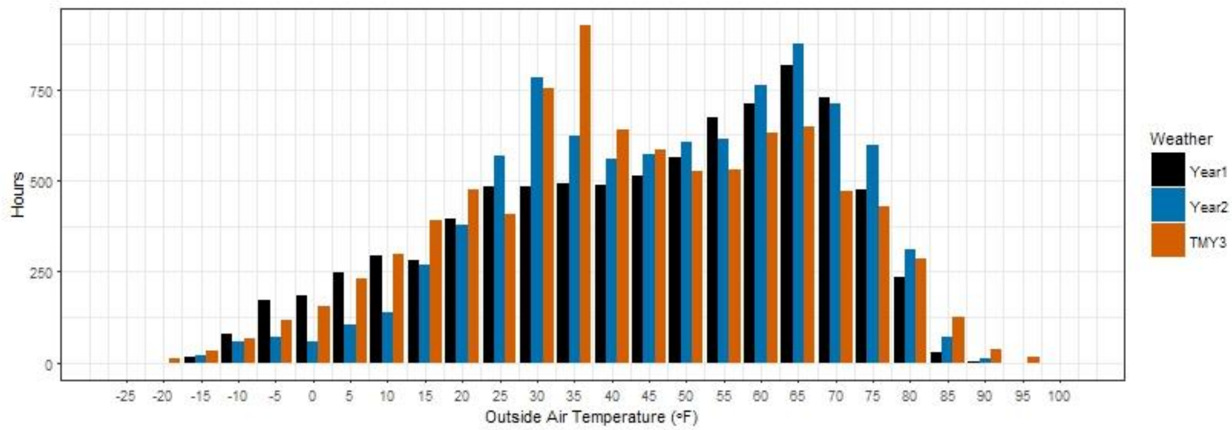
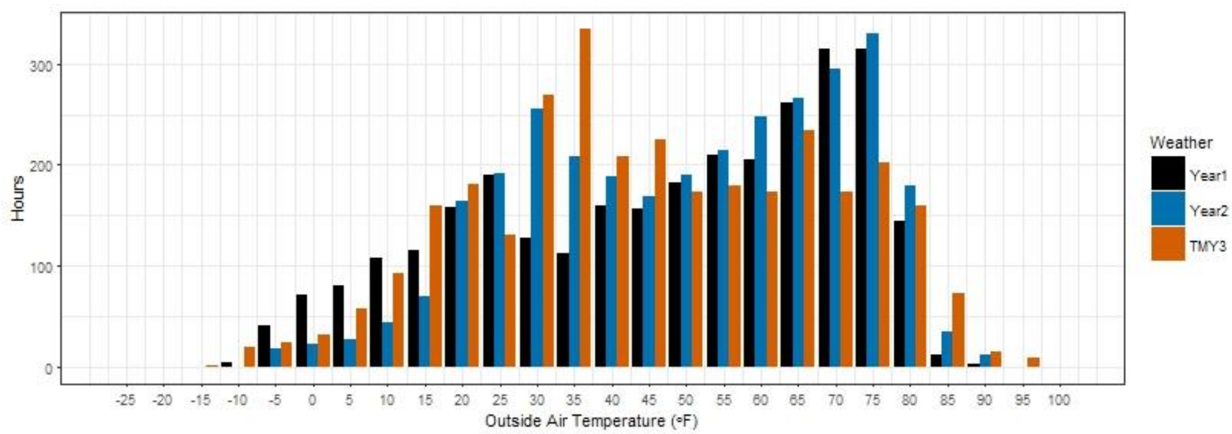


Figure 21: Operating condition distribution for fixed schedule (6A - 6P, M - F) in year 1, year 2, and TMY3



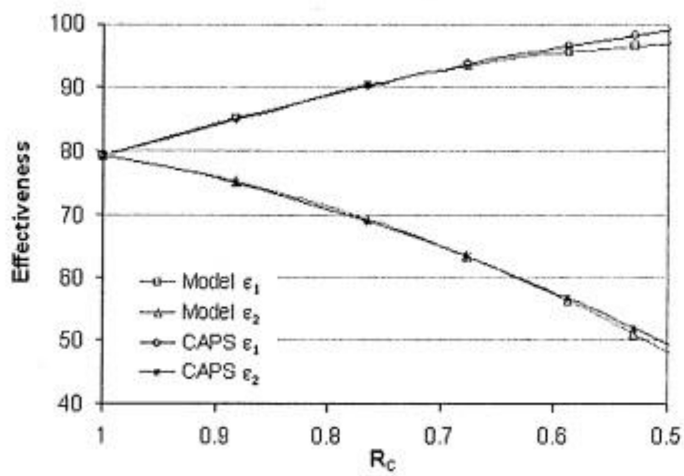
Energy savings and costs were estimated assuming standard heating and cooling efficiencies (80% heat and EER 11.7 cooling) and average energy costs at the time of the analysis (0.112 $/kWh and 0.82 $/Therm).

Modeling Energy Recovery

A basic performance model from the literature was used to extend measurements and calculations. The model was used to estimate changes in performance due to unequal and off-design flow rates, investigate the impact of specific issues on performance, and extend the data in cases where operating conditions were not encountered during the fieldwork (i.e. design conditions). The basic modeling procedure is outlined below.

A model developed by Freund et al. to estimate the effectiveness of counter flow heat exchangers, including rotary heat exchangers, was implemented (Freund et al., 2003). The model extends the effectiveness-NTU method with a correction factor to model the differences between a rotary heat exchanger and a conventional counter flow heat exchanger. This was deemed necessary due to the large uncertainties in measured effectiveness and the significant flow imbalances measured at several sites. As seen in Figure 22, unbalanced flows can have a dramatic effect on effectiveness compared to design values, which are typically given at balanced flow conditions (R_c = 1). Flow rates in this project tended to be smaller than design flow rates, which *increased* effectiveness but *decreased* the energy recovery rate (Btu/hr).

Figure 22: Effectiveness as a function of R_c, a ratio of the exhaust flow rate to the supply flow rate (Freund et al, 2003).

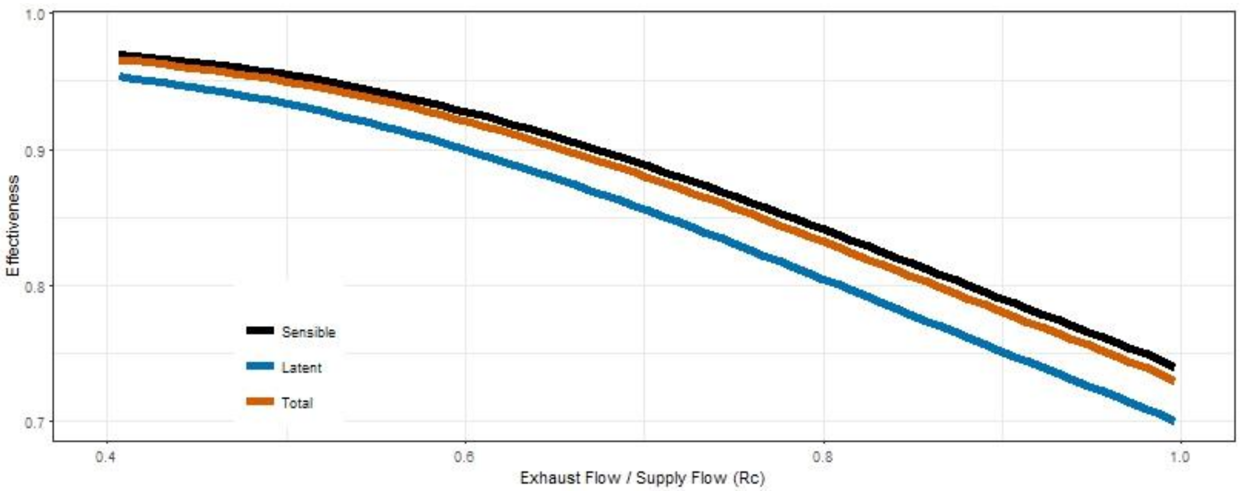


The semi-empirical model requires the effectiveness at two balanced flow reference points with known operating conditions. In all cases but one, these reference points were taken from AHRI certification data, which document effectiveness at given summer and winter design conditions using flow rates equal to 75% and 100% of design flows. The non-AHRI certified heat exchanger uses values derived from manufacturer data.

The model was used with both measured inputs including flow rate, temperature and relative humidity and modeled inputs (TMY3 data). From these data, the model predicted the change in effectiveness and performance under any balanced and unbalanced flow conditions. An example of the higher effectiveness expected in this study is shown in Figure 23, when the exhaust flow is less than the supply flow.

The model results (outputs) were validated against measurements for supply and exhaust air temperature and humidity. Paired with control sequences specific to each site, the validated model was used to explore specific operational changes and additional possibilities for ERV operation, extend the dataset, and generalize the results.

Figure 23: The change in effectiveness with the unbalanced flows encountered in this study



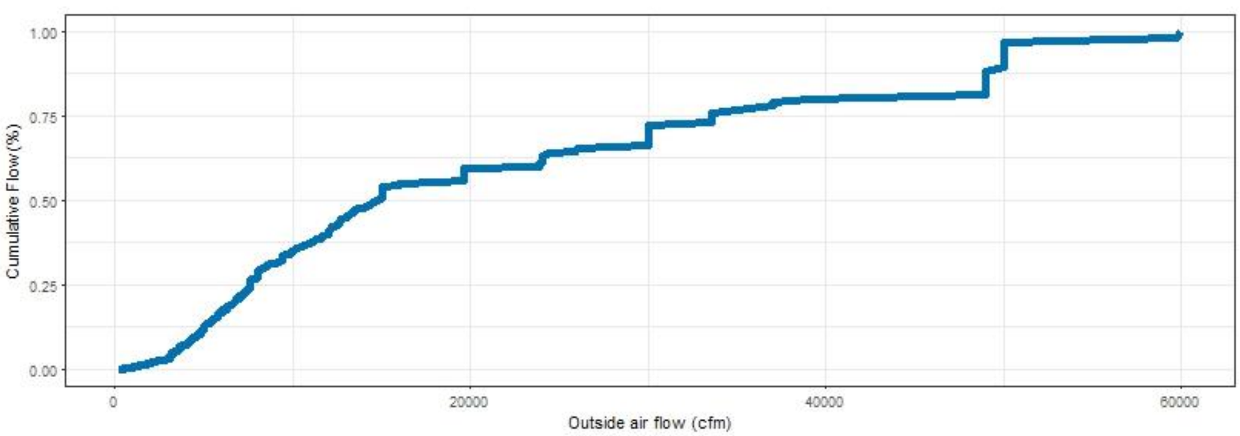
Results

ERV Systems in Minnesota

General information about commercial and institutional ERV units in Minnesota was reviewed and consolidated from past recommissioning work (Public Buildings Enhanced Energy Efficiency Program or PBEEEP), an ERV market characterization study (Hewett, 2010), and a limited dataset obtained from ERV CIP rebates (2009 - 2012). While limited in nature, these data provide some general sense of exhaust air-to-air energy recovery systems in Minnesota.

Partial data was available on 402 ERVs from 134 different buildings. While complete information about ventilation systems in these data was not available, the majority of these buildings have multiple air handling systems with energy recovery and often several ERVs of the same type. However, it is common that only a fraction of ventilation air in a building is served by energy recovery, particularly institutional buildings. Neglecting the PBEEEP dataset (institutional only), institutional buildings held 69% of the ERVs, while 31% of ERVs were found in commercial buildings (n = 101). The majority of institutional buildings were K-12 schools (51%) followed by higher education (22%), with municipal facilities making up the balance. While information on space use was only available from some of the data, it suggests that energy recovery systems are distributed among a variety of different types of commercial facilities that have larger than average ventilation loads including casinos, manufacturing and auto shops, assisted living, labs, and sports or gym facilities.

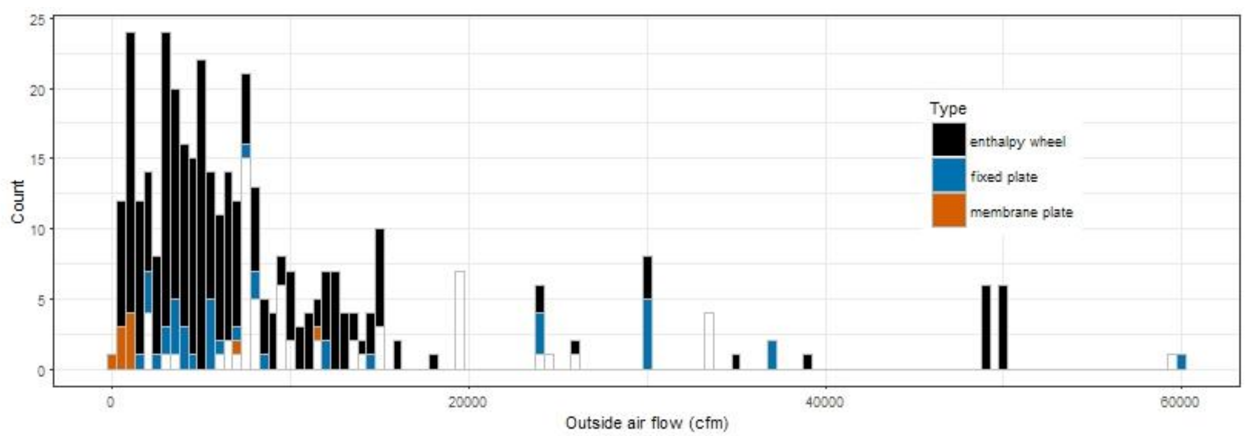
Figure 24: Cumulative fraction of flow rate by size (outside air flow rate)



Outside airflow rate sizing information was available for 375 units. Overall these units represent approximately 3,575,700 cfm of ventilation flow. The average flow rate was 9,510 cfm, whereas the median flow rate as 5,945 cfm. One quarter of all units were below 3,240 cfm and deliver less than 5% of the total flow. In contrast, one quarter of units were rated above 11,030 cfm and deliver over 63% of the total flow. Units ranging from 3,200 cfm to 11,030 cfm comprised 50% of the total number of units and delivered about 33% of the total flow. This distribution is shown visually in Figure 24, where the cumulative fraction of flow is plotted according to outside air flow rate. Despite the fact that units of less than 10,000 cfm make up 75% of the units, the majority of energy savings come from large units (over 10,000 cfm).

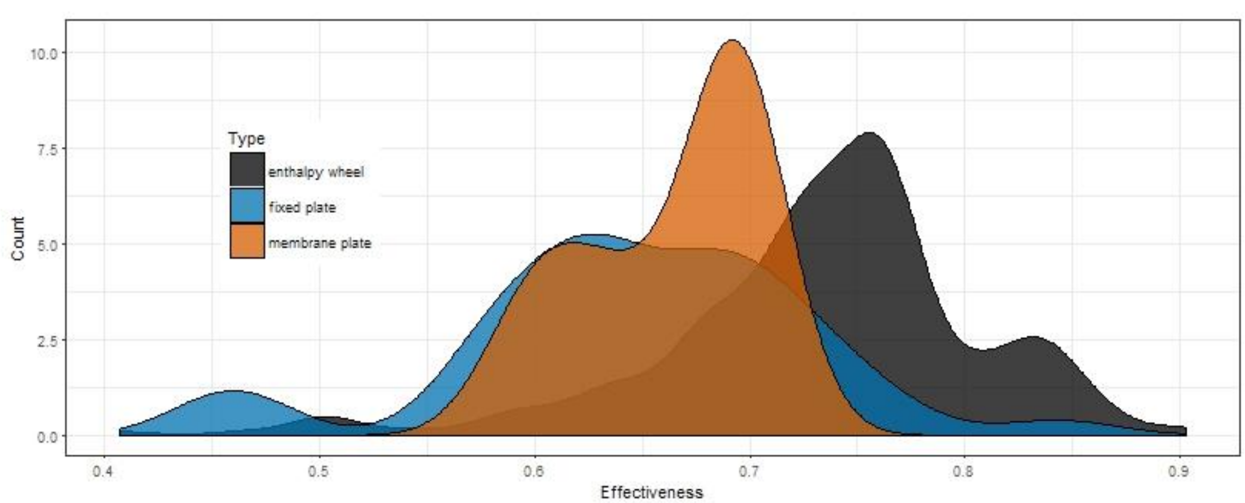
The type of energy recovery unit was specified for 296 units. Only three types of ERV systems were identified in these data: enthalpy wheels (80%), plate heat exchangers (13%), and membrane plates (7%). Units ranged in size (outside air flow) from 215 cfm to 60,000 cfm. The size distribution of units is shown in Figure 25. Enthalpy wheels encompassed the entire flow range, whereas plate heat exchangers were confined to a slightly narrower range (1,800 to 37,000 cfm). With two exceptions, membrane plates were only found in units with specified flow rates less than 1,200 cfm.

Figure 25: Size distribution (according to outside air flow rate) for three types of ERVs



The effectiveness figures are available on 314 units, as shown in Figure 26. Enthalpy wheels tend to have the highest effectiveness, followed by membrane plates and fixed plate heat exchangers, with average effectiveness of 0.73, 0.66, and 0.64, respectively. These figures should be interpreted with some caution as these values are likely a mix of total and sensible effectiveness.

Figure 26: Reported effectiveness for 314 units by ERV type



No significant trends were found when analyzing effectiveness, outside air flow, age, and unit type. There is no relationship between effectiveness and size. There are no trends over time in type, size, or effectiveness.

These data give some insight for how one might consider air-to-air energy recovery in Minnesota in terms of existing units. These data suggest that air-to-air exhaust energy recovery in Minnesota is most often implemented in the form of total enthalpy wheels within institutional buildings, predominately K-12 schools and to a lesser extend higher education. In commercial buildings, these units tend to be implemented in a variety of building types that have high ventilation loads. While there are an equal number of units below 3,200 cfm as above 10,600 cfm, the importance of large units to overall energy recovery is striking. The top quarter of units in terms of size are responsible for conditioning over 13 times the amount of ventilation air (and recovery potential) as the bottom quarter of units.

Representative ERV Systems

ERV units for this study were selected according to type, size, and space use in order to be representative of energy recovery systems in Minnesota commercial and institutional buildings, based on available data. Satisfying those requirements, sites were chosen based on a screening visit and an interview with building operators or owners. Preference was given to those sites with staff opinions or ERV operations that were incongruent with energy recovery expectations. Beyond that an attempt was made to sample different manufacturers, models, project engineers, and building owners to maintain a representative sample.

Table 5: General characteristics of ERV systems

ERV	Building	Use	Construction	Project Date	Similar ERVs (Site Total)	Application	Supplies
s1	Middle School	Classroom	Retrofit	2002	3	AHU	VAV
s2	High School	Classroom	Retrofit	2003	3	DOAS	AHU
s3	Middle School	Classroom	Retrofit	2007	3	DOAS	FCU
s4	Office / Lab	Office / Lab	New Construction	2006	5(1)	AHU	VAV
s5	Higher education	Classroom	Retrofit	2001	-(8)	AHU	CAV
s6	High School	Classroom	Retrofit	2004	1(4)	RTU	VAV
s7	High School	Classroom	Retrofit	2013	-(4)	RTU	VAV
s8	Office	Office	New Construction	2012	4	DOAS	AHU
s9	Office / Lab	Office / Lab	Replacement	2015	5	AHU	VAV

The buildings that house the ERVs that were investigated in this study are shown in Table 5 and are typical of Minnesota building stock for institutional and commercial buildings. Six units principally served classroom space, and the remaining three served office space or a combination of office and lab space. Six units were retrofit construction on existing buildings, two units were part of a new construction, and one was strictly the retrofit substitution of a new unit for an old one. Projects were between three and 13 years old at the time they were selected for this study. All buildings had multiple ERVs. In all cases except for sites s5 and s7, all buildings had multiple ERVs that were substantially similar to those studied. Units s5 and s7 were unique at their buildings, but these buildings contained other ERVs. All sites had other non-similar energy recovery systems as well as ventilation systems without energy recovery.

