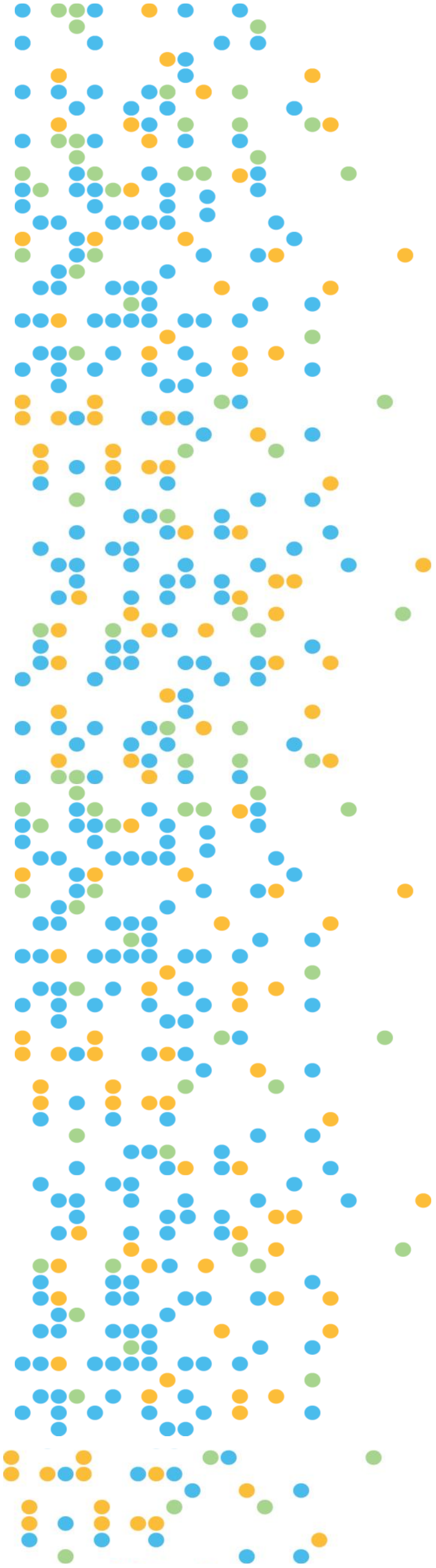

ENERGY RECOVERY IN MINNESOTA:

Practical Guide to ERV Operations

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INTRODUCTION

Are commercial and institutional energy recovery ventilation systems (ERVs) meeting performance expectations? A recent research project[1] funded by the Minnesota Department of Commerce sought to answer this question. The project was proposed because of a growing body of anecdotal evidence suggesting that, in practice, ERV systems are failing to live up to their expectations. The study compiled prior work on ERV system performance, commonly encountered problems, and subsequently field-tested nine representative ERV systems operating in Minnesota. This short guide was developed from these research findings.

ERV units are unique in that their problems are easily masked by heating and cooling systems. This guide focuses on practical details of ERVs such that operations and performance expectations can be developed by the staff that interact with these systems. Theoretical background on energy recovery and other technical considerations are available from other sources[2]. The aim of this document is to guide the operator/owner through the operation of common exhaust air-to-air energy recovery systems in institutional and commercial buildings in Minnesota based on up to date research results. Specific values and examples are referenced from recent work to add perspective, but temperatures, percentages, and operational details will vary with each ERV implementation.

INDOOR COMFORT: VENTILATION, TEMPERATURE, AND HUMIDITY

Indoor Comfort

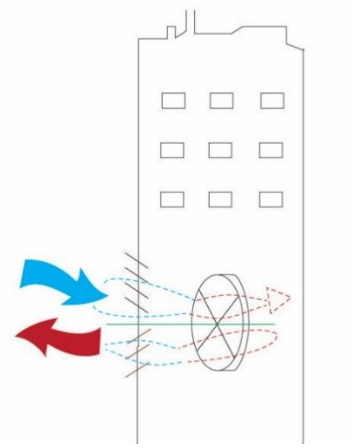
Occupant comfort in buildings is important for health, productivity, and well-being. Adequate fresh air (ventilation flow rate) is necessary to maintain indoor air quality while temperature and humidity levels are maintained to satisfy occupants. Incoming ventilation air displaces existing air which is discarded as exhaust air. Energy is used by heating or cooling coils in traditional HVAC systems to condition incoming ventilation air. Meanwhile the energy embodied in the exhaust air is discarded, which yields a savings opportunity.

