IS HEAT RECOVERY COST EFFECTIVE IN CANADIAN COMMERCIAL BUILDINGS?

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ABSTRACT

As part of an effort to continuously improve the National Energy Code of Canada for Buildings (NECB), this study, carried out for the Office of Energy Efficiency at Natural Resources Canada, assesses the NECB 2011 requirement for exhaust air heat recovery. The study examines the costs and benefits of adding heat recovery to exhaust across a wide range of available technologies. The annual energy cost savings derived from adding heat recovery to thirteen archetype buildings are calculated in each of the six NECB climate zones using CAN-QUEST. These cost considerations and energy cost savings form the basis of a cost benefit analysis that is used to determine where heat recovery is justified.

The results indicate that there is an opportunity to improve on the current NECB approach, and that heat recovery can provide a net cost benefit for most building types in all six NECB Canadian climate zones.

INTRODUCTION

The National Energy Code of Canada for Buildings 2011 or the NECB 2011 (National Research Council Canada, 2011) serves as a guideline for provinces and territories in developing energy efficient building codes by proposing minimum paths to energy efficiency. The Canadian climate is characterized by seasonal extremes with cold winters and hot, humid summers. In this climate, exhaust air heat recovery is an important tool for improving energy efficiency in new construction and in retrofits of existing buildings. A current requirement of the NECB 2011 is that heat recovery with a minimum sensible effectiveness of 50% be used on all exhaust systems carrying more than 150 kW of sensible heat (Article 5.2.10.1, NECB 2011). In Victoria, with a January design temperature of -5ºC, the exhaust air flow rate required to reach this 150 kW threshold is 4,900 litres per second. In Yellowknife, with a January design temperature of -43ºC, the required exhaust air flow rate is 1,900 litres per second. The NECB also requires heat recovery ventilation in self-contained ventilation systems serving single dwelling units in climate regions with more than 5000 Celsius heating degree days.

The purpose of the present analysis is to review this 150 kW sensible heat threshold in the context of heat recovery technologies currently available on the market, and to determine whether a lower threshold is justified based on a detailed cost-benefit analysis. In order to carry out this analysis, the performance of various heat recovery technologies are characterized by considering their placement in thirteen NECB archetype building energy models in CAN-QUEST. CAN-QUEST is based on DOE-2.2, a widely reviewed and validated simulation engine (Crawley, B. et al. (2005), Hirsch, J. (2004), Sullivan R. & Winkleman F. (1998)). The following technologies, in order of increasing performance, are analysed in this study: heat pipes, sensible and enthalpy heat cores, energy wheels, and reverse flow devices. The NECB archetype energy models analysed in this study include the Big Box Store, Large and Small Hotels, Long Term Health Care (LTHC), Large and Small Multi-Unit Residential Buildings (MURBs), Large and Medium Offices, Full Service and Fast Service (Quick) Restaurants, Primary and Secondary Schools, and the Warehouse. Appropriate heat recovery systems are selected for each heating, ventilating and air conditioning (HVAC) system in each archetype building from a variety of manufacturers. Detailed performance specifications for each heat recovery unit selected, including the sensible and latent effectiveness, and the increased electrical power required to operate the units, are obtained from manufacturer's specifications and entered into the NECB archetype energy models.

The incremental capital cost of adding heat recovery was obtained from manufacturers' representatives. For each heat recovery technology added to an air handling system in each archetype building, two prices were quoted: (1) an air handling system matching the specifications used in the archetype model, and (2) a second air handling system matching these specifications with the addition of heat recovery. The difference in price between these two systems is used to determine the increased capital cost of adding heat recovery to the system. Increases to installation costs were also estimated: increased electrical costs for upgrading electrical services and breakers to support a higher current draw; increased structural costs for supporting larger and heavier air handlers on roofs; increased costs for adding control points to allow for control of the heat recovery system; increased roofing costs; and increased ductwork and piping costs (air handlers with heat recovery tend to be larger and may require longer runs of ductwork, small heat recovery units in multi-unit residential buildings may also require additional condensate piping). Increased first costs are compared to the annual energy cost savings to determine a simple payback period that can be compared to the expected equipment lifetime.