The types of associated ventilation units were also classified by application. Four units were designed for and located within the main air handling units (AHUs) that supplied heated and cooled air to a variable air volume (VAV) supply system. One unit was designed for and located within a constant air volume (CAV) AHU that supplied heated and cooled air to reheat coils. Two units were packaged within roof top units (RTUs). Three units were classified as dedicated outside air systems (DOAS) and, of these, two provided air to AHUs and one provided air to fan coil units.

General information about the energy recovery units in this study is given in Table 6. This study included two types of energy recovery units from six manufacturers. Eight total enthalpy wheels and one plate heat exchanger were selected. Design outside air flows spanned from 5,000 to 33,600 cfm, and motor size varied between 5 hp and 100 hp. The importance of large units to state-wide ERV portfolio resulted in a preference toward large units and resulted in a selection of five units from the top quartile (10,600+ cfm) of unit size. S8 is somewhat unique in that two 5,500 cfm wheels were operated in parallel within the same air handler. Motors to spin enthalpy wheel units ranged from ¼ hp to 1 hp. All supply and exhaust fans were fitted with VFDs; however, at s5 speeds were manually fixed at the VFD. In practice units s4, s6, and s9 were also operated at relatively constant speeds. Two units, s3 and s5, were specified under unbalanced supply and exhaust flow rates.

Table 6: Specific energy recovery system details

ERV	Manufacturer	Type	VFD	WVFD	Design Supply/ Exhaust Flow	AHRI ε
s1	AIRotor	Wheel	Y	Y	5,600 /5,600	70
s2	Semco	Wheel	Y	Y	21,100 / 21,100	78
s3	AIRotor	Wheel	Y	Y	11,800 / 7,400	70
s4	Semco	Wheel	Y	Y	33,600 / 33,600	78
s5	HeatXChanger	Plate	Y*	-	24,000 / 17,000	44/24 (67**)
s6	AIRotor	Wheel	Y	Y	5,000 / 5,000	70
s7	Airxchange	Wheel	Y	N	5,600 / 5,600	66
s8	Innergy tech	Wheel	Y	Y	5,500/ 5,500(2)	71
s9	Thermotech	Wheel	Y	Y	33,600 / 33,600	73***

* Set to constant volume
** Sensible energy-only (sensible effectiveness)
*** No AHRI rating

The nameplate performance of these units was very similar, with an AHRI heating application effectiveness of between 0.66 and 0.78. Unit s9 was not AHRI certified at the time of the study, and the design effectiveness was calculated from manufacturer provided numbers. Unit s5 is a sensible plate heat exchanger unit with a sensible effectiveness of 0.67. As it does not recover latent energy, the total effectiveness is 0.44 (in heating mode) and 0.24 (cooling mode). Thus nameplate performance suggests that, at balanced flow design conditions, these units will recover between two-thirds and three-fourths of recoverable energy from the exhaust stream.

Preliminary Energy Savings

The ERVs studied in this project were initially outfitted with logging equipment, and BAS data were collected to assess the initial energy savings performance. Initial data were collected over a period of five to seven months between summer 2014 and winter 2015. The initial performance of these units varied between disabled and fully-functional. In this section, the as-found performance of these units is presented and discussed. These results are given separately for heating and cooling in Table 7 and Table 8. Heating and cooling energy and cost savings are compared in The initial state of energy recovery varied significantly. Heating energy savings (gas) ranged between 0 and 26,183 Therm while cooling energy savings (electric) ranged between 0 and 40,027 kWh for a typical year. For these nine sites, the energy savings (or lack thereof) resulted in cost savings of -$4,329 and $19,413 for a typical year. Negative costs suggest the energy used was greater than the energy saved. When normalized by supply airflow rates, operational units yielded a narrow range of cost savings ranging from 0.27 to 0.42 $/cfm, with both average and median costs of 0.34 $/cfm. Non-operational units failed to recover energy into the supply flow.

Energy recovery during cooling season (generally both latent and sensible loads, with the exception of sensible-only recovery on unit s5) was considerably less than heating season. Cooling recovery resulted in electric savings of 467 to 40,027 kWh, with resulting cost savings ranging from -0.04 to 0.09 $/kWh. About 10% of the total cost savings from this group of ERVs came from cooling energy recovery, which is consistent with other estimates for the Minnesota climate (AHRI, 2011).

These units can be conveniently divided into three groups: non-functioning units (s1, s2, s5), essentially functioning units (s3, s6, s7), and highly functioning units (s4, s8, s9).

Figure 27 and Figure 28. The savings results are presented for a typical year, which consists of normalizing the individual results according to the same operation schedule, mechanical heating and cooling equipment efficiencies, and outdoor air conditions as described in the Methodology section.

Table 7: Preliminary heating energy savings

ERV	Average Heating Recovery	Heating Savings	Heating Cost Savings	Heating Cost Savings
	Btu/hr	Therms	$	$/cfm
s1	0	0	-58	-

ERV	Average Heating Recovery	Heating Savings	Heating Cost Savings	Heating Cost Savings
s2	0	0	-4,329	-
s3	72,231	1,888	1,435	0.34
s4	1,001,734	26,183	19,413	0.42
s5	0	0	-352	-
s6	147,494	3,855	2,322	0.33
s7	56,941	1,488	973	0.34
s8	190,104	4,969	3,537	0.27
s9	737,231	19,269	13,609	0.34
Min	0	0	-4,329	0.27
Max	1,001,734	26,183	19,413	0.42
Average	245,082	6,406	4,061	0.34
Median	72,231	1,888	1,435	0.34
Sum	-	57,652	36,550	-

Table 8: Preliminary cooling energy savings

ERV	Average Cooling Recovery	Cooling Savings	Cooling Cost Savings	Cooling Cost Savings
	Btu/hr	kWh	$	$/cfm
s1	0	0	-29	-
s2	0	0	-2,153	-
s3	10,009	890	46	0.01
s4	391,779	34,832	2,917	0.06
s5	5,257	467	-175	-0.01
s6	11,906	1,059	-293	-0.04
s7	8,027	714	-41	-0.01
s8	70,138	6,236	438	0.03
s9	450,216	40,027	3,422	0.09
Min	0	0	-2,153	-0.04
Max	450,216	40,027	3,422	0.09
Average	105,259	9,358	459	0.02
Median	10,009	890	-29	0.01
Sum	-	84,224	4,133	-

The initial state of energy recovery varied significantly. Heating energy savings (gas) ranged between 0 and 26,183 Therm while cooling energy savings (electric) ranged between 0 and 40,027 kWh for a typical year. For these nine sites, the energy savings (or lack thereof) resulted in cost savings of -$4,329 and $19,413 for a typical year. Negative costs suggest the energy used was greater than the energy saved. When normalized by supply airflow rates, operational units yielded a narrow range of cost savings ranging from 0.27 to 0.42 $/cfm, with both average and median costs of 0.34 $/cfm. Non-operational units failed to recover energy into the supply flow.

Energy recovery during cooling season (generally both latent and sensible loads, with the exception of sensible-only recovery on unit s5) was considerably less than heating season. Cooling recovery resulted in electric savings of 467 to 40,027 kWh, with resulting cost savings ranging from -0.04 to 0.09 $/kWh. About 10% of the total cost savings from this group of ERVs came from cooling energy recovery, which is consistent with other estimates for the Minnesota climate (AHRI, 2011).

These units can be conveniently divided into three groups: non-functioning units (s1, s2, s5), essentially functioning units (s3, s6, s7), and highly functioning units (s4, s8, s9).

Figure 27: Initial energy savings of nine representative ERV units for a typical year

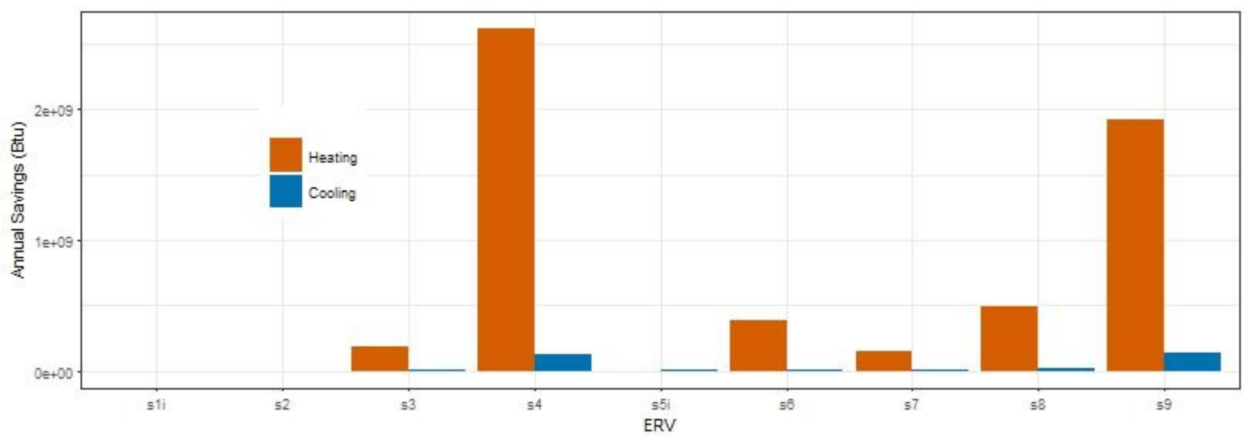
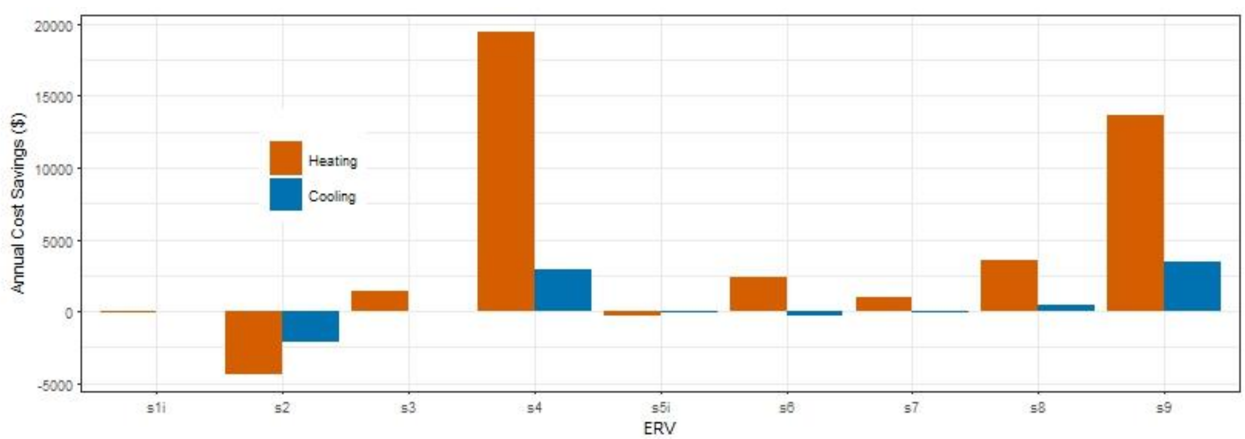


Figure 28: Initial cost savings of nine representative ERV units a typical year



Units s1, s2, and s5 were quickly determined to be non-functional during the initial screening and monitoring. The original aim was to assess their performance in an unmodified state; however, two units (s1 and s5) were effectively disabled by operator overrides. Shortly into the initial monitoring period these set points were adjusted to more reasonable values to enable more meaningful operational data on other potential issues. Unit s2 remained non-functional until the completion of a prolonged recommissioning process.

In their original state, units s1 and s2 saved no heating or cooling energy. Unit s5 was disabled in heating and only operated at outside air temperatures exceeding 80°F, which did result in some electric energy savings (467 kWh/yr). Despite low savings, there were electrical costs associated with operating all three units, such that there was an overall annual cost penalty for these energy recovery implementations. For s1, these costs were negligible ($58 for heating and $29 for cooling) due to extreme underutilization. While the energy cost to operate unit s5 ($352 for heating and $175 for cooling) was larger because the unit was larger, it was still relatively low because the unit was also underutilized. For unit s2, the costs were significant ($4,329 for heating and $2,153 for cooling) because the unit was large, fully-energized, and did not supply conditioned air (the output was bypassed), which wasted all fan energy.

Units s3, s6, and s7 were essentially functional. Problems were encountered on all three units, but none of the problems outright prevented energy recovery. In heating season, these units recovered on average 56,941 Btu/hr to 147,494 Btu/hr for overall gas savings between 1,488 therms and 3,855 therms during a typical heating season. The normalized heating cost savings were 0.33 $/cfm to 0.34 $/cfm, with annual savings of $1,435, $2,322, and $973 for units s3, s6, and s7, respectively

Unit s3 ran throughout cooling season to recover 10,009 Btu/hr on average for a total of 890 kWh per year. The electric savings were $46 or about 0.01 $/cfm. Units s6 and s7 did not operate in cooling mode and were not (directly) connected to mechanical cooling systems. However they still operated occasionally to save some energy in cooling season (1,059 and 714 kWh, respectively). These savings were not enough to overcome their operating costs during this period. They incurred annual operating cost penalties during cooling season of -$293 and -$41, respectively, or about -0.04 $/cfm and -0.01 $/cfm.

Units s4, s8, and s9 were highly functional throughout the year with no major problems impacting energy recovery. These units saved 1,001,734 Btu/hr, 190,104 Btu/hr, and 737,231 Btu/hr for total gas savings of 26,183 therms, 4,969 therms, and 19,269 therms, respectively. These gas savings correspond to cost savings of 0.42 $/cfm, 0. 27 $/cfm, and 0.34 $/cfm. While normalized heating cost savings match other operating units, total annual savings were large due to large supply air flows. When operating on a fixed 6a-6p, M-F schedule, s4, s8, and s9 save $19,413, $3,537, and $13,609 in heating costs in a typical year, respectively.

As larger buildings with larger cooling loads, units s4, s8, and s9 had relatively stronger cooling recovery performance, which provided a greater overall portion of savings. Average cooling recovery rates were 391,779 Btu/hr, 70,138 Btu/hr, and 450,216 Btu/hr, respectively, for total cooling energy reduction of 34,832 kWh, 6,236 kWh, and 40,027 kWh. The normalized savings per cfm were 0.06 $/cfm, 0.03 $/cfm, and 0.09 $/cfm or $2,917, $438, $3,422 for a typical year.

Final Energy Savings

Over the course of this study 40 issues were resolved on seven units. Monitoring continued after this process to determine the post-implementation performance of these units. The final energy savings figures are given in Table 9 for heating and Table 10 for cooling. A comparison between preliminary savings and final savings is given for each site for heating (gas) in Figure 29 and Figure 30 and for cooling (electric) in Figure 31 and Figure 32.

Post-implementation, all treated units were improved in terms of both energy and operating costs. Normalized heating cost savings ranged from 0.18 to 0.48 $/cfm. Annual heating operating costs savings varied from $573 to $21,757 for a typical year. Cooling recovery also increased, resulting in 511 to 40,027 kWh/yr of cooling energy savings, or in -$24 to $3,422 of electric savings per year.

In aggregate, if this group of ERVs is viewed as a portfolio of devices, changes resulting from recommissioning the units were significant. Initially these units were saving a combined 57,652 Therm and 84,224 kWh for total annual savings of $40,683. Recommissioning these units increased combined annual savings to 69,752 Therm and 91,140 kWh, resulting in cost savings of $57,851 for a typical year. In other words, this project resulted in a direct savings of $17,168 over a typical year.

Table 9: Post-implementation heating savings

ERV	Average Heating Recovery	Heating Savings	Heating Cost Savings	Heating Cost Savings
	Btu/hr	Therm	$	$/cfm
s1	29,547	772	573	0.26
s2	85,397	2,232	1,522	0.18
s3	122,255	3,195	2,394	0.48
s4	1,111,505	29,052	21,757	0.47
s5	180,633	4,721	3,506	0.27
s6	150,069	3,922	2,770	0.40
s7	61,903	1,618	1,079	0.38
s8	190,104	4,969	3,537	0.27
s9	737,231	19,269	13,609	0.34
Min	29,547	772	573	0.18
Max	1,111,505	29,052	21,757	0.48
Average	296,516	7,750	5,639	0.34
Median	150,069	3,922	2,770	0.34
Sum	-	69,752	50,747	-

Table 10: Post-implementation cooling savings

ERV	Average Cooling Recovery	Cooling Savings	Cooling Cost Savings	Cooling Cost Savings
	Btu/hr	kWh	$	$/cfm
s1	5,743	511	28	0.01
s2	23,120	2,056	80	0.01

ERV	Average Cooling Recovery	Cooling Savings	Cooling Cost Savings	Cooling Cost Savings
s3	17,473	1,553	66	0.01
s4	391,779	34,832	2,917	0.06
s5	36,807	3,272	192	0.01
s6	19,325	1,718	-24	0.00
s7	10,523	936	-16	0.01
s8	70,138	6,236	438	0.03
s9	450,216	40,027	3,422	0.09
Min	5,743	511	-24	-0.01
Max	450,216	40,027	3,422	0.09
Average	82,374	7,324	543	0.02
Median	23,120	2,056	80	0.01
Sum	-	91,140	7,104	-

Figure 29: Initial and final heating savings (Btu) for each recommissioned ERV

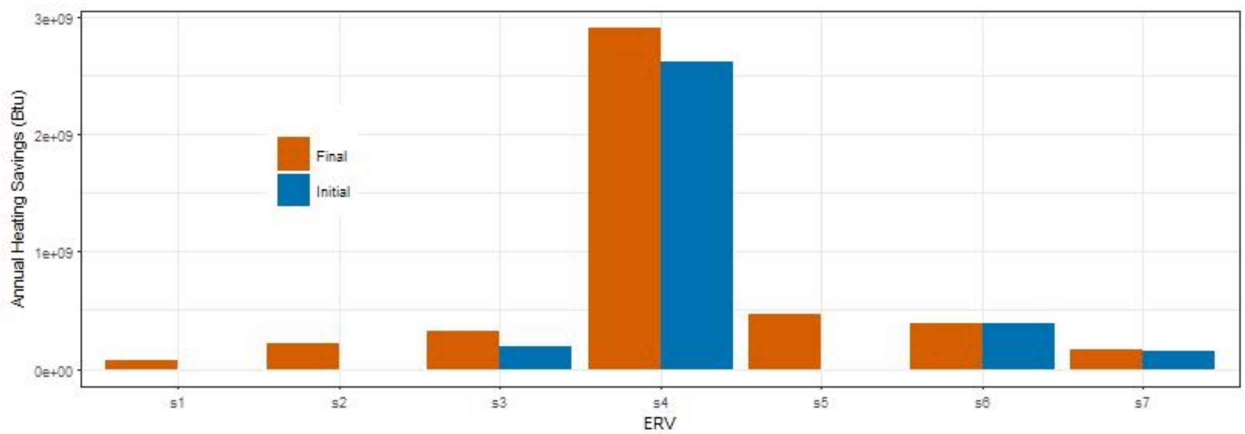


Figure 30: Initial and final heating cost savings ($) for each recommissioned ERV