Energy Recovery: Key Takeaways

- ERVs reduce heating and cooling energy, operating costs, and initial capital costs by using outgoing exhaust air to pre-condition incoming fresh air.
- ERVs transfer both heat (temperature change) and moisture (humidity change) in any direction necessary to save energy.
- Energy savings depend on the relative amount of exhaust and ventilation flow. The lower flow rate stream dictates maximum energy savings.
- Energy recovery is subordinate to ventilation needs; ventilation air flow should not be increased to improve energy recovery.

Energy recovery ventilation (ERVs) systems transfer energy between the exhaust air and the ventilation air streams to reduce the energy necessary to condition ventilation air. ERVs can transfer both heat (temperature change) and moisture (humidity change) in the direction necessary to minimize load. Thus, throughout all seasons ERVs can save energy. One exception occurs when the outdoor air is at such conditions that it can be directly used to meet the cooling load (i.e. free cooling or economizing mode). Over 80% of commercial and institutional C&I energy recovery systems in Minnesota use a total energy wheel, which are rotating discs that transfer both temperature and humidity. Fixed plate heat exchangers (13%) are also found and they usually only transfer heat. Other ERV types are rare, but many principles discussed here still apply.

Figure 1. Air-to-air exhaust recovery ventilation systems (ERVs) transfer energy between the exhaust (relief) air and the ventilation (outside) air streams in whichever direction lowers the ventilation load.



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[1] Quinnell J.A., (2017) *Energy Recovery in Minnesota Commercial and Institutional Buildings, (To be Published).*

[2] ASHRAE. (2016) *HVAC Applications and Systems.* Chapter 26, Air-to-Air Energy Recovery Equipment

Ventilation Adds Building Load

Ventilation air is typically introduced through one or more mechanical air handler systems, which use fan energy to move the air. These systems also use energy to condition the air to maintain thermal comfort. For ventilation air to enter, exhaust air must leave. Typically air is exhausted through central exhaust (relief) systems and multiple point exhaust systems (e.g. restrooms).

Building Pressurization and Infiltration

For maximum energy recovery all exhaust air should pass through the ERV system to recover energy. In practice, ERVs compete with other building airflow needs. Point exhausts are used to evacuate restrooms or kitchens; it is uncommon that these exhaust streams are centralized through an ERV. Infiltration and exfiltration (air movement small gaps and cracks in the building envelope) also result in air bypassing energy recovery systems.

Why do flow rates matter?

Energy savings from ERVs depend on the amount of air in both streams (exhaust and ventilation). The most energy that can be recovered is equal to the smallest flow rate times the difference between inside temperature and outside temperature (or enthalpy).

Air Stream Classification

Air streams are classified based on contaminants.

Class 1: Low contaminants, inoffensive (e.g. office space).
Class 2: Moderate contaminants, mildly offensive odors (e.g. lavatory)
Class 3 & 4: Significant or harmful contaminants

ERV systems mostly operate in class 1 air streams. With some restrictions, class 2 and class 3 air streams can be incorporated, but this is not common and outside the scope of this document.

Care should be exercised such that design flows closely estimate as-operated flows. ERVs that operate below design flow rates will not reach energy savings expectations based on design flow rates. On the other hand, energy recovery is subordinate to ventilation needs; ventilation air flow should not be increased to improve energy recovery.

Understanding Flow Rates

Figure 2. Balanced flows: Temperature and humidity changes of each flow stream are about the same.