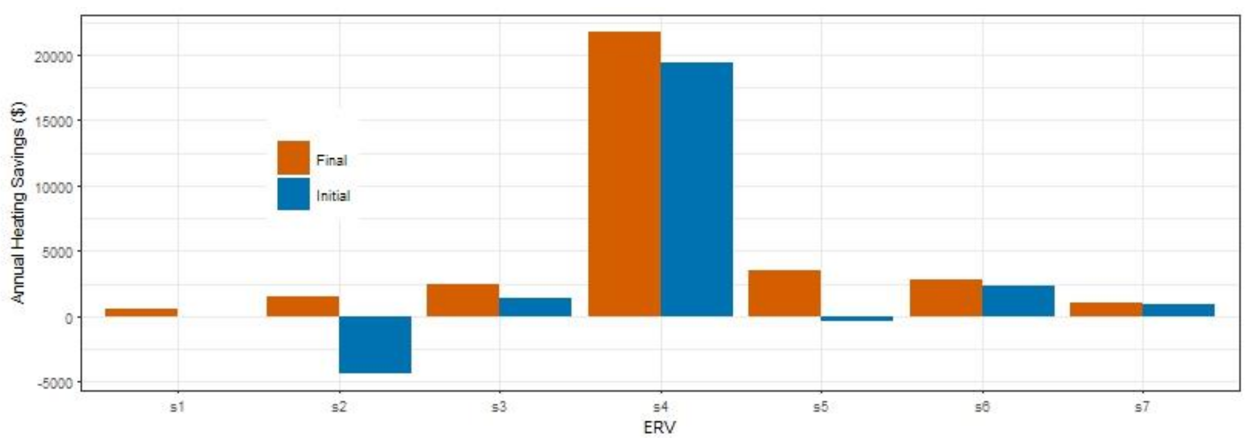


Figure 31: Initial and final cooling savings (kWh) for each recommissioned ERV

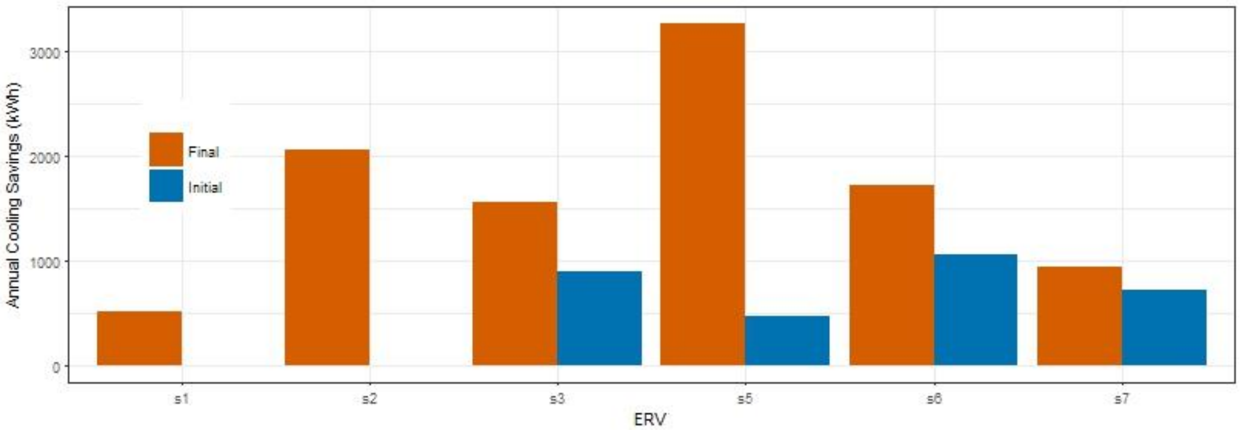
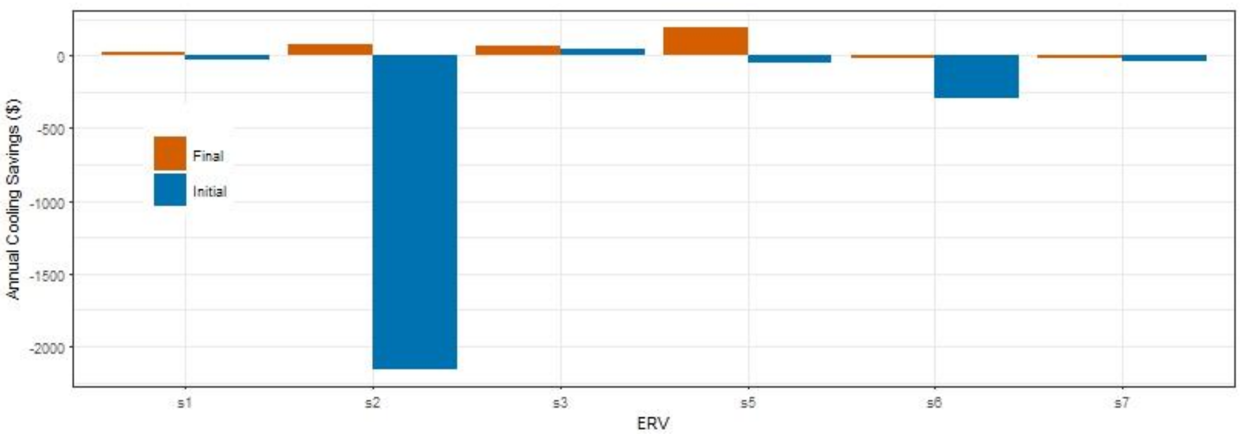


Figure 32: Initial and final cooling cost savings ($) for each recommissioned ERV



The three initially nonfunctional units (s1, s2, and s5) were operational after implementation with normalized heating and cooling savings on par with other units. The units s3, s6, and s7 were previously functional, but each had several problems addressed. Significant additional heating savings were achieved from unit s3 and s7 (70% and 9%, respectively), while heating savings from unit s6 was essentially unchanged (2% increase). Increases in cooling savings were more significant at 75% for s3, 62% for s6, and 32% for s7. Additional recovery on unit s3 came from the higher supply flows achieved by repairing a failed velocity sensor. Additional heating savings on units s6 and s7 came by improving frost control and eliminating a constant 20% bypass. Cooling savings came by adding cooling sequences. Although unit s4 was initially characterized as a highly-functional unit, opportunity for increasing the ERV discharge temperature to match the AHU discharge temperature resulted in an 11% increase in both heating recovery and heating cost savings.

All units were saving energy and lowering operating costs during cooling season. Cooling cost savings remained about one tenth of heating, ranging from 0 $/cfm (breakeven) to 0.06 $/cfm, consistent with initial performance. Units s6 and s7 still used more energy than they saved and hence incurred a cost energy penalty during cooling mode, however, in the absence of a mechanical cooling system, these unit still provided some conditioning benefit during ventilation periods. These costs were very minor at $24 and $16 per year for s6 and s7.

Two factors contribute to lower cooling savings. First, excluding economizer operation, cooling season makes up less than 20% of the operating hours in a typical year. Secondly the cooling season load is relatively mild and mechanical cooling systems operate relatively efficiently at the mild loads encountered in climate zones 6 and 7. ERVs offer substantial load reduction at higher cooling loads (i.e. design conditions), but these loads are relatively infrequent. For example, summer design conditions were not encountered at any of the 9 sites throughout this entire study. The Minneapolis TMY3 data set suggests the majority of the cooling will occur near economizer conditions.

Overall these results reinforce the notion that large air-to-air energy recovery in Minnesota is primarily a heating season energy efficiency technology. For all units heating savings exceed 75% of the total, more frequently 90% of all savings occur during heating mode. Relatively mild cooling season conditions diminish the potential savings from energy recovery in warm weather. It remains important that energy recovery be properly integrated with economizing functionality as such not to diminish economizing savings. Nonetheless, while energy recovery may be primarily motivated by heating energy savings, it pays to use energy recovery systems year-round. Furthermore, although summer design conditions are rare, energy recovery systems operating at these times greatly diminish the ventilation load. In this way, the energy efficiency motivation for cooling season energy recovery is peak-load reduction and potential demand savings.

Performance

Recommissioned ERV performance is summarized in Table 11, and Figure 33 through Figure 36 using an average recovery energy ratio (RER) and the percent total ventilation load satisfied by the energy recovery equipment for heating and cooling seasons. More so than effectiveness, both metrics allow these energy recovery systems to be quantitatively compared to conventional heating and cooling equipment. The percent load satisfied by the energy recovery is directly comparable to conventional systems which would otherwise meet the complete load. The RER provides a measure for how much energy is saved with respect to the energy each ERV uses. For the purposes of comparison, the RER_h for conventional heating equipment (natural gas heat) would vary between about 0.8 and 0.9 W/W, consistent with their typical efficiency. The RER_c for conventional cooling equipment has a broader range, but might typically vary between 10 and 16 Btu/hr-W and 20 to 30 Btu/hr-W for air and water cooled systems, respectively.

Table 11: Final ERV Performance

	Heating		Cooling	
	% Load	RERh	% Load	RERc
	%	W/W	%	Btu/W-hr
s1	34%	35	9%	19
s2	35%	19	10%	15
s3	90%	39	19%	16

	Heating		Cooling	
s4	86%	39	22%	21
s5	36%	35	9%	20
s6	54%	24	-	10
s7	53%	17	-	10
s8	45%	25	23%	22
s9	66%	24	24%	22
Min	34%	17	9%	10
Max	90%	39	24%	22
Average	55%	29	16%	17
Median	53%	25	19%	19

These performance metrics reinforce the notion that energy recovery in a Minnesota climate is about heating energy savings (Figure 36). Not only are heating loads larger than cooling loads, but energy recovery systems satisfy a higher proportion of those loads. ERVs in this project serve between 34% and 90% of the heating ventilation load, while recovering heating energy at between 17 and 39 times the electrical energy they require to operate. The average load served in heating season is 55%, which includes periods of frost control, full-heating recovery, and partial heating recovery during mild weather. Units with the lowest percent of load served (s1, s2, s5) are hindered by unbalanced flow conditions; supply flows are greater than exhaust flows. On the other hand, the unit with the highest load served (s3), is aided by an unbalanced flow where the supply flow is less than the exhaust flow. These flow imbalances have a larger impact on energy savings than the (relatively) minor differences in design effectiveness between units. This study did not assess the flow rates with respect to the ventilation needs of the spaces they served.

Similar trends are evident in cooling season, albeit with a lower contribution to ventilation loads. Ventilation loads served by these ERV units vary between 9% and 23% with an average and median of 16% and 19%, respectively. Units s6 and s7 are excluded due to the absence of associated cooling equipment. The lower portion of ventilation load served is due to the substantial role played by economizer functionality as well as generally mild cooling conditions with respect to the design load. High cooling RERs (e.g. 80 – 130 Btu/h-W) are often cited at design conditions, but these are reduced by less recovery during mild weather (for essentially constant operating energy). Average cooling RERs are also reduced by the fact their pressure drop is incurred even during economizer operation (and in some cases, it is increased due to higher outside air). Generally the cooling load is met by the economizer about half the time, which effectively halves the average RERc for systems without bypass because energy is used to overcome the ERV pressure drop but no energy savings occur. RERc is reduced by a lesser amount for the two units bypass units, which do not entirely eliminate these pressure drops. These cooling RERc range from 10 to 22 Btu/hr-W, with an average and median RERc of 17 Btu/hr-W and 19 Btu/hr-W, respectively. ERVs with high cooling loads (s4, s8, and s9) have RERc (21 - 22 Btu/hr-W) exceeding the top range of cooling equipment, but the remaining 6 ERVs have RERc that is quite similar to mechanical cooling systems. Lower performance is also expected somewhat in cooling mode, as latent effectiveness is generally less than sensible effectiveness. Nonetheless these systems do make contributions toward the cooling load, provide net-savings, and substantially reduce peak cooling load allowing smaller cooling systems. These remain substantial benefits on top of the motivating heating (gas) savings.

Figure 33: Portion of ventilation load met by energy recovery system

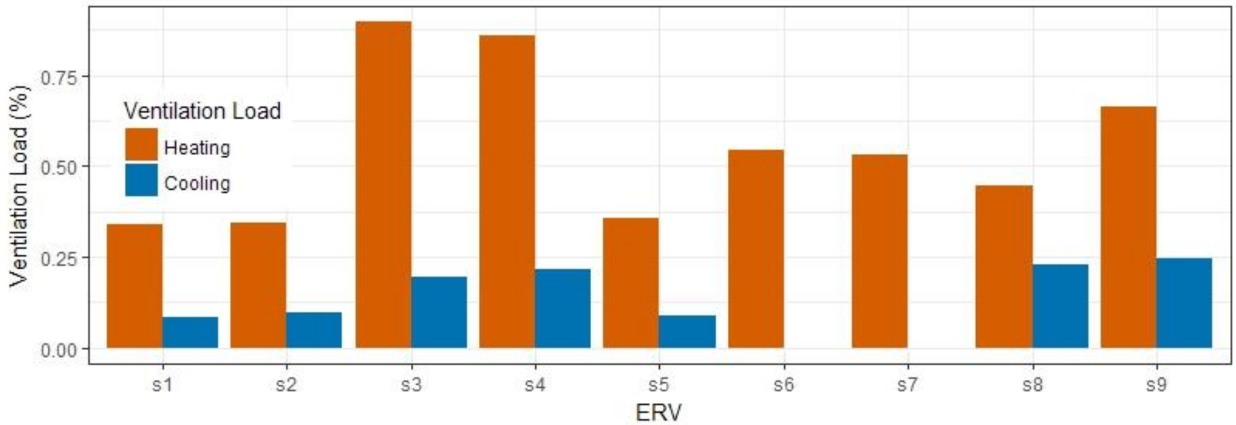


Figure 34: Final recovery energy ratio (RER) for heating (W/W)

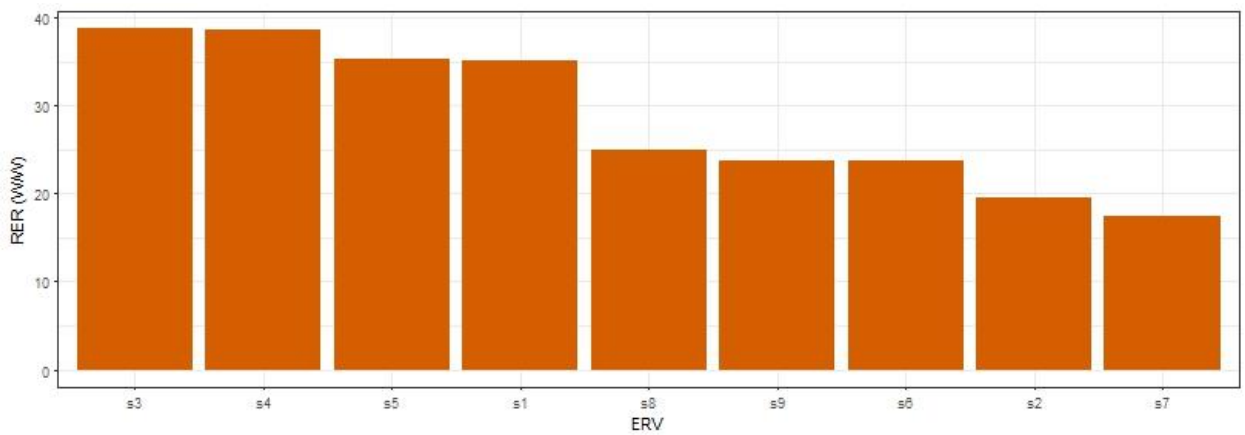


Figure 35: Final recovery energy ratio (RER) for cooling (Btu/hr-W)

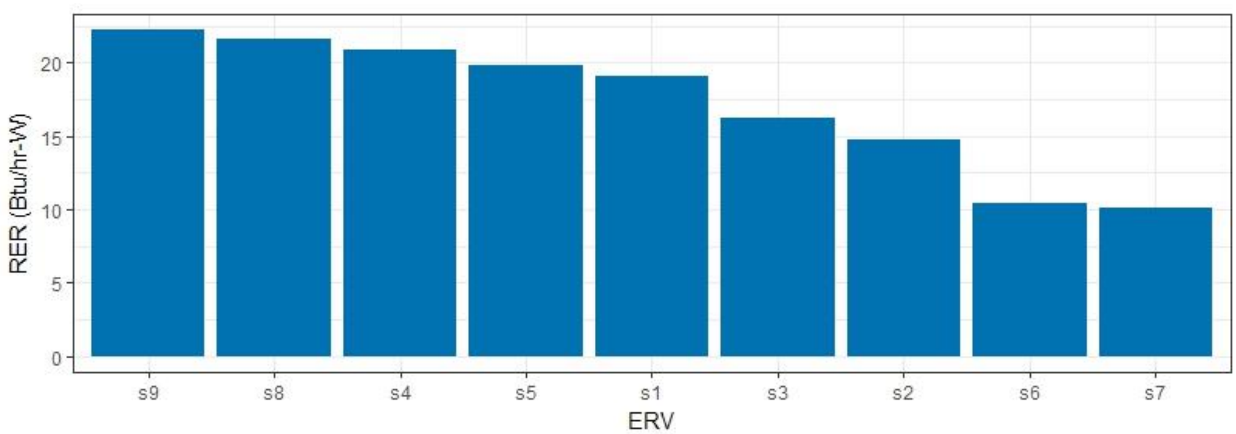
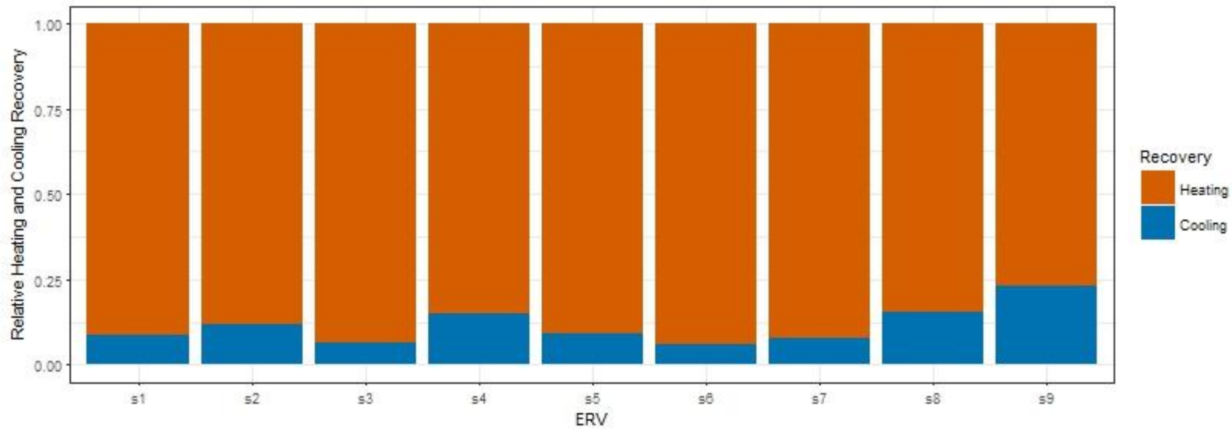


Figure 36: Proportion of recovered energy (heating v cooling)



The energy necessary to run the energy recovery systems is shown in Figure 37. These values are normalized by supply airflow rate. The electrical energy includes the energy necessary to push supply and exhaust flows through the ERV as well as the energy to spin the ERV unit, where necessary. Energy used by the ERVs in this study varied between 0.11 and 0.36 W/cfm. These systems are impacted by face placement, equipment efficiencies, and the level of utilization. At the low end (s2, s5, and s1) are the underutilized systems with very low pressure drops. Underutilized system costs do not drop significantly due to the lower system efficiencies. At the high end (s7) is a compact RTU with relatively inefficient supply and exhaust fans. Unit s3 also has a somewhat inflated value when presented this way due to exhaust flows that exceed supply flows. Other units, with nominally balanced flow rates near design conditions, range between about 0.17 to 0.3 W/cfm.

Figure 37: Energy consumption of energy recovery devices due to added fan energy from pressure drop and to spin rotating media

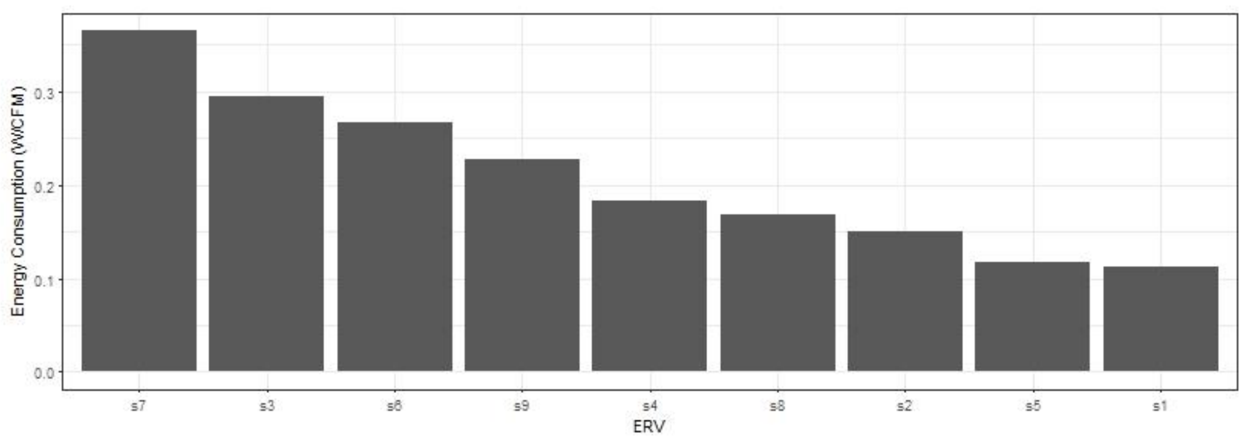
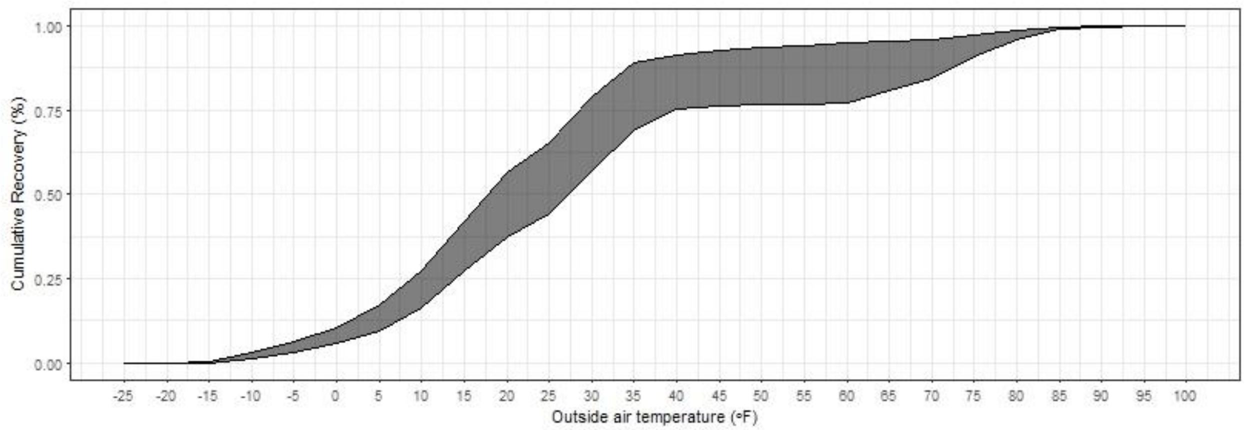


Figure 38: Range of cumulative energy recovery (%) for sites in this study



Energy savings from energy recovery depend on whether it is activated at the right time, with the right time determined by the ventilation load and the frequency of the load. This can be explored by calculating the cumulative energy recovery of ERVs as a function of outside conditions. In Figure 38, the percentage of cumulative energy recovery is plotted for maximum and minimum values obtained from the nine ERVs in this study for each 5°F outside air temperature bin using TMY3 data on a fixed 6A – 6P, M-F schedule. All ERVs fall within this bin after recommissioning. There are several important observations with energy savings: (1) half of all energy recovery in Minnesota occurs between about 12°F and 35°F; (2) less than 10% of energy recovery occurs below -5°F or above 80°F; and (3) very little energy recovery takes place between 45°F and 65°F. At a bare minimum, an ERV should be activated between 0°F and 45°F to realize between 60% and 80% of potential savings.

In Figure 39 and Figure 40, the range of cumulative energy recovery for units in this study is compared for TMY as well as local NOAA data for each year in this study. In this case, the deviation between the actual data in this study and the TMY3 year are less than 10%. In year 1, there was more mildly cold weather resulting in a larger portion of energy recovery during the heating season. In year 2, there was less mildly cold weather and more hours under a mild (heavy economizer) cooling mode, 60°F to 70°F. In this case, TMY3 data is fairly representative average of the years in this study.

Figure 39: Range of cumulative energy recovery (%) for sites in this study under different weather conditions

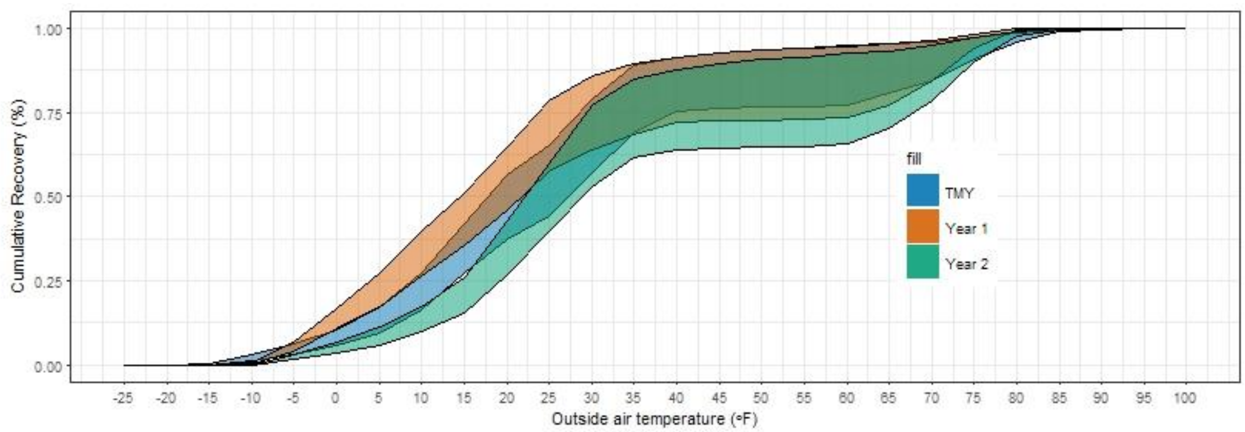
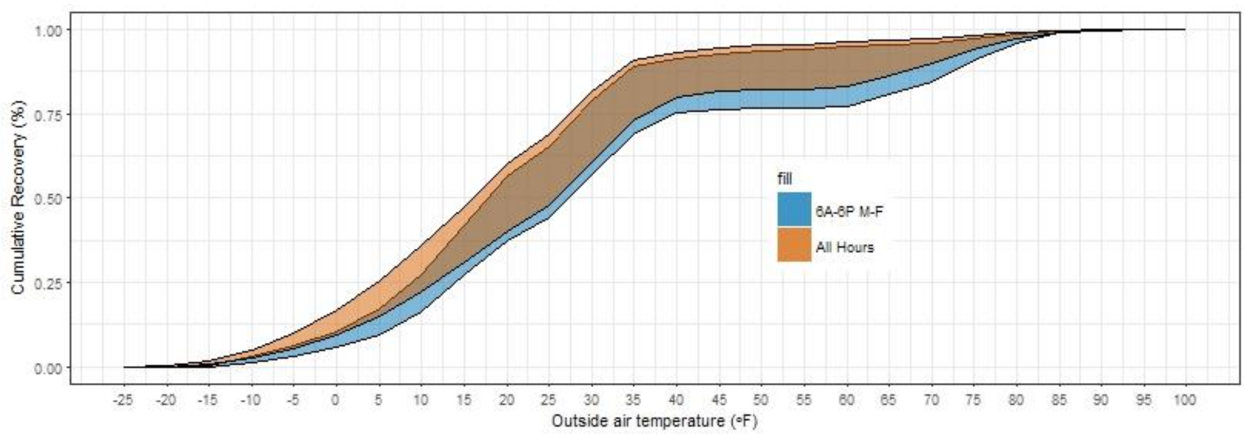


Figure 40: Range of cumulative energy recovery (%) for sites in this study different runtime schedules



In Figure 40 the consequence of the schedule is shown. The TMY3 data with the occupied schedule is compared with all hours. The main difference is the additional energy recovery between -15°F and 10°F due to colder winter temperatures.

These data illustrate two important facts. First, the most important guarantee of energy savings is simple: an ERV must be active in cold to mild weather (0°F to 40°F). Various frost control set points and sequencing choices that impact recovery below about 0°F will not strongly impact cumulative recovery. The same can be said for economizer mode; as long as the unit is disabled between approximately 50°F and 70°F, economizer savings will be achieved.

Issues Encountered with ERV systems

Seventy-five issues varying in both scope and consequence were uncovered while investigating the nine ERVs in this study. These issues are qualitatively categorized and described in this section, and the energy penalties are estimated for a subset of the issues. Many of the reported issues do not directly affect the performance of energy recovery; however, they do impact expectations, perceptions, and unit reliability. Several associated issues, particularly with heating and cooling equipment (set points, schedules, valves), were found during the course of the investigation, but are not included in this tally and are not discussed in this report. However, it is an important reminder that ERV systems are integral components to larger HVAC systems.

A complete list of found issues can be found in Appendix A, and they are discussed below in the context of 11 general categories. These categories and the problem counts are given in Figure 41 and Table 12. Where multiple categorical distinctions were possible, care was taken to consistently categorize problems for the purposes of identifying a root cause and generalizing the results.

Figure 41: General categories of ERV issues

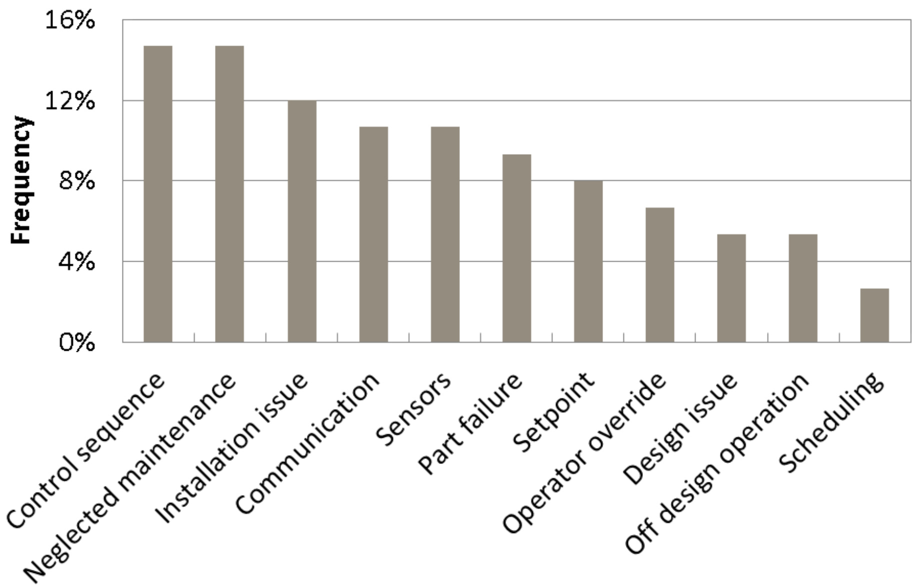


Table 12: General categories of ERV issues

General Category	Count	Frequency
Control sequence	11	15%
Neglected maintenance	11	15%
Installation issue	9	12%
Communication	8	11%
Sensors	8	11%
Part failure	7	9%
Setpoint	6	8%
Operator override	5	7%
Design issue	4	5%
Off design operation	4	5%
Scheduling	2	3%

Control Sequence

Control sequence issues were the most prevalent types of problems encountered at 11, or 15% of the total issues. In these cases, the as-operating control sequences were suboptimal or nonexistent. In four cases there were missing control sequences (e.g. no economizer, frost control, or cooling modes). In four cases, the implemented control sequences were either not behaving as expected or they interfered with other sequences. In one case the control sequence was incomplete. In another case the control sequences depended on two unreliable velocity sensors, which resulted in unexpected behavior. However, these issues generally directly impacted only a specific mode or modes of energy recovery. In most cases there was some energy penalty, but consequences were minor to moderate due to the low ventilation loads during economizer mode and the low operational hours in frost control mode.

Neglected Maintenance

Eleven neglected maintenance items were discovered, representing 15% of the total issues. The majority of these issues were excessively fouled air filters (outside or return air). While the energy consequences are negligible, in two more extreme cases the fouled filters were blown out of the housing, allowing bypass of the filter rack and leading to increased fouling on the ERV and all downstream components. In two cases motor shaft lubrication tubes were broken and continued lubrication resulted in excessive grease build up near sensitive components. In one case, the issue had escalated as the excess grease lead to extreme fouling of fan blades and a velocity sensor that was used for control. While these issues had negligible energy consequences, they can lead to excessive wear or long-term reliability issues.

Installation issue

Nine issues (13%) are believed to have occurred during the installation of the ERVs either by mechanical or control contractors. These issues are more likely the result of decisions or oversights made by staff at the time of installation or programming, possibly due to the lack of appropriate specification from design engineers. Five of these issues were observed at one installation, four of which may be considered gross incompetence and each of which profoundly affected potential recovery. Four issues were related to sensor placement that lead to diminished or suboptimal control. All of these issues had a range of energy impacts varying from minor to severe.

Communication

Eight (11%) of the issues encountered were classified as communication issues. Communication problems include both issues related to the transmission of control signals and incomplete or incorrect BAS representations of the ERV system or its controls. Typically this refers to failures of the BAS to accurately describe and report current operations. These issues did not have direct energy impacts; their main consequence was a negative impact on the expectations among staff. In at least two cases these issues were cited as reasons that ERVs were unreliable systems.

Sensors

Eight (11%) of the issues were related to the sensors that measure parameters used to control the energy recovery unit. Sensors encountered in this project that control ERVs include temperature, humidity, velocity, and static pressure. This section emphasizes sensors that have some obvious malfunction or calibration error. The sensor problems encountered were a faulty duct static pressure sensor, a failed thermal dispersion velocity sensor, an outside air temperature obtained by an error-prone BAS program, and an uncalibrated thermal dispersion sensor. The energy consequences of these sensor malfunctions were generally either indirect or small. Four of these issues were the use of outdoor air sensors (both site-wide and local station) that were not representative of outside air temperature at the ERV inlet. Nonetheless, these issues primarily resulted in suboptimal economizer operation and the energy consequences were small.

Part Failure

Seven (9%) of the issues were failed parts encountered throughout this study. In some cases inspection of ERVs uncovered existing part failures. In other cases, parts failed during the study period or during the post-implementation period. These problems included a torn canvas vibration isolation, a broken mixed air damper actuator, several issues with pneumatic damper linkages, a failed velocity transmitter, a failed wheel VFD, and a leaky heating valve.

Setpoints

Six (8%) instances had to do with suboptimal set points that were off by more than a few degrees, excepting those thought to be intended to override the system. In three of four cases these were conservative frost control set points ranging between 35°F to 45°F. In one case a minimum wheel speed of 20% was specified such that the ERV continued partial operation in economizer mode. In another case, a minimum bypass flow of 20% of air was specified even during periods of peak recovery.

Operator Override

Five (7%) instances were found where operators overrode energy recovery controls using either manual controls or the automation system. Automation system overrides are distinguished from poor set points by the nature of the change. Operator overrides are usually for the purpose of temporarily disabling energy recovery or some other temporary purpose. It is difficult to assess the reasons that parameters were adjusted; in some cases this occurred due to lack information from operators and in other cases it was due to the lack of an audit trail. These very basic changes can have very large energy consequences, among the largest in the study. In two cases these problems were encountered during initial inspection, and it was later discovered they had persisted for years. In two cases these changes were made during the study and persisted until the investigators interfered. In one case the override was observed after the study period when an operator adjusted a frost control value for an unstated purpose.

Design Issue

Four (5%) design issues traced back to the specification, including either lack of or major changes in as-built versus design. The energy consequences ranged from minor to severe depending on the specific issue. In most cases these were design oversights or choices imposed by project limitations; for example, specifying an intake plenum adjacent to the exhaust plenum, specifying equipment that did not fit, or insufficient frost control specification.

Off-Design Operation

Four units (5%) operated at significantly lower flows than designed. When operational flows differed from design flows by greater than 50% they were tallied here. Energy recovery units continue to operate at reduced flows, but fail to recover the energy estimated by rebate or design performance estimates. In other words, they recover less energy because overall loads are less than anticipated. Two units were mixed air units, where ERVs were sized for full flow but never operated beyond a fraction of those design conditions, typically less than 30% of rated flow. One unit was subject to problematic velocity sensor controls and ultimately oversized for the load it served and operated at about 10% to 30%of its design flow. One system had its flow rate adjusted to 50% of the design values by manually fixing fan speeds at the supply and return VFDs.

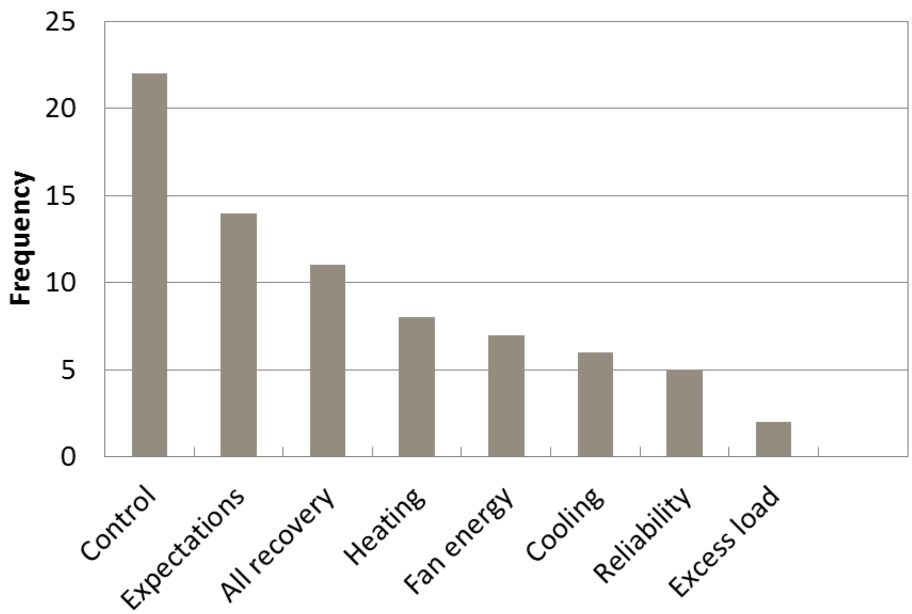
Scheduling

Two wheel (3%) scheduling issues were uncovered. The only scheduling problems encountered in this project were sub-optimal warmup scheduling. Two sites drew in regular outside airflow during morning recovery. Energy recovery systems operated as intended and lowered the ventilation load, yet the ventilation load was unnecessary.