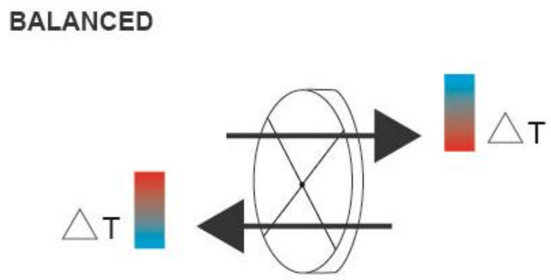
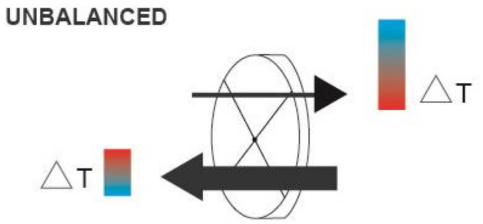


Figure 3. Unbalanced flows: Larger temperature and humidity changes occur in the lower flow rate stream. Smaller changes occur in the higher flow rate stream.



Unbalanced Conditions

When supply is greater than exhaust: The largest temperature/humidity changes occur in exhaust stream and the unit may not meet ASHRAE 90.1-2010 performance requirement (somewhat common).

When exhaust is greater than supply: The largest temperature/humidity changes occur in the supply stream (uncommon – may indicate exhaust deficiencies elsewhere).

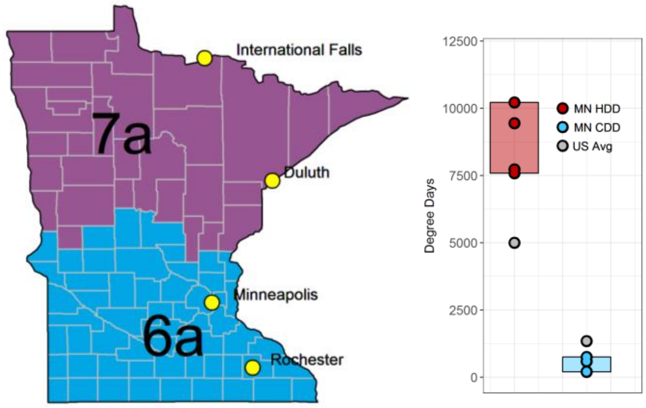
Purge and Air Leakage

Wheel-based ERV systems are not air tight. In fact they usually purge some outside air directly into the exhaust to reduce the amount of exhaust air transferred back into the supply flow. Generally air leakage and the purge flow rate are low (e.g. <10%), but it is important they be accounted for in operations. ERV capacities reference both supply and outside airflow, which creates some ambiguity about true ventilation flows. This is frequently complicated by design documentation, which may not include purge flows. While purge flows are typically low; they can be proportionately large at low flow rates near design pressures.

MINNESOTA CLIMATE SPECIFIC CONSIDERATIONS

Total energy savings opportunities depend on average climate conditions. Minnesota is contained by climate zones 6 and 7 (cold and very cold). These climate zones are defined by a high heating load (7,500 – 11,000 HDD) and a low-to-moderate cooling load (0 – 1,500 CDD). The long, cold, and dry heating season in Minnesota provides the majority of the opportunity for energy recovery. The short and somewhat humid cooling season allows some cooling savings opportunity, but ERVs are best for reducing the peak cooling load, resulting in potential for cooling system downsizing and reduced first costs.

Figure 4. Minnesota is contained within climate zones 6 and 7 (cold and very cold). These climate zones are defined by a high heating load (7,500 – 11,000 HDD) and a low-to-moderate cooling load (0 – 1,500 CDD).



Energy Recovery Priorities

Energy recovery priorities follow the opportunity for energy savings. The priority for MN energy recovery systems is to remain active during cold weather. About half of all energy recovery will take place between 12ºF and 45ºF. Based on recently studied units, somewhere between 60% and 80% of all energy recovery occurs between 0ºF and 45ºF. Below 25ºF, ERVs meet the heating load in cooperation with the heating system. At very cold temperatures, some precaution (frost control) may be necessary depending on the system and conditions (Section 4). At moderately cold temperatures but below the balance point (25ºF to 35ºF +), ERVs may meet the entire heating load and require controls that prevent overheating ventilation air.

Between the balance point and the indoor conditions (~55ºF to 75ºF), energy recovery systems are usually inactive. At these temperatures ventilation air can be used directly for free cooling (economizer function). ERVs operating during this period yield an energy penalty. ERV systems must be inactive for maximum economizer savings.

When outside conditions approximately exceed desired indoor conditions (~75ºF) energy recovery is fully active. The ERV preconditions the outside air and reduces the load seen by the cooling system. At cooling design conditions, ERV systems reduce the load on the cooling system by as much as 30% to 70%.

Figure 5. In Minnesota, ERVs mainly recover temperature in the winter and reduce humidity in the summer. They remain inactive during economizer operation.

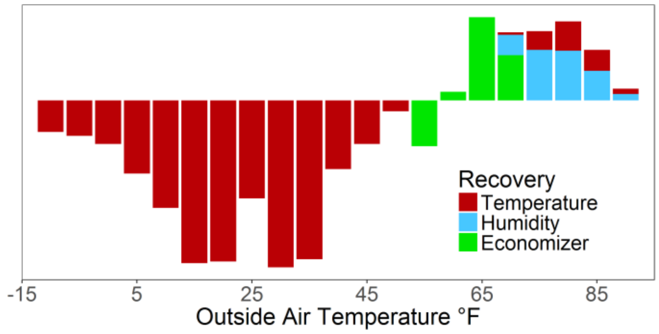
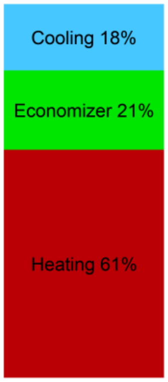


Figure 6. During typical occupied hours, ERVs in Minnesota spend 61% time heating, 18% time cooling, and 21% time inactive during economizer operation.



Typical Energy Recovery Results

- 80% of energy recovery is heating (up to 45ºF)
- 50% of all energy recovery takes place between 12ºF and 45ºF
- <20% of energy recovery is cooling (70ºF +)
- Peak cooling recovery occurs around 80ºF to 85ºF, coincident with hot, humid weather

OPERATIONS

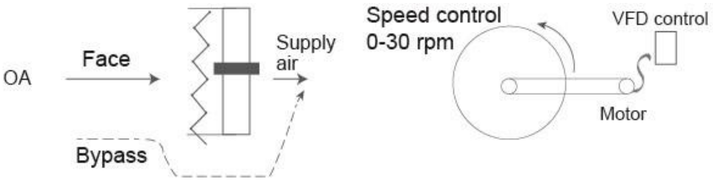
Basic controls: Key Takeaways

- There are two ways to change energy recovery: using dampers to direct flow through/bypass the ERV or by changing wheel speed
- In Minnesota, ERVs will typically need to operate in 5 different modes
- A variety of sensors and sequences are available for control
- Simple control solutions offer lower cost, fewer problems, and usually no performance penalty

Changing the amount of energy recovery

There are two ways to change the amount of energy recovery on a typical ERV; changing the outside air flow rate through the energy recovery media, or in the case of rotating ERVs (wheels), changing the rotational speed. The flow rate is varied using a face/bypass damper set, which directs the flow through the ERV or around it. Bypass systems offer the advantage of lower energy costs (lower pressure drop during inactive periods), but typically at larger space requirements (separate bypass ductwork). For wheel-based systems, the wheel speed is varied to change energy recovery. Speed-based control carries an extra pressure drop even when ERV systems are inactive or underutilized, but have little added size requirements.

Figure 7. There are only two ways to change the amount of energy recovery 1) controlling the air flow rate through/bypass the ERV or 2) changing the wheel speed.