Consequences

The general consequences of the observed issues and their frequency are given in Figure 42. Twenty-two issues diminished control of the units, and the energy consequences varied from minor to severe. Fourteen were related to expectations, usually unrealistic or inaccurate expectations of ERV operation or performance. Issues directly impacting all energy recovery modes equally were the most common (15%), followed by heating-only modes (11%) and cooling-only modes (8%). Fan energy is represented in a minor way due to excessively fouled filters at most sites. Reliability impacts (e.g. lubrication problems and heat exchanger fouling) and excessive ventilation loads (i.e. unneeded ventilation air) were the remaining categories.

Figure 42: Consequences of issues identified during screening and monitoring



Control issues predominate as expected. This includes incomplete or nonexistent sequences, as well as sequences that interfered with other recovery controls or were not properly integrated with operation of other equipment. Limitations in local controllers and automation systems were also cited by controls contractors to explain unorthodox ("work-around") sequences such as timer-based frost control and improper equipment staging. In at least two cases an attempt to fix one control sequence resulted in unintended consequences during other operations. In other cases control was impeded by sensor placement and reliability.

The second category was titled expectations for either establishing unrealistic expectations in the design or installation phases or fostering inaccurate expectations for operation or performance through communication of operations. Issues that contributed to inaccurate or unrealistic expectations were documented to point out a practical weakness in energy recovery systems; these systems remain somewhat mysterious to operators, owners, and technicians. These issues do not directly impact performance or recovery, but they do address the other side of the equation, which is the standard to which ERVs and their performance are held.

In terms of energy recovery performance, the problems encountered in this study can be considered in three broad groups. Overall about one third of the encountered issues had some significant and measurable energy impact. Another one third of the issues had only a minor or insignificant impact because they tended to occur outside the most important operational regimes for energy recovery in Minnesota. The last one third of issues are related to the expectations for energy recovery themselves. While they do not impact energy savings, they may be indirectly responsible for unrealistic expectations, the persistence of other problems, the regard to which critical staff hold ERV systems, and the knowledge staff may have about current and past ERV operations.

Energy Penalties

About one third of the issues (24) encountered in this project were believed to have significant energy impacts. Energy and cost penalties for these issues are tabulated for heating and cooling in Table 13 and Table 14. These estimates are for the additional load passed onto the heating and cooling systems due to energy recovery underperformance. The costs and energy penalties for each ERV often add up to more than the possible recovery, particularly at sites with many overlapping problems.

Twenty-one issues reduced energy recovery during heating season. These issues increased the ventilation load between 16 and 4721 therms and increased operating costs from $13 to $3,857. There were six issues that essentially prohibited energy recovery completely during heating mode, three of which were operator overrides and three of which were gross negligence during installation. Several issues had very minor impacts; in particular, the adjustment of frost control sequences and the adoption of more aggressive frost control set points had very minor impacts on energy recovery. The impacts were minor because operating hours under frost control conditions are low, especially during occupied (daytime) hours. For ERVs that operate at night, frost control settings may have a significantly higher energy impact (although no large impacts were encountered in this study). While it still makes sense to follow manufacturer suggestions and best practices for frost control, these results suggest that there is not a compelling argument to do so from a savings perspective, especially without other motivating factors.

Table 13: Issues with significant heating energy penalties

Tag	Description	Category	Heating Penalty	Heating Cost Penalty	Heating Cost Penalty
			Therm	$	$/cfm
s1i1	Stuck MAD	Part failure	293	239	0.11
s1i2	High EAT lower limit	Operator override	354	289	0.13
s1i3	High MAT lower limit	Operator override	772	631	0.29
s1i4	Very low flow	Off design operation	118	96	0.04
s2i1	Backward bypass control	Installation issue	2,232	1,824	0.21
s2i2	Incomplete bypass sequence	Control sequence	2,232	1,824	0.21
s2i3	Torn canvas	Part failure	1,533	1,252	0.15
s2i4	EAT at purge	Installation issue	240	196	0.02
s2i5	Miswired wheel speed control	Installation issue	2,177	1,779	0.21
s2i6	No heat valve and wheel staging	Installation issue	1,742	1,423	0.17
s3i1	Failed velocity sensor	Sensors	624	510	0.16
s4i1	Discharge 10F below DAT	Setpoint	2,869	2,344	0.05

Tag	Description	Category	Heating Penalty	Heating Cost Penalty	Heating Cost Penalty
s5i1	Reverse damper polarity	Operator override	4,721	3,857	0.30
s5i2	High EAT lower limit	Operator override	4,721	3,857	0.30
s5i4	High EAT lower limit	Setpoint	167	136	0.01
s5i5	Warm up schedule	Scheduling	425	347	0.03
s6i1	High OAT lower limit	Setpoint	27	22	0.00
s6i2	Failed wheel VFD	Part failure	2,452	2,003	0.29
s7i2	OAT based frost control	Control sequence	16	13	0.00
s7i3	Wheel set to 20% bypass	Setpoint	42	34	0.01
		Min	16	13	0.30
		Max	4,721	3,857	0.00
		Average	1,388	1,134	0.14
		Median	698	571	0.14
		Sum	27,756	22,676	-

Sixteen issues increased the ventilation load during cooling season, which resulted in increased ventilation loads of 67 kWh to 5,213 kWh and $7 to $584 additional operating costs in a typical year. The same six issues that prevented heating recovery (operator override and installation negligence) were also responsible for eliminating cooling recovery. Otherwise, issues impacting cooling mode generally had lower energy and cost penalties than heating mode. Similar to frost control, economizer issues had relatively low energy impact.

Table 14: Issues with significant cooling energy penalties

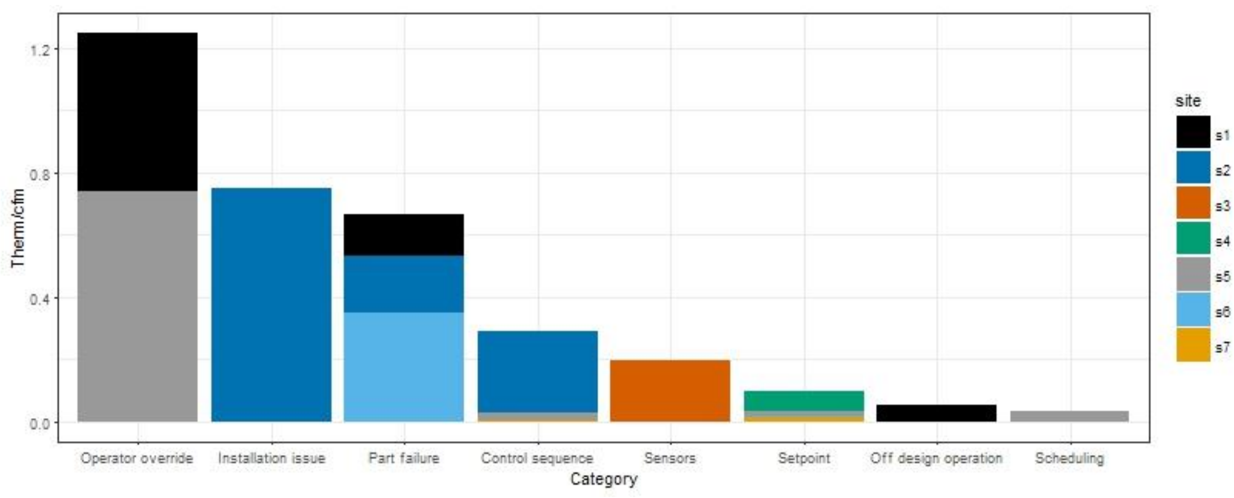
Issue	Description	Category	Cooling Penalty	Cooling Cost Penalty	Cooling Cost Penalty
			kWh	$	$/cfm
s1i1	Stuck MAD	Part failure	302	34	0.02
s1i3	High MAT lower limit	Operator override	511	57	0.03
s1i4	Very low flow	Off design operation	405	45	0.02
s2i1	Backward bypass control	Installation issue	2,056	230	0.03
s2i2	Incomplete bypass sequence	Control sequence	2,056	230	0.03
s2i3	Torn canvas	Part failure	5,213	584	0.07
s2i7	No Cooling sequence	Control sequence	1,955	219	0.03
s3i1	Failed velocity sensor	Sensors	304	34	0.01
s5i1	Reverse damper polarity	Operator override	3,272	367	0.03
s5i2	High EAT lower limit	Operator override	2,837	318	0.02
s5i3	No economizer	Control sequence	3,097	347	0.03
s5i5	Warm up schedule	Scheduling	138	15	0.00
s6i2	Failed wheel VFD	Part failure	1,074	120	0.02

Issue	Description	Category	Cooling Penalty	Cooling Cost Penalty	Cooling Cost Penalty
s6i3	No cooling sequence	Control sequence	553	62	0.01
s7i1	No cooling sequence	Control sequence	141	16	0.01
s7i3	Wheel set to 20% bypass	Setpoint	52	6	0.00
		Min	52	584	0.07
		Max	5,213	6	0.00
		Average	1,498	168	0.02
		Median	813	91	0.02
		Sum	23,963	2,684	-

When treated independently, the total annual costs associated with these issues are $22,934 for heating and $2,684 for cooling. The total of $25,618 is about 50% higher than the additional savings of $17,168 that were found by recommissioning the units. Given that several units (namely s1, s2, and s5) had multiple issues prohibiting operation, this discrepancy seems reasonable.

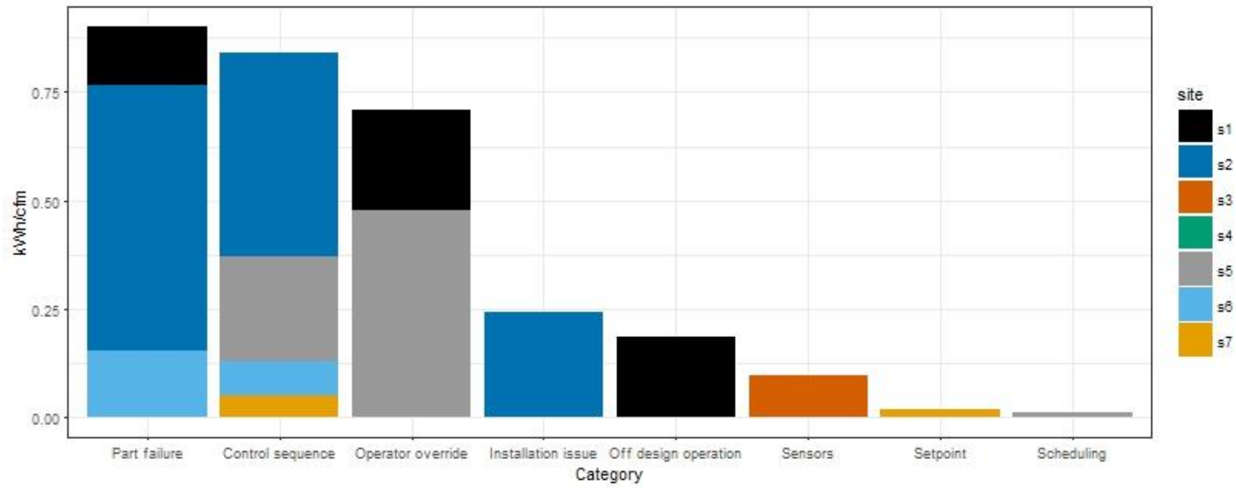
In Figure 43 and Figure 44 the energy penalties are sorted into the general categories discussed previously and normalized against the supply airflow of each recommissioned unit. About three quarters of the total energy penalties encountered in this study occur from issues in three categories that prevent the units from running in heating mode.

Figure 43 Heating energy savings penalty by category and site



The contribution to cooling energy penalties was only slightly different than heating energy penalties due to the absence of cooling sequences on several systems. Otherwise, operator adjustments, installation issues, and failed parts cause the bulk of missed energy recovery. The severity of these mistakes is plain compared to the minor energy penalties associated with sensor placement, sub optimal set points, or scheduling problems.

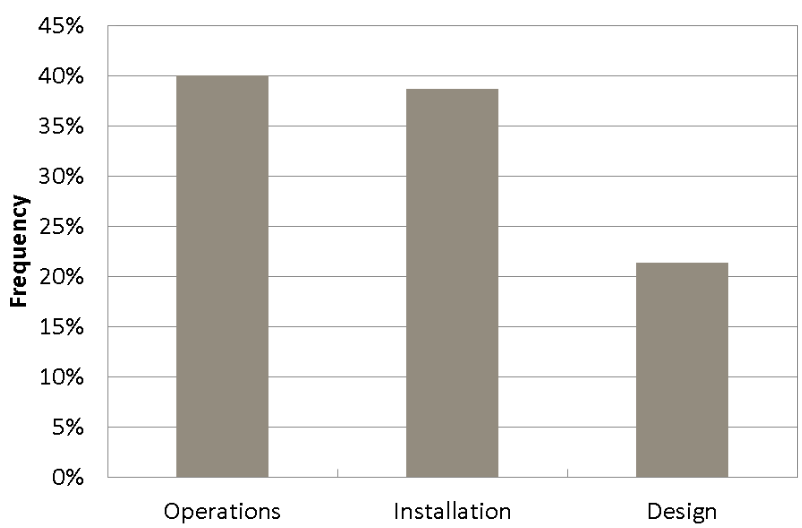
Figure 44: Cooling energy savings penalty by category and site



Energy Recovery Life Cycle

Issues as they occur in the life cycle of an energy recovery system are shown in Figure 45. Four fifths of problems occur after the design stage, during operation and installation (40%and 39%, respectively). Some issues, such as part failures or clear design flaws, can be readily categorized. However, many of the issues are difficult to categorize because either the documentation (including specifications or start-up processes) or the responsible parties are not available for consult. It is also difficult to accurately trace the source of these problems, particularly during the installation, operation, and commissioning of a new project where multiple parties may be involved. That is not to say that this is where correction may occur; for example, installation mistakes may be best avoided through improved design specification and project hand-offs.

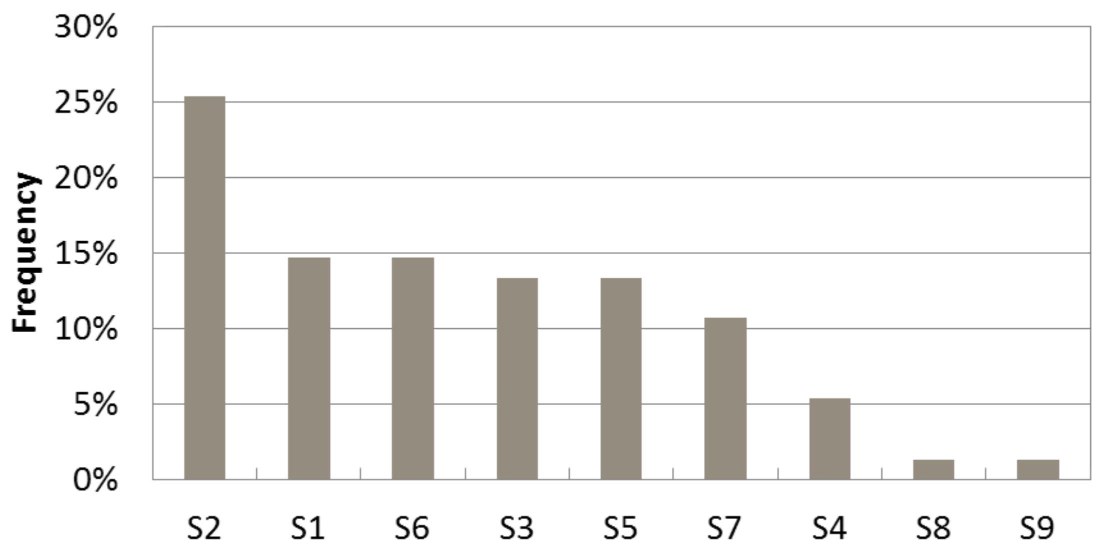
Figure 45: Problems in terms of when they occur in the life cycle.



Issues by Site

Problems varied greatly by site as shown in Figure 46. Two units (s8 and s9) had only one observed issue each. Unit s8 had an irreversible design limitation requiring that some outside air bypass the ERV and unit s9 had fouled filters. These also happened to be the two newest and highest performing units so they had complete and accessible documentation, including start-up and commissioning reports. Unit s4 was fully-functional with three issues, one of which resulted in a moderate energy penalty. While units s1, s3, s5, s6, and s7 had between seven and 11 issues each, typically only one or two problems rendered them inoperable or otherwise significantly reduced energy recovery. A quarter of all problems were discovered on unit s2; several of the 19 issues were systemic problems traced back to its original installation over a decade ago. Installation mistakes essentially prevented the unit from ever recovering energy in its lifespan. These mistakes were compounded by staff that were not trained to recognize the issues and an incomplete controls switchover. These installation mistakes even survived a prior recommissioning effort.

Figure 46: Issues by site



Discussion

Expectations

This project was in part predicated on observations that, in practice, ERV systems were not meeting expectations. Detailed study of several representative units uncovered a litany of problems. The majority of these problems did not have a substantial impact on energy recovery, but about 1/3 of the problems did significantly reduce energy recovery, several of which, completely prohibited energy recovery. While some ERVs may not be working some or all of the time, a significant reoccurring observation in this study is that there are no standard expectations for ERV operations and performance. Many of the mild and relatively inconsequential problems reveal how expectations and opinions of energy recovery systems are established and proliferated. Expectations for energy recovery varied substantially over the individuals encountered in this project. They were largely qualitative and generally resulted from experience operating, maintaining, and installing these systems with incomplete training.

In this section we discuss energy recovery expectations within the context of the results. Several examples are used to highlight how performance and operating expectations themselves are part of the problem.

Operating Expectations

One of the key findings in this project is the absence for clear performance expectations for exhaust air energy recovery systems. This is important because a widely held belief that energy recovery systems are not living up to expectations was the motivating factor in this study. Nonetheless the wide variance of knowledge and interest among stakeholders encountered in this study was in retrospect coincident with the lack of expectations. Low knowledge, mediocre rapport between operators and technicians, and persistent automation system problems tended to add a level of skepticism about energy recovery that impacted their reputation. In most cases owners (facility managers) were significantly influenced by attitudes of the controls contractors and operating staff. It is the case that at least some of the failing to live up to expectations is synonymous with lack of understanding and a general (often earned) skepticism about operations and performance.

Another key finding of this work is that ERV systems tend to go unnoticed. ERVs are not deemed critical components in any of the buildings we visited. That is, in the event of ERV under performance or failure, heating and cooling systems are (over)sized to meet the load. In three of the four units with long standing performance issues, only one operator was generally aware of some kind of problem. However even in that case the concern was not great and there were lingering doubts due to his reoccurring issues with the automation system and its representation of the ERV system. Operator mistrust of automation system details was frequent. However skepticism wasn't usually associated with energy recovery performance, but more on minor issues associated with administering the automation system, HVAC system, and associated equipment. Even contractors' disparaging remarks about the efficacy of specific equipment seemed to lend justification to existing attitudes about troublesome systems.

Design Conditions

Based on the units encountered in this study, ERVs are usually specified at design conditions, whereby energy recovery rates and the impact on associated heating and cooling systems are determined. Designs are typically specified at balanced flow conditions without purge or exhaust air transfer specifications. The design information produces estimates for the effectiveness (sensible and latent) at winter and summer design conditions. These effectiveness values and possibly the discharge air properties at the design points are the only point of comparison by which an ERV could be evaluated in practice without extensive calculations. Yet, an as-operated effectiveness may be higher or lower than a design value and has little bearing on energy savings.