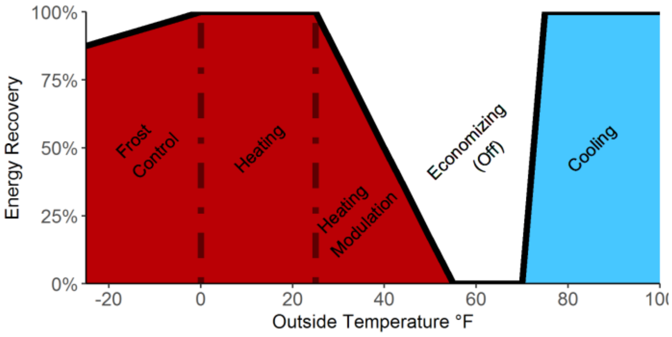
In simple systems, energy recovery is either off (100% bypass or 0% speed) or on (0% bypass or 100% speed). More complex systems enable partial energy recovery by modulating damper positions or wheel speeds to intermediate values (between 0 and 100% damper position and/or wheel speed). Wheel speed is typically modulated by adding a VFD. It is not uncommon to see bypass and wheel speed controls combined, but this is not necessary and it complicates control sequencing.

Two other controls commonly affect energy recovery. They are mixed air damper settings and ventilation flow rates. In both cases, these are primarily ventilation air controls. They indirectly affect energy recovery by controlling ventilation air. This introduces a key point. Energy recovery systems act upon ventilation air and should be interlocked with supply fan systems. Wheel speed adjustments and damper modulation serve no purpose without ventilation air.

Energy recovery modes

ERV operations can be described by five distinct modes. The amount of energy recovery varies from mode to mode based on desired outcome.

Figure 8. There are 5 basic operations of an energy recovery system that occur depending on outside air temperature (or enthalpy).



Mode 1: Heating

In Minnesota, ERVs are usually heating outside air. At cold temperatures, ~0ºF to 25ºF, the ERV discharge temperature remains below the supply air temperature. Energy recovery is fully active and the heating system, downstream of the ERV, is controlled to meet the supply air discharge temperature.

Mode 2: Frost Control

At frosting conditions, energy recovery is reduced to prevent damage to the ERV or prevent the pressure drop of frost build up. Frost control regimes depend on make, model, and implementation. It can vary from exhaust air temperatures between -20ºF and ~34ºF. There are two approaches, frost prevention and frost control. In fixed plate heat exchangers, frost is often prevented from building up at all. A simple way to prevent frost is to make sure exhaust discharge temperatures remain above freezing (32ºF). In wheel systems, frost control can engage at much lower temperatures depending on the unit performance and return air humidity.

Mode 3: Discharge Temperature Modulation

At moderate outside temperatures, ~32ºF+, energy recovery is reduced to avoid overheating. This is accomplished by reducing wheel speed or opening a bypass damper to maintain a constant ERV supply air discharge High performance ERVs may modulate below freezing temperatures to avoid overheating the space.

In most cases the ERV discharge temperature should be the same as the air handler supply air temperature. In other words, if energy recovery systems are modulating to prevent overheating, heating coils should be off unless necessary for some other reason (e.g. minimum output).

Mode 4: Economizer
At mild cooling temperatures < 75ºF outside air, energy recovery is replaced by economizer functionality to meet some of the cooling or dehumidification load of the ventilation air. ERVs that are active when outside temperature (or enthalpy) is less than return air temperature (or enthalpy) yield an energy penalty.

Mode 5: Cooling
The corollary to economizer function is cooling mode. If the system is in cooling mode and it is not economizing, then energy recovery is fully enabled (100%) to meet the ventilation cooling load. Cooling systems downstream of the energy recovery unit will run in turn to meet supply air discharge set points. As outside conditions get warmer and more humid, the ERV system will meet more of the load. At design conditions, a functioning ERV can meet 30% to 70% of the cooling load. With judicious planning, cooling systems can be downsized to account for this energy recovery.

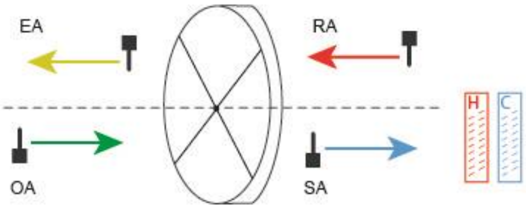
SENSORS AND CONTROL

Basic controls: Key Takeaways

- Confusion in ERV control is exacerbated by lots of different implementations and naming conventions, but most implementations work adequately
- During heating, the supply temperature leaving the energy recovery should be controlled to the discharge air temperature
- Frost controls should stop or slow energy recovery under very cold conditions. They are usually overly conservative. Frost control should not be appropriated for other purposes.
- Economizer modes should stop cooling recovery below room temperature. They should likewise not be adjusted or used for other purposes