Effectiveness at design conditions is not the right metric by which to field-evaluate an ERV. First of all design conditions, or even conditions near them, are very rare by definition. Secondly effectiveness is a difficult parameter to measure. Building automation systems are not equipped to estimate effectiveness within useful uncertainty. In-situ measurements of effectiveness are difficult and subject to large uncertainty even under specialized study. Lastly there is little doubt that an energy recovery system, when operated as specified at design, will achieve its rated effectiveness, but that isn't ultimately that important with respect to the real-world situations encountered in this project.

In this study as-operated energy recovery was impacted by off-design operation (unbalanced flows), purge and exhaust air transfer values, sensor placement and control, scheduling, building characteristics, set points, and sequencing for economizing and frost control. None of these, possibly with the exception of the flow rate variations impacts effectiveness. That said, many of the energy consequences were minor. Despite the performance variations caused by all these details, units in this study, particularly in heating season, used little power to significantly reduce the ventilation load. The main energy penalties occurred because the energy recovery system was disabled due to a simple and easily correctable mistake. Thus, the most important thing to ensure is that the ERV is activated an approximately the right times.

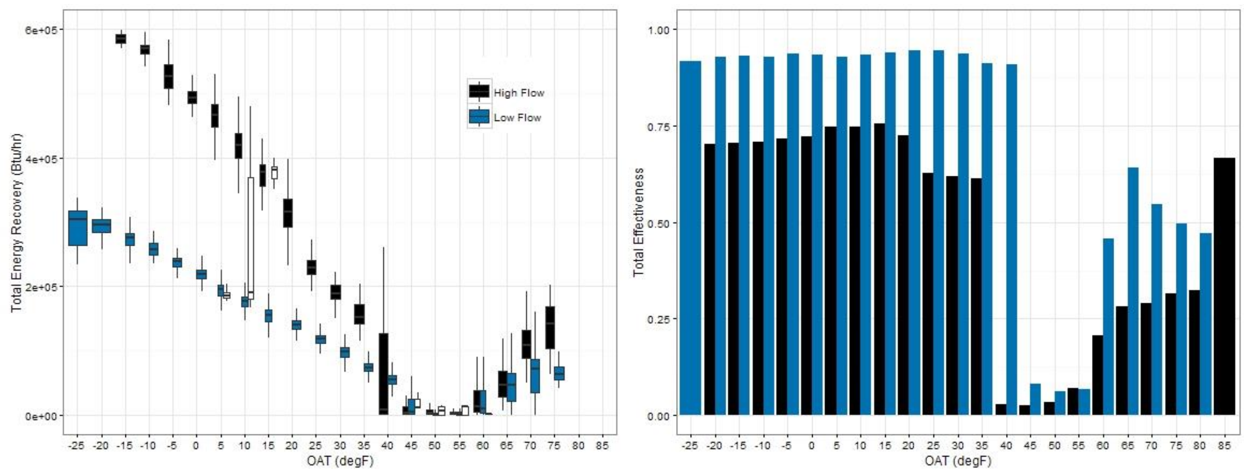
In causes one to step back and realize the resources to fully characterize ERV operation especially in a retrofit situation are probably neither available nor cost-effective. As-operated performance will likely deviate from simple-design representations (e.g absent energy modeling). Hence practical guidelines are to accurately specify the ventilation load, bring back as much exhaust as possible, make sure the ERV is commissioned, and ensure familiarity of operating staff.

Effectiveness

As a reminder the effectiveness is the ratio of the actual energy transfer compared to the physical maximum energy transfer. The "effectiveness at design condition" is the most common performance parameter, but it is an incomplete expression for energy recovery savings as illustrated in Figure 47. In this figure, the energy recovery rate (Btu/hr) and the effectiveness is shown for unit s8 at two operating conditions. This unit operates at design conditions (high flow) during regular occupied hours. Off-hours, the unit continues to operate at lower flow rates and the ratio between the flow rates is unbalanced in favor of the supply side.

It is immediately apparent that the unit has a substantially higher effectiveness during the low-flow period, yet the net-recovered energy is about half. Hence the effectiveness is not by itself a very useful parameter. In most cases, effectiveness will go up when flow rates are slowed, while the energy recovery rate will go down.

Figure 47: Energy recovery rate (Btu/hr) and effectiveness at balanced and unbalanced flows for s8



Rebate Driven Performance Expectations

While rebating methodologies and savings calculations were not cited by any staff encountered in this project, they play a key role in establishing expectations for energy recovery performance because they estimate total recovery rather than design condition performance. Typically ERV savings are calculated at design including flowrates, effectiveness, and outside air conditions at summer and winter design conditions. The savings are then scaled based on a representation of the load (such as degree days).

Heating savings calculations including a rebate calculation, a few calculations based on Minnesota TRM v2.1, the model from this report, and measured savings, are compared in Figure 48. In the Minnesota Technical Reference Manual (TRM v2.1), energy savings are limited to heating savings and peak load reduction, which are consistent with the findings of this study and prior work. The calculations are explained below.

- Design Rebate: This savings figure was obtained from a rebate form for the unit. It was calculated based on the design documentation. It included purge air and an assumption of balanced flow condition at the outside air flow rate.
- TRM v2.1: Savings were calculated using the TRM calculation using the design information where possible, including a balanced flow assumption at the outside air flow rate.
- TRM v2.1 (no frost penalty): The frost control penalty (25%) was removed from the TRM calculation, resulting in 25% higher savings.
- TRM v2.1 (default): The TRM calculation was repeated with the default values.
- TRM v2.1 (corrected): The TRM (no frost penalty) calculation was adjusted for the unbalanced flow condition by using the smaller of the two flow rates (return air).

- Design CEE Model: The savings were calculated from the design data and a model to adjust the effectiveness and energy savings rate for the unbalanced flow condition.
- Measured (initial): The measured savings prior to recommissioning the unit
- Measured (final): The measured savings after recommissioning the unit.

There are several differences revealed by the calculations. First of all, the largest discrepancies are due to the flow rate assumptions. The TRM and rebate calculations assume balanced flow conditions, equal to outside air flow rate, which leads to a savings estimate that is high by nearly a factor of two. The adjusted TRM calculation and the Design CEE model consider that exhaust flow is about 45% less than supply flow and that supply flow is reduced by about 9% from outside flow due to purge air. In practice, the maximum potential energy recovery is constrained by the lower flow rate and reduced accordingly.

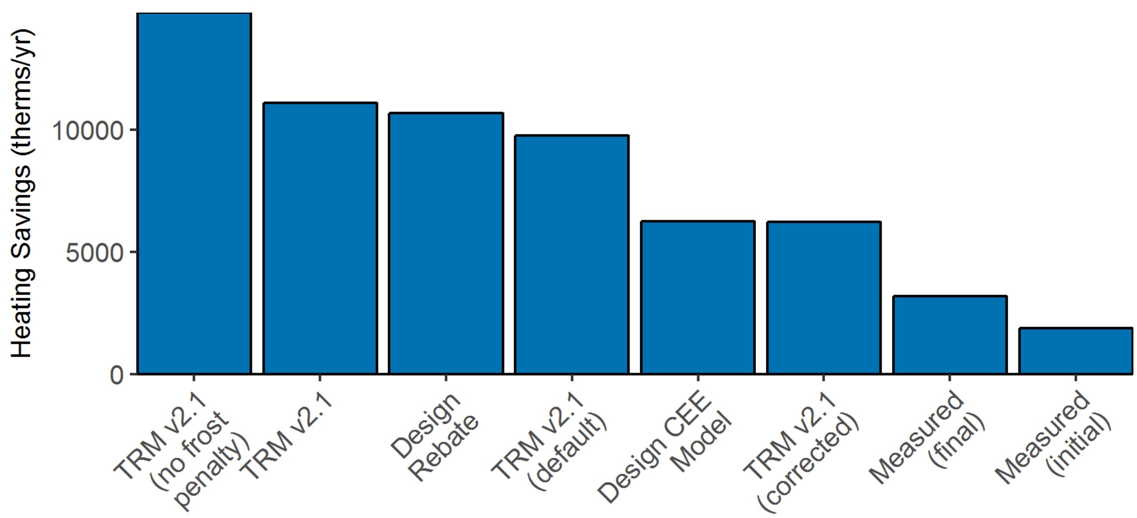
The measured savings values are based on as-operated flow rates which are substantially less than the design flow rates, resulting in even lower energy recovery rates. Thus, the accuracy of flow rates, particularly the lower of the flow rates (usually exhaust) is paramount for estimating energy savings. This effect may be even more exaggerated in mixed-air units where ERVs are rated for 3 to 5 times more airflow than they receive under normal outside air fractions.

The remaining differences play a smaller role.

- The assumption that frost control reduces energy recovery by 25% in the TRM calculation leads to an *underestimate* of energy savings with respect to the rebate, model, and measured savings estimates by about ~22%. Based on results in this study, the TRM frost control assumption is very conservative.
- The TRM calculation is based on the total effectiveness and the enthalpy difference between outside air and return air. About 30% of this enthalpy difference is due to the latent energy difference or the potential for humidification of outside air. However the TRM calculation expressly neglects savings from decreased humidification load. Thus, the enthalpy-based method *overestimates* sensible energy savings by about 30%.
- The choice of effectiveness represents some difference between the models as well. The rebate and model methods use sensible effectiveness (0.936), TRM calculations use total effectiveness (0.866), and the default value for the TRM method is (0.647). The first two values will lead to errors when applied in a balanced flow calculation because they are from unbalanced flow design documentation. The default wheel total effectiveness will tend to *underestimate* savings because it is low compared to AHRI certified values of enthalpy wheels encountered in this study.

These calculations show that the key detail in estimating savings is to get accurate as-operated flow rates, including unbalanced conditions and purge values. In practice this means understanding both design figures as well as final, as-operated values. The TRM method contains various differences with respect to the other calculations, but they mainly cancel each other out to produce adequate savings estimates.

Figure 48: Heating energy saving estimates according to several calculations



Stakeholder Analysis

This project uncovered a large set of diverse issues that occur throughout design, installation, and operational stages of energy recovery units and hence involve many different parties. Experience has shown that energy recovery is commonly misunderstood at all stages and these misunderstandings are exacerbated during the transition of responsibilities, particularly in the absence of rigorous documentation and a strong hand-off process. Furthermore when energy recovery is not functioning correctly, there is often no direct impact on operations or occupants other than higher energy use. In these situations performance issues may persist for long periods and dramatically effect lifetime energy savings.

Stakeholders of Energy Recovery Systems

In this section the relationships between the stakeholders involved in the different stages of ERV life were analyzed on a subset of issues. This analysis was based on observational data collected throughout the project. At each of the study sites, anywhere from six to eight stakeholders were identified. Each stakeholder is described in Table 15. The role each stakeholder plays depends on the stage of the project. Thus, we identify the stakeholders as they are involved in three stages of ERV life. We consider three stages of the energy recovery system, design, installation, and operations. Building occupants, while stakeholders in the design, installation and operation of overall building HVAC systems, are not considered stakeholders in this matter as ERVs have no direct impacts to occupant health or comfort. As a result, they are not listed in Table 15.

Table 15: Stakeholders in energy recovery

Stakeholder	Description	Design	Install	Operation
Air Handler Manufacturer	May or may not be distinct from the ERV manufacturer	X		
Commissioning (Cx) Agent	Owner advocate overseeing commissioning on the system during startup		X	
Contractor	The control, mechanical, and electrical contractors who install and service units. Includes technicians and engineers.		X	X
Recommissioning (EBCx) Agent	Existing building agent if an RCx study was done.		X	
Equipment Distributor	Sales representative, coordinates between manufacturers & engineers, may assist design and startup.	X	X	
ERV manufacturer	Provides unit; establishes control and installation best practices	X		
Independent Energy Professional (inc. ESCO)	Individual or group hired to address targeted inquiries, or assist with energy upgrades or retrofits.		X	X
Operator(s)	Staff responsible for ERV & HVAC operations & maintenance			X
Owner	Building owner or representative, such as facilities manager	X	X	X
Project Engineer	Provides engineering design and specification, may include general contractor, mechanical and electrical engineers.	X	X	X

The building owner is the only stakeholder guaranteed to have a role in every stage of the process. The owner's influence over the outcome is dependent on how involved they are at each stage. This stakeholder has the power to ensure knowledge transfer between groups and influence the quality of work through setting requirements and checking in throughout the project stages. This is unsurprising, as in energy management, the most successful energy management policies and programs have the support of top management (Capehart, 2016). This is an essential point for energy recovery systems, which are strictly energy efficiency systems. Owners also hold responsibility for the training and hiring of the building operators, who interact most often with the ERV and therefore can arguably have the strongest influence over proper ERV operation.

The project engineer has a key role in system design and installation. Depending on the particular project contract, they may also have a role in the operation of the system for some period of time. However, continued involvement through the operational phase of a site does not necessarily mean that the project engineer is accountable for or will proactively address issues, especially if issues point toward their prior mistakes or lapses.

Contractors have a role in both the installation and operation of the system. They should know the history of the unit, and while they do not influence the design of the system, they do have the influence to ensure the system is operating properly. Contractors have the responsibility to hold the project engineer accountable for complete specifications. Specifically it is not their job to complete incomplete specifications or interpret vague or incomplete control intent. Arguably as the eventual service provider, they should seek justification for any lapse or deviation from manufacturer specifications. Conversely contractors need to be held accountable for implementing those expectations.

The remaining stakeholders involved in energy recovery play a role in just one stage of the project. These include ERV and HVAC manufacturers, equipment distributors, energy professionals, and Cx/EBCx providers. These remaining stakeholders have an expert role in either energy recovery or energy management. Due to their limited involvement and expertise, it is essential to have a strong process for transitioning their contributions forward.

Examining Stakeholder Influence

Each of the identified stakeholders can contribute to a problem or its solution. The next step in this process is to look at a subset of system failures and the root causes of failures. As discussed earlier, amongst the nine ERVs in this study, a total of 75 issues were uncovered that impacted expectations, operations, and in many cases energy savings of the units. These 75 issues were separated into 11 general categories as described previously. They are summarized here in in Table 16.

Table 16: General categories (themes) of issues encountered during the study

Issue category	Description
Control sequence	Related to or caused by the programmed control sequences for the ERV unit
Installation issue	Errors or oversights made during installation, e.g. bad wiring, poorly located sensor
Neglected maintenance	Maintenance that should have been addressed by building staff, that has gone unaddressed
Communication	Poor BAS communication to the operator. For example, the graphic does not accurately represent the system, or control points are mislabeled
Design issue	Issues from the design stage, e.g. adjacent exhaust and outdoor air intakes
Operator override	A temporary or specific override by an operator that disables the system, e.g. unit disabled by set point changes to frost or economizer control
Part failure	A part that has failed over the normal course of operations, e.g. failed wheel VFD
Off design operation	Operation of the unit is (significantly) off design estimates
Sensors	Sensor issue outside regular uncertainty, e.g. sensor out of calibration
Set point	A poorly chosen set point, e.g. overly conservative frost prevention
Scheduling	Suboptimal scheduling of HVAC/ERV systems, e.g. ventilation during unoccupied recovery

As shown in Table 17, the top three issue categories, control sequence, neglected maintenance, and installation issues, make up almost 41% of all the issues found during the study. Of these 31 issues, most of them occur during the installation stage, and as a result should have been detected during a commissioning or recommissioning process. Of the 75 issues identified, over 90% are correctable once identified. The only issues that were not correctable were related to the design phase of the project, which after installation, cannot be cost-effectively addressed

Table 17: Observed issues by category and implementation phase

Category	Count	Design	Installation	Operations	Correctable
Control sequence	11	5	5	1	11
Neglected maintenance	11	0	0	11	11
Installation issue	9	1	7	1	9
Communication	8	0	8	0	8
Sensors	8	2	4	2	8
Part failure	7	0	0	7	7
Set point	6	0	3	3	6
Operator override	5	0	0	5	5
Design issue	4	4	0	0	1
Off design operation	4	4	0	0	0
Scheduling	2	0	2	0	2
Total	75	16	29	30	68

Six issues, summarized in Table 18, were selected to reflect the diversity of issues encountered. Each of these distinct issues strongly impacted the actual, perceived, or expected energy recovery performance. It is important to note that five of the six issues occur during either the installation or operations phase, indicating that these issues are correctable or could have been caught through proper commissioning and recommissioning processes. A closer look at these issues identifies which stakeholders have the most influence over preventing these issues from occurring, and what the major impacts are to ERV expectations.

Table 18: Six ERV issues and their impact on ERV expectation

Issue Category	Phase	Detailed Description	Impact on ERV expectation
Operator Override	Operations	Mixed air temperature lower limit set to 100 °F	Recovery reduced 100% (disabled)
Installation Issue	Installation	ERU dampers controlled backwards	Recovery reduced 100% (disabled)
Part Failure	Operations	Broken mixed air damper, actuator stuck open	Recovery reduced by approx. 40%
Communication	Installation	BAS Screen wheel graphic doesn't represent wheel status	Negative influence on operator expectations
Control Sequence	Installation	Poor heating valve and heat wheel staging	Heating recovery reduced by 80%
Off Design Operation	Design	Operation very far off design flows	Unrealistic recovery expectations

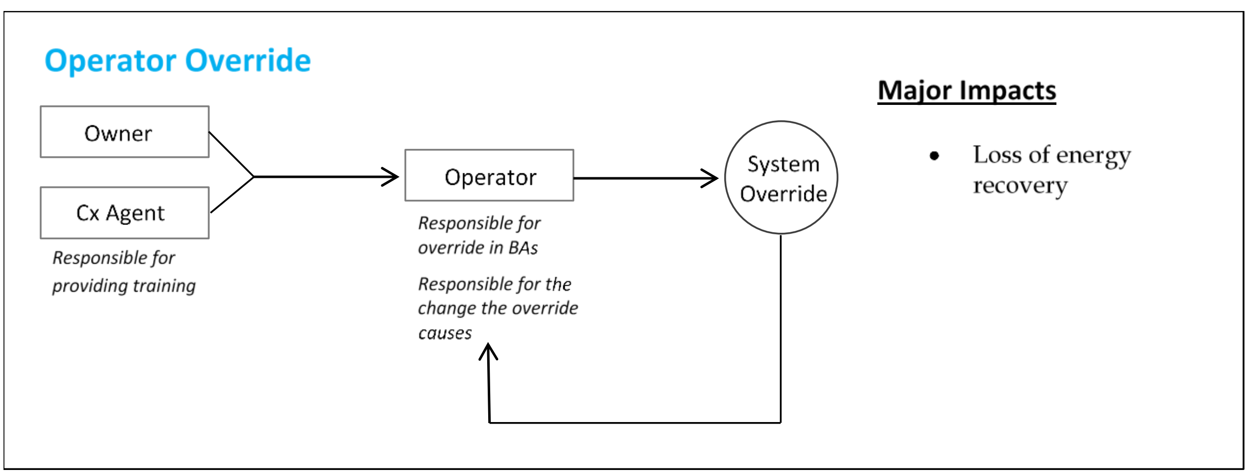
Operational Issues

Operator overrides were responsible for the largest impacts on energy recovery operation, especially those that effectively disable the unit under normal operating conditions. In this case, the mixed air temperature lower limit was set to 100 °F for unknown reasons. Intended as a coil freeze prevention, this set point persisted for some time and overrode both calls for outside air and energy recovery. The influence of the stakeholders over this issue is outlined in Figure 49.

The building operator holds the primary responsibility for this issue. An operator can casually override the system through the BAS or through physical manipulation of controls. If the operator is misinformed about the consequences of the override, or forgets to return the override to its proper state, loss of energy recovery will occur in the system. Because it requires a properly trained operator to identify reasonable set points and damper positions for the various stages of ERV operation, the building owner and the commissioning agent are secondarily responsible for this issue. ASHRAE guidelines for commissioning new and existing buildings state that the Cx or EBCx agents are responsible for training operators and maintenance personnel (ANSI/ASHRAE/IES Standard 202-2013; ASHRAE Guidline 0.2-2015). Owners should ensure that this training was completed, and after the commissioning process is complete, future training falls to the responsibility of the owner to ensure operations staff can properly operate and maintain systems.