Wheel speed and face/bypass damper positions are adjusted according to sensor measurements and control sequence logic. Control is usually exposed to staff through a building automation system (BAS) or hidden within a local controller. Sensors measure either temperature or temperature with relative humidity (total enthalpy sensors), placed in the incoming and outgoing air streams. Energy recovery units can operate in simple or complex ways, depending on the specific sensors and integration with other components. At a minimum, ERVs usually have dedicated exhaust and supply flow discharge temperatures. Return air and outside air sensors may be present, but equivalent measurements from other equipment are often used.

Figure 9. ERV units can be outfitted with a variety of sensor configurations.



Sensors placed in the ERV supply discharge flow, (often called discharge or supply temperatures) before mixed air or heating and cooling coils are used in heating mode to prevent overheating the space. Because discharge conditions vary over the cross section and there is little space to mix flows, averaging sensors are useful here. Controls sequences should usually modulate this supply air temperature to be the same as the discharge temperature (50ºF to 65ºF) to maximize recovery and minimizing heating fuel.

Frost control

Frost controls are implemented in a variety of ways. They are usually enabled by temperature sensors located in the exhaust flow (flow leaving the building envelope). Temperature based frost controls in Minnesota are often overly-conservative due to low wintertime indoor humidity. A humidity sensor in the return flow (or relevant zone) enables more aggressive frost control when indoor humidity is low. Very simple frost controls can also be enabled according to the outside air temperature. In these cases, energy recovery systems are disabled below a fixed temperature. In most cases with reasonable set points, the performance differences between these sequences are small because the operating hours at very cold outdoor temperatures are low.

Frost Control

There are several ways to control frost:

Exhaust Temperature: Energy recovery is inactive or modulated to maintain an exhaust air temperature lower limit.

Exhaust Enthalpy: Energy recovery is inactive or modulated to maintain an exhaust air enthalpy lower limit, which depends on exhaust temperature and return air humidity. Low winter humidity in cold climate buildings enables significantly lower limits.

Outside Temperature: Energy recovery is inactive or modulated below an outside air temperature lower limit.

Preheat Coils: Frost control is achieved by preheating outside air prior to energy recovery.

Pressure: Energy recovery is modulated according to the pressure drop across (which increases from frost build up) (uncommon)

Adjustable frost controls are subject to abuse because they can effectively disable energy recovery. Frost control beyond reasonable levels is a somewhat common way to disable energy recovery. Frost controls have been observed with set points ranging from 45ºF to 80ºF, essentially eliminating 50% to 80% of ERV savings. For units in the non-humidified buildings encountered in this study, simple controls that disable total enthalpy wheels below -10ºF outside air temperature are adequate.

Economizer

Economizer mode functions the same with or without energy recovery with the added requirement that energy recovery be disabled during economizer functionality. Control logic is implemented based on outside air sensors and optionally return air sensors. Cooling and economizer controls come in many forms. They measure outside conditions and compare them to a fixed goal or measured return air conditions. Sometimes outside conditions are measured at a fixed location for the whole site or at a local weather station. Simple fixed controls compare the outside temperature or enthalpy to some fixed upper limit, below which (in cooling mode) energy recovery is inactive and above which energy recovery is fully active. Differential controls will economize as long as the outside temperature or enthalpy is less than the return temperature or enthalpy. Performance variations with different economizer sequences are small and other system details are more likely to determine overall energy savings. Prior work has found that sophisticated economizer controls do not provide additional savings in Minnesota. In buildings encountered in our study, an adequate economizer sequence disables energy recovery (cooling mode only) below room temperature or about 72ºF.

Economizer Control

Most economizer controls are compatible with energy recovery.

Outside Air Temperature: Energy recovery is inactive or modulated to maintain an economizer air temperature upper limit.

Outside Air Enthalpy: Energy recovery is inactive or modulated to maintain an economizer air enthalpy upper limit.

Outside & Return Air Temperatures: Energy recovery is inactive or modulated when outside air temperature is less than return air temperature.

Outside & Return Air Enthalpies: Energy recovery is inactive or modulated when outside air temperature is less than return air enthalpy.

Enthalpy controls require additional humidity sensors, which are prone to larger uncertainty and drift, without a clear benefit.

Discharge Air Temperature

Discharge conditions of ERVs (supply and exhaust), vary significantly over their cross sectional area. To get sensor measurements that represent average conditions, some care is necessary to specify sensor locations. The discharge temperature is measured downstream of the ERV on the supply side. Point sensors should be located in the middle of the discharge plane and averaging sensors should uniformly cover the entire exit plane. Exhaust temperature sensors should be placed away from purge air sections. Sensor placement for inlet conditions (outside air, return air) is not as crucial because flows are usually well mixed. Outside air sensors that are not co-located with ERV units (offsite or off-unit) may result in sub optimal control.

Outside Air Sensors

There are a variety ways to measure outside air for ERV control. In order of preference:

Outside air temperature located at the ERV inlet will provide the most accurate basis for controlling energy recovery

Outside air temperature at outside air plenum: May result in some error depending on ductwork or solar radiation

Outside air temperature on site: A site-wide sensor may not best represent inlet conditions with other unit.

Offsite Outside air temperature: Local weather station data may give conditions very different than those of air entering the ERV.

Table 1. Potential energy recovery sequences, possible sensor implementations, and potential control point names.

Control Sequence	Possible Sensors	Behavior	Potential control point names
Supply temperature control Maintain discharge temperature and avoid overheating	Supply air temperature (point or averaging)	Modulate recovery	Wheel/ERV/ERU/HX: • Discharge air temperature, • Supply air upper limit, • Energy recovery upper limit • Temperature
	Shared HVAC discharge temperature sensor	Modulate recovery (as first stage in multi-stage with heating system)	
Frost Control/Prevention Minimize frost or prevent formation of frost at very cold temperatures	Exhaust air temperature (point or averaging)	Modulate recovery	Wheel/ERV/ERU/HX: • Exhaust air lower limit, • Frost control temperature, • Frost control lower limit, • Disable/enable temperature • Defrost set point • Lower limit • Frost mode enable • Frost/freeze set point
	Outside air temperature	On/off	
	Exhaust air temperature with return air humidity	Modulate recovery	
Economizer/Cooling control Disable energy recovery when it inhibits free cooling	Outside air temperature	On/off	Economizer/econ: • Set point, • Lockout • Bypass Wheel/ERV/ERU/HX: • Cooling mode enable
	Outside air enthalpy	On/off	
	Outside and return air temperatures	On/off	
	Outside and return air enthalpies	On/off	

ESTIMATING ENERGY RECOVERY PERFORMANCE

ERV Performance: Key Takeaways

- Design effectiveness does not predict energy savings.
- The average Recovery Energy Ratio (RER) is a metric to compare installed ERV systems as well as traditional heating and cooling equipment
- ERVs in Minnesota are about 40X times more efficient than conventional heating systems
- For typical configurations, ERV in Minnesota are 1 to 2X as efficient as conventional AC

Performance

There are three performance metrics for ERVs in the design literature, effectiveness (ε), recovery energy ratio (RER), and combined efficiency ratio (CEF). While effectiveness is the only commonly referenced metric, RER better reflects installed performance. RER can be used to compare ERV performance to conventional equipment and other energy recovery systems at both average and design conditions. CEF combines RER with heating and cooling equipment efficiency to get a HVAC system plant performance.

Effectiveness: Heat Exchanger Efficiency

The most referenced performance metric is the effectiveness; it's also the least informative. Effectiveness (or net effectiveness) typically rates the performance of the temperature or moisture transfer of an ERV with respect to the maximum possible performance, typically at summer and winter design points and balanced flow conditions. ERVs, especially AHRI certified units, achieve expected effectiveness under controlled conditions. It is a design parameter, most useful for sizing units and adjusting ventilation loads for associated heating and cooling systems. Design effectiveness does not predict energy savings. Actual ERV performance varies due to installation, unbalanced flows, outside air conditions, and controls programming. Therefore, design effectiveness, as usually quoted, is not useful in understanding atypical ERV performance. These issues are documented in AHRI Guideline W, but rarely discussed in practice.