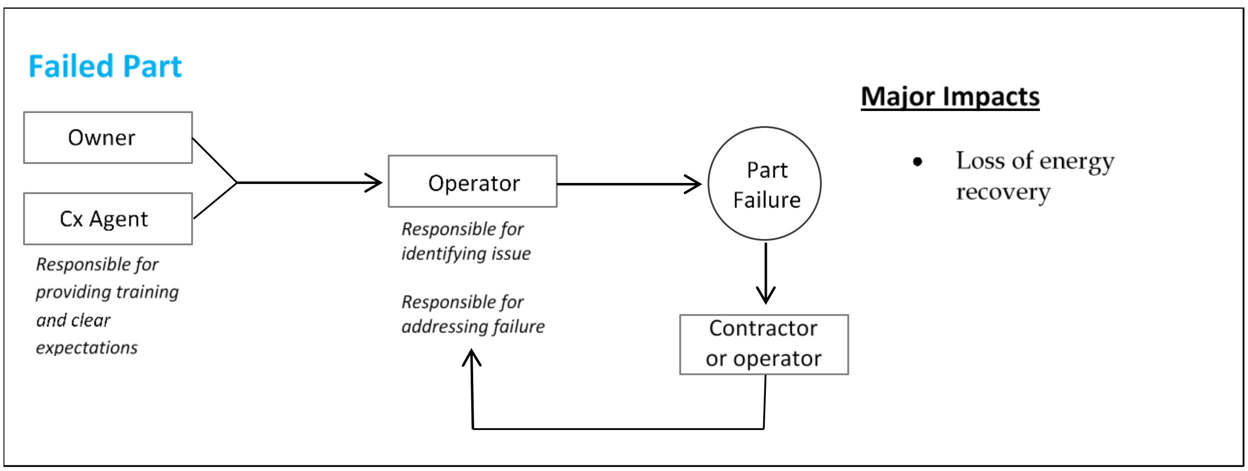
In this particular scenario, when the mixed air damper lower limit was set to 100 °F, the energy recovery wheel was disabled for months. This issue wasn't deemed important because due to a compilation of other issues, the operator had low confidence in the energy recovery system and did not have a strong understanding of its purpose. In other cases in this project, where an operator override disabled energy recovery, the conditions persisted for months or years. In one case, the override was dutifully implemented manually on a daily basis for an indeterminate amount of time. To avoid these situations it is crucial that staff be trained on these systems and their controls; otherwise such lapses will exist until identified by a third party.

Figure 49: Stakeholder influence over operator override



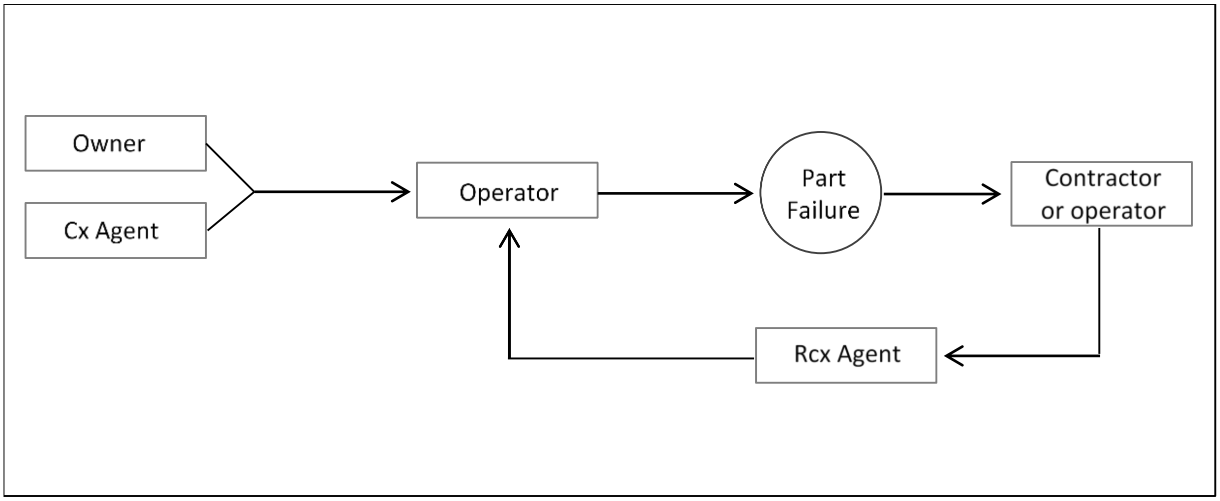
In examining the ERV part failure scenario, the operator is identified as the primary stakeholder responsible for this issue. The operator must identify the issue and take action to recover. Depending on the failed part, the operator may be able to fix the issue, or may need to call in a contractor. In the latter case, the contractor also holds a shared primary responsibility, as they are being paid to fix an issue. However, after the part has been fixed, either by an operator or a contractor, the operator must be able to determine if the part has indeed been fixed or if the issue persists. For the operator to be able to identify the failed part and proper recovery, he or she must have been properly trained to identify the issue have established procedures or processes to follow for recovery. Therefore, as outlined in Figure 50, both the building owner and the commissioning agent are secondarily responsible for the issue. The major impact in this study was that failed parts prohibited energy recovery. This situation was unique in that the operator had long since identified the broken actuator, but did not prioritize its replacement because of his long standing impression that the energy recovery system was not working due to a misleading BAS graphic. While recovery from this failure was impeded by a BAS communication issue causing further confusion (this issue described in further detail under *Installation Issues* below), the situation still reinforces the need for standard operating procedures and energy recovery training. Had a process been in place for the operator to bring up or address the issues, including the fact that he thought the ERV was not functioning properly in the first place, it might have been corrected prior to this project.

Figure 50: Stakeholder influence over failed parts



For operational issues, the common themes are 1) the operator is primarily responsible for any issues, and 2) the owner and Cx agent are secondarily responsible. The operator must have proper training and clear expectations and understanding of the ERV system to address operational issues. However, it is the role of the owner and Cx agent to provide those expectations, training and standard operating procedures. Currently, with primary responsibility, the operator acts as a sounding board for ERV operations. If proper training cannot be provided to ensure the operator is a quality sounding board, able to detect and address operational issues, one solution is for the owner to instate regular recommissioning of the unit or solicit the service of an independent energy professional. Bringing in a qualified professional should ensure these issues are identified and addressed. In this case there is a shared responsibility between the owner and independent agent to communicate the findings to the operator to avoid the issue in the future. Figure 51 inserts the independent agent (in these influence diagrams the RCx agent) in a position where they would identify and correct any operational issues such as broken parts or system overrides. If occurring regularly, this relieves the operator from having to identify and correct these issues and adds an additional layer of assurance of proper system operation.

Figure 51: Third party (Rcx provider) influence over operational issues

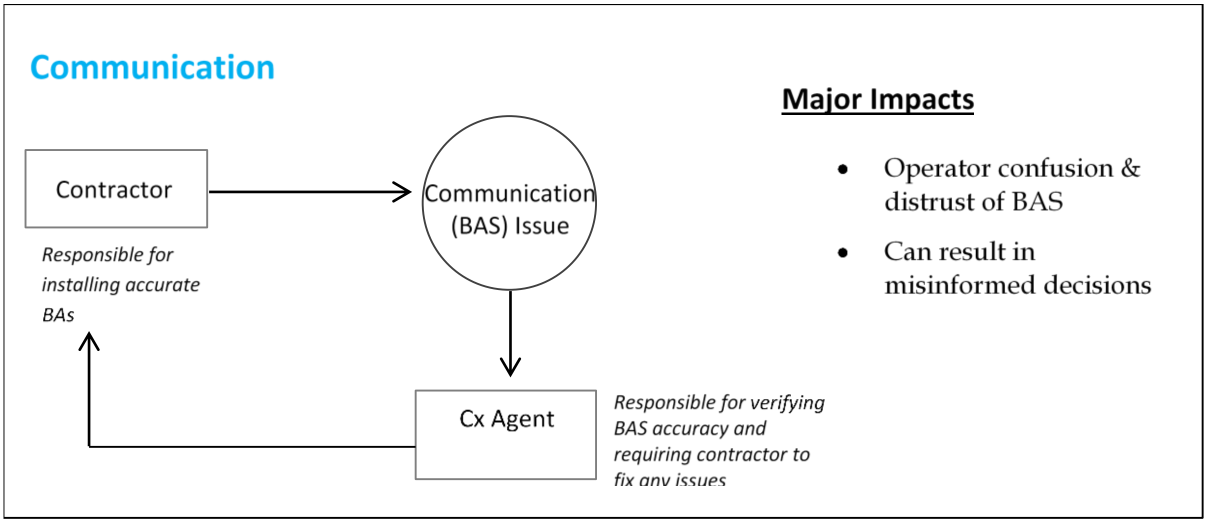


Installation Issues

The building automation interface is the most frequent point of contact between an operator and energy recovery and HVAC systems. Sloppy or incomplete front end interfaces can mislead operators and cause them to distrust both the automation system and underlying equipment. In this example, an incomplete building automation system (BAS) front end signaled an ERV to be in a perpetual state of alarm despite normal operation. While this issue might not result in the loss of energy recovery, it can impact the operator's ability to properly operate the system. This can result in misinformed decision making, operator confusion, and distrust of the BAS – all of which could lead to the operator taking an action that could impact energy recovery. For operators who do not have energy recovery training, poor building automation interfaces further exacerbates the issue. This was often the scenario in this project, leading to a false understanding of energy recovery and further confusion of correct or expected ERV operations.

Figure 52 identifies two stakeholders with influence over BAS communications, the contractor installing/maintaining the BAS, and the commissioning agent responsible for verifying accuracy of the system. While the contractor is being paid to install the BAS, the commissioning agent is primarily responsibility for identifying BAS issues that might occur. In this situation, the errant alarming of the ERV on the automation system was cited by the operator as evidence that energy recovery did not work and was unreliable. In fact, the recovery system was generally reliable; the issue was a broken graphic on the automation display. This simple problem eroded the operator's confidence in the energy recovery system and inevitably caused the operator to neglect a critical part failure (damper actuator – described above) for a long time because his impression was the system didn't function anyway. For operators that are primarily concerned with making customers happy, the loss of energy recovery is of no consequence. If energy training and energy goals are not available, ERVs are dead capital.

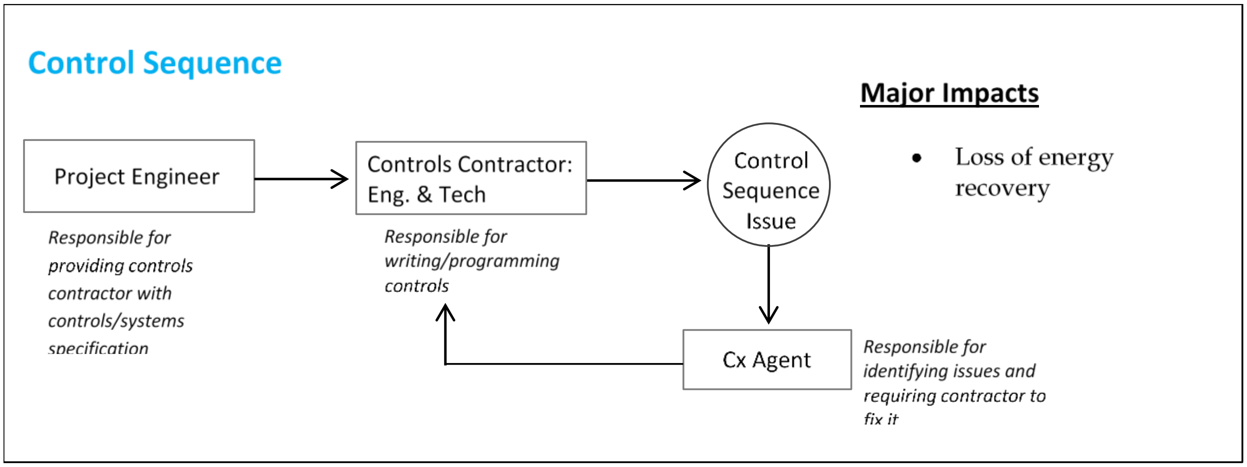
Figure 52: Stakeholder influence over BAS communications issue



Another influence diagram is shown in Figure 53 where, during installation, control sequences are poorly implemented. However, in this scenario, the project engineer assumes some of the secondary responsibility along with the controls contractor, as the project engineer provides the specification for the controls during the design phase. During the design phase, the project engineer is responsible for providing manufacturer recommended control sequences or justifying any deviation from manufacturer instructions. Consequently, contractors need to hold project engineers accountable for sufficiently detailed control intent; it is not their job to tease out the true intent of a vaguely described or repurposed sequences.

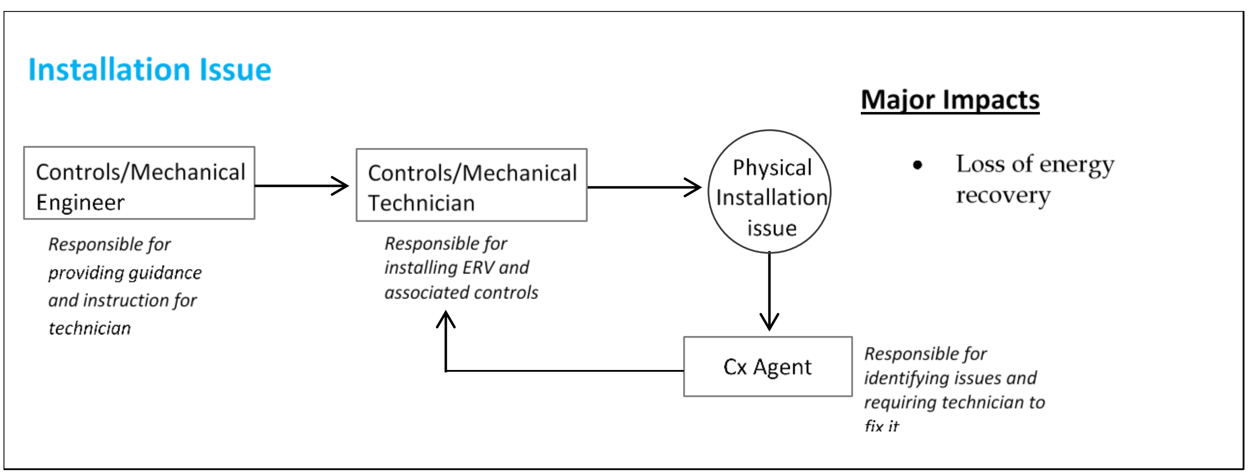
Despite there being two stakeholders holding secondary responsibility, the commissioning agent still holds primary responsibility for the issue. They must identify the error in the control sequence and require the contractor to fix the issue before leaving the system in the hands of the operator. In this example, a single discharge temperature was used to control both an enthalpy wheel and a heating valve. The sequence was implemented in a way that favored the heating valve, such that each time the sequence was initiated, the heating valve would open up to meet the load and cause the enthalpy wheel to spin down. Consequently energy recovery during heating mode was virtually eliminated in favor of direct heating.

Figure 53: Stakeholder influence over system control sequence issue



Physical installation issues can also result in a significant loss of energy recovery. In this particular example, the controls for the ERU dampers were wired backwards, preventing the ERV supply air from reaching downstream air handlers during recovery mode, effectively disabling the unit. Parties responsible for this issue are laid out in Figure 54. While the controls/electrical technician is to blame for physically installing the wiring incorrectly, it is the commissioning agent that holds primary responsibility. Part of the Cx agent's role is to identify this issue, require the technician to fix it, and verify the fix was implemented. In this example, the system was not commissioned and obviously lacked even a basic start up process. Coupled with some other issues, the energy recovery unit had failed to operate its entire 13 year life and managed to persist through at least one EBCx program.

Figure 54: Stakeholder influence over physical installation issues

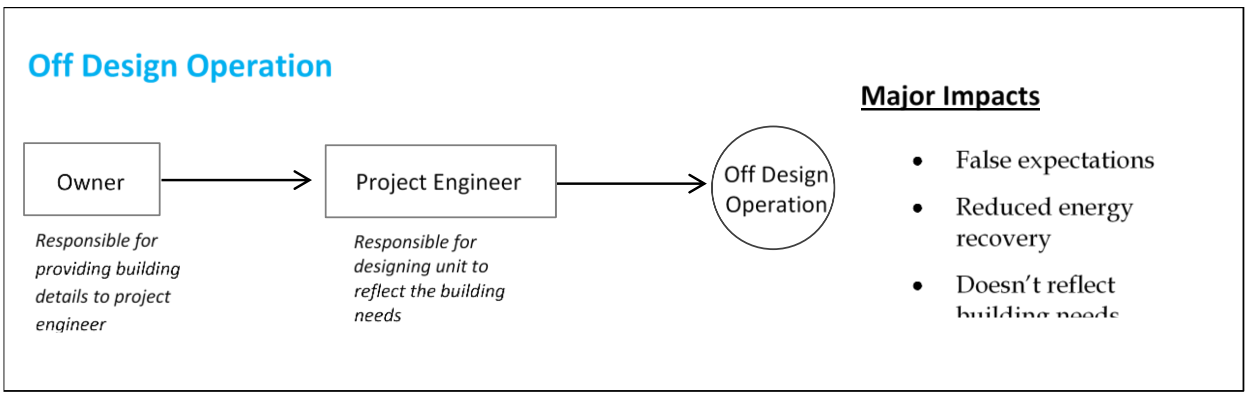


These three examples of installation issues all show that while the contractor is the stakeholder commonly responsible for causing ERV installation issues, it is the Cx agent who is ultimately responsible – the last line of defense to ensure proper operation before handing the unit over to building staff to operate. The Cx agent is responsible for representing the interests of the building and holding the contractor/engineer accountable for their work. This demonstrates the important of the role commissioning has in building systems, particularly systems like ERVs, where poor operation does not (usually) impact comfort. Without a Cx agent, the building owner becomes responsible for holding the contractor and project engineer accountable. Building owners encountered in this project generally did not have the time, knowledge or capability to carry out this task.

Design Issues

The only design stage issue treated here is off design operation. While the building owner is responsible for providing the project engineer with building details or requirements, the project engineer holds primary responsibility for designing a unit that reflects the building needs (Figure 55). When a unit operates off design (reduced flow), it will not meet anticipated energy recovery rates. In this case, the unit operated at about 30% of design flow. Any performance reference based off design figures (including rebated energy savings), grossly overestimate the achievable energy savings of the unit. Subsequently it is the duty of the Cx agent or balancing firm to inform building owners and engineers when exhaust or supply flows deviate strongly from design figures so that the issue can be corrected (in the case of insufficient ventilation air) or in the case that the deviations are acceptable, performance expectations reexamined.

Figure 55: Off design operation



Throughout the course of this project, it was observed that several stakeholders are involved in the ERV life cycle, with a majority of stakeholders having expertise but only limited involvement. This makes it essential to have strong processes in place for transitioning between design, installation, and operation to ensure ERVs meet expectations. We observed that operators and owners are often uninformed of energy recovery processes and expectations. Without auditing processes or documentation in place to identify errant system changes, issues can go unaddressed for months or even years. Because there are several stakeholders involved, responsibility for various issues is decentralized, adding to the potential for the issues to go unaddressed. With a decentralization of responsibility, stakeholders must hold each other responsible for their assigned tasks. For example, contractors must hold project engineers responsible for incomplete or conflicting specifications and Cx agents must hold contractors responsible for poor installation practices.

Analysis of stakeholder influence over the performance of ERVs through an examination of six issues demonstrated a need for:

1) Operator training on energy recovery OR an energy professional specifically tasked to oversee energy performance and identify operational issues
2) Commissioning agent, representing the building owner, to commission ERV systems to identify installation issues and hold contractors/engineers accountable for their work
3) Increased diligence on the part of project engineers during the design phase to make complete specifications

The decision to provide operator training, hire an independent energy professional, or require project commissioning ultimately falls on the building owner. It is not a coincidence that the best performing systems in this study came from units in buildings with ongoing relationships between owners, project engineers, and commissioning agents. The worst performing projects did not have these strong (or in some case any) relationships. While this stakeholder analysis was able to identify the influence stakeholders have over ERV performance and highlight three key needs to improve ERV performance, further work is necessary to broadly address these needs; work on other related topics demonstrates these issues are not unique to ERV systems.

Conclusions and Recommendations

Over the last 20 years, air-to-air exhaust energy recovery systems have become more common in Minnesota commercial and institutional buildings because of their potential for cost-effective energy efficiency benefits. Evolving energy code is expected to increase requirements for energy recovery in the future. While ERVs are in fact capable of achieving impressive savings of up to 80% of the ventilation air heating load, anecdotal evidence suggested they may not live up to their potential. The goal of this project was to assess whether ERVs are meeting their expectations and if not, why.

Existing data sources on exhaust air-to-air energy recovery systems in Minnesota commercial and institutional buildings were reviewed. Energy recovery systems in Minnesota buildings are predominately small systems (75%), but most of the flow (and energy savings potential) is provided by a minority of large units (<25%), over 10,000 cfm. Enthalpy wheels make up 80% of units, plate heat exchanges 13%, and membrane units 7%. To date, ERVs have mainly been implemented in institutional buildings (predominately K-12 and higher education). Energy recovery tends to be found in commercial buildings that have above average ventilation loads including casinos, manufacturing and auto shops, assisted living facilities, labs, and sports and gym facilities.

Nine energy recovery units were studied in depth. Of these systems three were highly functional, three were adequately functional, and three systems were initially non-functional. Seventy five issues were uncovered over the monitoring period. Forty of these issues were corrected resulting in nine operational units, all achieving cost-effective energy savings. Additional savings of about $17,000 were found, predominately from four units.

Despite the relatively large number of findings, only 24 of the issues were deemed to have significant energy penalties. The issues uncovered were categorized in a variety of different ways. Issues stemming from the installation and operation are responsible for most lost energy recovery opportunity. Part failures, operator overrides, and installation mistakes account for 75% of the lost energy recovery. Issues impacted heating savings between 16 and 4721 therms per unit and increased operating costs from $13 to $3,857 for a typical year. Issues reduced cooling savings between 67 kWh and increased operating costs by 5,213 kWh and $7 to $584 in a typical year. These mistakes persist due to unfamiliarity among operations staff and controls technicians as well as the absence of system feedback from poorly functioning ERVs.

The remaining problems either had minor energy consequences or contributed to negative perceptions of ERVs and related systems. Negative expectations develop and proliferate due to negative experiences with ERVs and associated systems. These experiences and perceptions generally have little to do with the energy efficiency performance, but instead the typical processes involved with implementing the technology. Nonetheless, these attitudes do impact how the systems are operated, maintained, and repaired in the event of a problem.

Despite the wide variety and large number of issues encountered, most of them can be easily identified and corrected. Most of the issues encountered in this study would be avoided by commissioning new units. Those issues that develop during the operational stage are easily identified by operators who know when energy recovery should occur and can evaluate if energy recovery systems are active. A practical manual on ERV operations and a short validation manual were created to fill in some of the knowledge gaps identified throughout this project and instruct staff when to expect energy recovery and how to validate it.

The performance of recommissioned ERVs was determined according to the percentage of the heating and cooling load served by the unit as well as the average recovery energy ratio (RER) for heating and cooling operation. ERVs in this project serve between 34% and 90% of the heating ventilation load, while recovering heating energy (RER_h) at between 17 and 39 times the electrical energy they require to operate. ERVs met between 9% and 23% of the cooling load with average cooling RER_c ranging from 10 to 22 Btu/W-hr. Generally the cooling load is met by the economizer about half the time, which effectively halves the average RER_c for systems without bypass. These performance metrics reinforce the notion that energy recovery in a Minnesota climate is about heating energy savings and peak cooling load reduction.

CIP Recommendations

Commissioning New Systems

Reviewing the issues encountered in this project as well as the stakeholder relationships around these issues demonstrates a strong need for commissioning new energy recovery systems. Without the ability to measure performance and the difficulty posed in recognizing performance problems, systems have to be installed and verified from the start. Therefore, commissioning efforts must take place on new units, particularly rebated units, to ensure quality installation by licensed contractors and that installation does not diminish savings. Similarly, the commissioning process must include some hand-off and training such that operators understand and can operate the recovery systems to achieve expected savings.

Some general commissioning guidelines:

1) Large ERV systems (10,000 cfm+) must be commissioned. They are fewer in number, but comprise most of the expected energy savings from energy recovery in Minnesota. They are large capital investments and missed energy recovery is devastating on payback and assumed energy savings.
2) Design flow rates (and subsequent savings estimates) need to be validated against as-operated flows.
3) Control sequences should follow ERV manufacturer recommendations or deviations need to be justified by project engineers
4) Both control intent and detailed sequences need to be specified; as-implemented sequences either verified or-signed off by an accountable party
5) Commissioning agents need to provide basic operator training to explain controls, warn about overriding controls, and offer guidance on when and how to verify ERV operation.

Improving Existing Systems

The majority of energy penalties in this project can be avoided if energy recovery systems are touched by staff that are capable of assessing whether an ERV is "basically" functional and to assess the risk that controls pose for overriding ERV system. The most costly ERV mistakes are casual manipulation of controls by uninformed operators. These changes go unnoticed for two primary reasons, 1) understanding of ERVs by operating staff is exceptionally weak and the sensitivity of ERV operations to control changes is not appreciated, and 2) there is no performance monitoring, the consequences of a disabled or severely malfunctioning ERV will go unnoticed, particularly if heating and cooling systems are sized to meet building loads without energy recovery.

However touching an ERV system does not necessarily require a full recommissioning effort. Tools such as CSBR Energy Efficient Operations offer simplified instruction for how staff can assess the basic operation of an ERV system. For example, as was shown in plots of cumulative energy recovery, about 60 - 80% of energy recovery will be achieved if a system is operating between 0 °F and 45 °F. A simple procedure to verify that an ERV is spinning or not in bypass in this temperature regime is a strong indicator that an ERV system is achieving a majority of its savings. Extending this simple process to validate frost controls, mixed air settings, and economizer settings against reasonable values would help communicate to staff the importance of not overriding these controls while also limiting their persistence.

The remaining 20% of ERV energy savings requires significant more time or resources and may require engineering attention; however these issues are also likely to only affect a subset of ERV operations and thus have less consequential impacts on overall savings.

Outreach

Lack of understanding of energy recovery systems is a persistent problem among building owners, operators, and contractors. Manufacturers and perhaps to a somewhat lesser extent, design engineers have a firm grasp of how these units should be specified and operated. Commissioning agents who start-up these systems understand how to verify their operation against specification. There are significant gaps that have prevented this knowledge from permeating to building owners, operators and control contractors. There seems to be ample opportunity for operator and building owner on energy recovery training.

Targeted Recommendations

Design Engineers need to provide more rigorous specifications with regard to the control of energy recovery systems. This includes full-specification of sensor locations and control sequences. For situations where as-operating sequences deviate from manufacturer recommendations (best practices), designers need to offer a full justification of these choices. An exception can be made for the "simplification," of controls from differential control to fixed comparison control or from enthalpy control to dry bulb control. In these situations, the manufacturer best-practices for frost control, economizer allowance, and overheat prevention should be preserved.

Mechanical and controls contractors need to follow engineer specifications and push-back against engineers that do not sufficiently specify sensor placement and control sequences. Control technicians should push back when clarity is required to interpret engineering specifications or design intent. Technicians should not bear the burden of making significant decisions on sensing and control. These are best specified at the manufacturer level or justified in detail when deviations made.

Commissioning agents (other transitional, knowledgeable parties) need to ensure knowledge transfer about system intent (including control) as well as design-based expectations for ERV performance. Whereby as-operated conditions differ significantly from as-designed conditions, variances need to be documented and communicated to building staff (including owners & operators) in order to establish appropriate performance expectations. Project engineers and commissioning agents should also be responsible for communicating upstream changes in as-operated performance (e.g. strong deviations in design flow, changes due to make up air) so that claimed savings are accurate (for CIP accuracy and an emphasis on improving accuracy of design estimates). Commissioning agents need to flag incomplete automation systems and systems that are overly complex, offer unnecessary control, and do not facilitate ERV operations and understanding from the perspective of future operators. Particularly, frost control is an often abused control; after commissioning the appropriate manufacturer sequence and sensor installation, there is no need for operations staff to adjust frost control!

Owners need to provide resources for operators to understand systems they are in charge of and motivate operators on preventative maintenance, specifically with respect to filters and lubrication. Owners hold the responsibility of training operators on ERV operations. Of 9 systems in this study, 2/9 had 'filter blow out' caused by excessively fouled filters, and 2/9 systems had careless lubrication in one case resulting in sensor failure. Beyond basic maintenance, buildings owners must ensure operators understand basic ERV operations throughout all seasons. It is critical to give operators a sufficient understanding such that they can 1) expect when an ERV should operate (based on specific controls), and 2) recognize when ERV systems are not operating as expected. Owners should establish protocols (aka CSBR) and ensure that operators are able to perform annual or semi-annual operational checks on ERV systems as they would heating and cooling equipment. Lastly, owners need to communicate the importance of ERV systems for energy and cost. Owners and control technicians need to ensure that operators have sufficient training to understand the consequences of ERV controls to prevent casual yet highly consequential meddling with control parameters.

Rebates and Energy Savings

Savings and rebating techniques for utilities have been refined over the past several years, but have settled upon reasonably methods that, when based on reasonable inputs (e.g. accurate flows and realistic performance metrics) provide a sufficiently accurate estimate of energy savings. Nonetheless design information is not a reliable way to estimate savings from energy recovery. Five of nine units in this study operated at flow rates well below design figures, consequently reducing potential energy savings by a similar amount. ERVs, particularly those that are rebated or used to meet CIP goals, need to go through a basic validation process to either ensure design flows are accurate or reassess savings under realistic flow conditions. This validation should be part of a basic commissioning in order to validate design estimates (particularly with flow and flow ratios) as well as demonstrate that basic sequencing allows ERVs to operate, particularly in cold to mild weather. This is also necessary such that appropriate savings are sent back upstream and properly allocated in CIP totals.

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Appendix A: Complete list of issues

Table 19: List of issues identified during screening and monitoring

Site	Tag	General Category	Issue Description	Phase	Fixed
s1	s1i1	Part failure	Mixed air damper actuator stuck in open position	Operations	Y
s1	s1i2	Operator override	Exhaust air lower limit set to 54F	Operations	Y
s1	s1i3	Operator override	Mixed air damper lower limit set to 100F	Operations	Y
s1	s1i4	Off design operation	Operation off design flow	Design	N
s1	s1i5	Design issue	Poor air handler fan configuration (draw-through blow through)	Design	N
s1	s1i6	Design issue	Exhaust plenum adjacent to outdoor air intake	Design	N
s1	s1i7	Installation issue	Poorly located velocity sensor array	Design	N
s1	s1i8	Sensors	Outside air temperature from weather service doesn't match intake temp	Design	N
s1	s1i9	Communication	BAS screen wheel graphic doesn't represent wheel status	Installation	Y
s1	s1i10	Communication	Economizer indicator doesn't represent economizer status	Installation	Y
s1	s1i11	Neglected maintenance	Heavily fouled outdoor air filters	Operations	Y
s2	s2i1	Installation issue	Bypass dampers controlled backwards	Installation	Y
s2	s2i2	Control sequence	Bypass damper control sequences not completed	Installation	Y
s2	s2i3	Part failure	Torn canvas in supply fan vibration damper	Operations	Y
s2	s2i4	Installation issue	Exhaust air temperature sensor located at purge	Installation	Y
s2	s2i5	Installation issue	Heating valve and wheel speed signal wires crossed	Installation	Y
s2	s2i6	Control sequence	Poor heating valve and heat wheel staging	Installation	Y
s2	s2i7	Control sequence	No cooling sequence	Design	Y
s2	s2i8	Part failure	Broken pneumatic actuator	Operations	P
s2	s2i9	Part failure	Broken actuator linkage	Operations	Y

Site	Tag	General Category	Issue Description	Phase	Fixed
s2	s2i10	Installation issue	Exhaust and supply fan vfd signal wires crossed	Installation	Y
s2	s2i11	Sensors	Outside air temperature from weather service doesn't match intake temp	Design	Y
s2	s2i12	Sensors	Uncalibrated outside airflow sensors (4)	Installation	N
s2	s2i13	Sensors	Dust static pressure bias by 0.48 in. w.c.	Operations	Y
s2	s2i14	Installation issue	ERU damper signal wires crossed	Installation	Y
s2	s2i15	Operator override	Economizer upper limit set to 100F	Operations	Y
s2	s2i16	Communication	BAS gives no indication of economizing or cooling functionality	Installation	Y
s2	s2i17	Communication	Incomplete BAS control screen	Installation	Y
s2	s2i18	Neglected maintenance	Return air filters heavily fouled	Operations	Y
s2	s2i19	Setpoint	Frost control lower limit set for frost prevention (35F)	Operations	Y
s3	s3i1	Sensors	Failed velocity sensor	Operations	Y
s3	s3i2	Installation issue	Contractor implementation of odor control sequence overrides wheel modulation sequence	Operations	Y
s3	s3i3	Part failure	Failed velocity transmitter	Operations	N
s3	s3i4	Part failure	Leaking heating valve	Operations	P
s3	s3i5	Control sequence	Control sequences require 2 sets of velocity sensors	Design	N
s3	s3i6	Neglected maintenance	Heavily fouled velocity sensor	Operations	Y
s3	s3i7	Scheduling	Warm-up scheduling: OA open & ERV running	Installation	Y
s3	s3i8	Off design operation	Operation off design flows	Design	N
s3	s3i9	Control sequence	Odor problems	Operations	N
s3	s3i10	Neglected maintenance	Broken lubrication tube	Operations	N
s4	s4i1	Set point	ERV discharge temperature set 10F below supply discharge temperature	Installation	Y
s4	s4i2	Neglected maintenance	Outdoor air filters heavily fouled	Operations	Y
s4	s4i3	Design issue	Absent frost control, wheel stopped and partially contributed to a coil freeze	Design	Y
s4	s4i4	Neglected maintenance	One blown out OA filter	Operations	Y

Site	Tag	General Category	Issue Description	Phase	Fixed
s5	s5i1	Operator override	Damper actuator polarity (direction) swapped	Operations	Y
s5	s5i2	Operator override	Frost control lower limit set to 80F	Operations	Y
s5	s5i3	Control sequence	No functioning economizer mode	Installation	Y
s5	s5i4	Setpoint	Frost control lower limit set too high 45F	Operations	Y
s5	s5i5	Scheduling	Warm-up scheduling: OA open & ERV running	Installation	Y
s5	s5i6	Installation issue	Exhaust air temperature sensor located very far downstream	Installation	N
s5	s5i7	Installation issue	Supply air temperature sensor located very far downstream	Installation	N
s5	s5i8	Off design operation	Operation very far off design flows	Design	N
s5	s5i9	Neglected maintenance	Outdoor air filters heavily fouled	Operations	Y
s5	s5i10	Neglected maintenance	Two blown out OA filters	Operations	N
s6	s6i1	Setpoint	Frost control setpoint 35F OAT	Operations	Y
s6	s6i2	Control sequence	No cooling mode	Design	P
s6	s6i3	Part failure	Wheel VFD failed	Operations	P
s6	s6i4	Sensors	Site-wide OAT sensor	Installation	N
s6	s6i5	Sensors	Unreliable OAT sensor	Installation	N
s6	s6i6	Setpoint	Minimum wheel speed setpoint 20%	Installation	P
s6	s6i7	Communication	Mislabeled control points	Installation	P
s6	s6i8	Communication	Status point not updated on BAS	Installation	N
s6	s6i9	Neglected maintenance	Outdoor air filters heavily fouled	Operations	P
s6	s6i10	Control sequence	Outside air temperature based frost control	Installation	P
s6	s6i11	Neglected maintenance	Broken motor shaft bearing lubrication tube	Operations	N
s7	s7i1	Control sequence	No cooling mode	Design	P
s7	s7i2	Control sequence	Outside air temperature based frost control (10F)	Installation	P
s7	s7i3	Setpoint	Wheel set to 20% bypass	Installation	Y
s7	s7i4	Control sequence	Unreliable OAT sensor	Design	N
s7	s7i5	Sensors	Site-wide OAT sensor	Installation	N
s7	s7i6	Off design operation	Operation very far off design flows	Design	N
s7	s7i7	Communication	Mislabeled control points	Installation	P
s7	s7i8	Communication	Misleading BAS graphics	Installation	P

Site	Tag	General Category	Issue Description	Phase	Fixed
s8	s8i1	Design issue	Auxiliary outside airflow bypasses energy recovery (up to 50% flow)	Design	N
s9	s9i1	Neglected maintenance	Outdoor air filters heavily fouled	Operations	Y

Appendix B: ERV screening form

ERV Screening Visit Form

Date of Site Visit:

Attendees:

General Site Information			
Site Name			
Site Address			
Site Representative			
Chief Engineer/Building Operator			
General Building Information			
Square Footage			
Year(s) Constructed			
Number of Floors			
Space Types and % Usage			
Utility Information			
Electric Utility			Annual Use: kWh
Natural Gas Utility			Annual Use: Therms
Other Utility			Annual Use: (units)
EUI (kBtu/sqft)			
Utility Data Available?	Gas	Electric	

Staff Interview

Question	Response
Specific ERV opportunities or issues identified by staff	
Most common occupant complaints or concerns related to spaces served by ERV system	
Significant ERV efficiency upgrades or modifications in the last few years	
Planned ERV upgrades for next few years	
Expectations of the research project (timeline, updates/communication, reporting, implementing CEE recommendations, etc)	

Documentation (Y or N)

Sequences of Operation		TAB Reports	
Control Drawings		Commissioning Report	
Mechanical Plans		Energy Study	

Mechanical Equipment

Energy Recovery Equipment					
Equipment Tag	**Equipment Type** (wheel, plate, etc)	**Manufacturer**	**Model Number**	**AHU Served**	**Notes**

Air Handling Equipment				
Equipment Tag	**Equipment Type** (AHU, RTU, etc)	**Approximate Capacity**	**Areas Served**	**Notes**

Air Handling Equipment				

Cooling Equipment (Chillers, Cooling Towers, DX Units, Pumps, etc)

Heating Equipment (Steam Boilers, HW Boilers, Pumps, etc)

Controls System

Type (DDC, pneumatic, t'stats)	
Equipment served by each type	

List any equipment not monitored/controlled by DDC	
BAS manufacturer / make / system model	
BAS front end software	
Year of most recent front end software update	
Controls Contractor	Name: Phone Number: Email:
Is remote access available?	
Is the BAS capable of trending?	

Building/Equipment Schedules

Occupancy Schedule (e.g. M-F, 6am-7pm)	
Equipment Schedule	
Do hours vary by season?	
Equipment that operates outside of schedule above	