A very common situation is that as-operated exhaust flows are less than as-designed exhaust flows. This flow deficiency occurs due to exfiltration, point exhausts, and the interactions between multiple air handlers. In this case the exhaust side limits the total energy that can be exchanged and less recovery occurs.

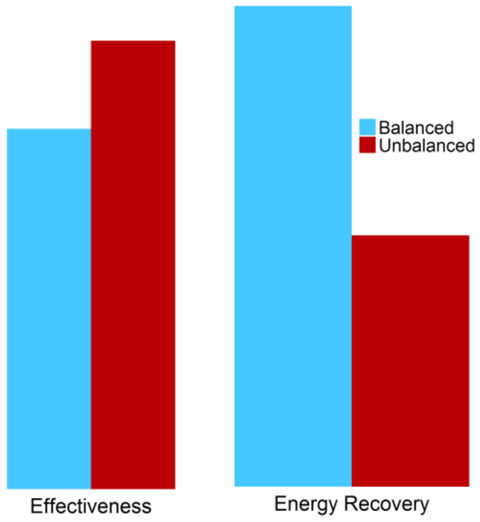


Figure 10. As-operated exhaust flows that are less than design values (unbalanced) typically increase effectiveness, but starve the supply flow of available energy and total energy recovery decreases.

RER – Recovery Efficiency Ratio: Ratio of energy recovered vs used

The recovery energy ratio is the metric for comparing the energy saved by an ERV system to the energy used by an ERV system. It may also be used to compare energy recovery to conventional equipment. That said, like effectiveness, RER (especially seasonally averaged values) calculations are time consuming and nuanced, unlikely to prove cost-effective for field investigations. Measurements on several units presented here give context for the overall energy efficiency benefits of ERV units.

Heating RER_c depend strongly on outside air conditions. RER_h is as high as 110 W/W at -20ºF and as low as 4 W/W at 50ºF in typical configurations. For a typical year in Minnesota, an average RER_h is about 35 W/W. Conventional gas-based heating equipment has an equivalent RER_h of 0.8 to 0.9 W/W. In other words energy recovery is about 35 times more efficient than heating ventilation air directly.

Cooling performance varies nearly as much. RER_c is expressed in units of Btu/W-hr, the same units as EER (energy efficiency ratio), an often used metric to describe the performance of cooling systems. In Minnesota, a total enthalpy wheel may have an RER_c of 26 Btu/W-hr at 70ºF and 130 Btu/W-hr at 85ºF. RER_c above 85ºF is approximately constant as increasing temperatures are balanced by decreasing humidity. The average RER_c is about 17 Btu/W-hr for a total enthalpy wheel without a bypass. For systems with bypass the average RER_c may be twice as large. ERVs compete with cooling systems that operate at EERs (AC equivalent of RER_c) between about 10 and 27. In other words, cooling equipment is significantly more competitive with energy recovery than heating equipment at mild Minnesota cooling loads. Total enthalpy wheel ERV systems can outperform most cooling equipment, but it depends on system configuration and cooling system performance as much as ERV characteristics.

Table 2. Recovery energy ratios compare favorably to conventional systems at design conditions. Although seasonal average RERs are significantly lower, ERVs yield energy savings year-round.

RER	Range	Seasonal Average	Improvement over typical HVAC
Heating (W/W)	3 - 110	29	~35X
Cooling (Btu/W-hr)	20 - 140	17	~1 – 2X

CONCLUSION

This guide represents air-to-air exhaust energy recovery as typically found in Minnesota C&I buildings. There is tremendous variation in implementation, which can lead to ambiguity about performance and correct operation, especially given the lack of expectations outside design conditions. Nonetheless many different implementations achieve significant energy savings in line with the reported seasonal average RERs. Most importantly, ERV savings depend on the people that touch these systems. They must understand when ERVs should and should not run and then field validate this expectation.