Energy costs are based on the 2014 average prices across Canada as published by Quebec Hydro (2014) and by the Canadian Gas Association (2014). Since most of the climate regions studied cross several provincial boundaries, a Canadian average utility rate provides a clear basis for comparison of the various heat recovery technologies from climate region to climate region. In the north, where more expensive fuel oil is often used, the cost benefit analysis is not sensitive to the price of heating fuel as the annual cost savings from adding heat recovery to exhaust air are high even for less expensive natural gas. An average rate of $0.1128/kWh is used for electricity and a 2014 average commodity supply rate of $0.186/cubic metre is used for natural gas. An additional distribution and transportation charge of $0.1589/cubic metre, which is based on a provincial population weighted average of distribution charges from published commercial rates from eight natural gas distributors across Canada[1] is added to the supply rate for a total rate of $0.3449/cubic metre. As natural gas prices are currently low, the cost-benefit analysis in warmer climate regions is skewed toward electricity savings. In many cases, the annual energy cost savings from adding heat recovery are negative even when the annual energy consumption savings are positive.

From the thirteen archetype models provided, 82 different configurations of the building energy models were created and simulated across all six Canadian climate regions. In total, the results of 492 energy models were obtained and analysed.

HEAT RECOVERY IN THE NECB ARCHETYPE BUILDINGS

Big Box Store

The Big Box Store model has 9,290 square meters (100,000 square feet) of floor area and is served by nine single-zone constant-volume packaged systems with natural gas-fired furnaces and direct-expansion cooling. The average outdoor air fraction is 0.268 and the maximum supply air temperature is 48.9ºC (120ºF). The sensible heat in the exhaust stream ranges from a per system average of 26.7 kW in climate region 4 to 67.3 kW in climate region 8. Energy recovery wheels or heat core exchangers are easily built into rooftop units as part of a packaged unit. In many rooftop units, adding heat recovery does not add to the capital cost of the units. However, there are less expensive units available for which adding heat recovery does add to the capital cost of the units. In this analysis, it is assumed that the less expensive units would be chosen, and that the increase in capital cost is equal to the cost of adding heat recovery to these less expensive units. Reverse flow units are substantially more expensive and

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[1] FortisBC (Schedule 3, Large Commercial), ATCO Gas (Mid-Use Delivery Service) in Alberta, SaskEnergy (Large Commercial), Manitoba Hydro (Small General Service Commercial), Engridge Gas (Rate 6) in Ontario, Gaz Metro (Rate D1 General Service) in Quebec, Enbridge Gas New Brunswick (Large General Service), and Heritage Gas (Commercial) in Nova Scotia. Rates were retrieved in February, 2015.

require greater structural support in the roof. Since big box stores tend to minimize the material required for the roof to keep costs as low as possible, and since the outdoor air flow rates are relatively low, improvements in performance for reverse flow units may not be sufficient to make up for the increase in up-front capital costs.

The sensible and enthalpy heat core, energy wheel, and reverse flow heat recovery systems were modelled. All four heat recovery technologies provide annual energy savings in all six climate regions. The energy savings increase with increasing sensible and latent effectiveness, and the highest annual energy savings are obtained with the reverse flow device. The simple payback is shorter than the lifetime of the equipment in climate regions 5 through 8 for the sensible and enthalpy heat core, the energy wheel and the reverse flow unit. The enthalpy heat core and the energy wheel have an expected lifetime of 15 years and the reverse flow system has an lifetime of 30 years.

The additional latent heat recovered by the three enthalpy recovery technologies offers a good payback relative to the sensible core which only recovers sensible heat. The energy wheel shows the shortest payback periods with a simple payback of less than 5 years in climate regions 6 through 8, 6.4 years in climate region 5, and 11.7 years in climate region 4.

Large Hotel

The Large Hotel model uses a large make-up air variable air volume (VAV) system to serve the common areas and corridors. Four-pipe fan coil systems draw outdoor air from the main system into the hotel rooms through doorways or transfer ducts. The central plant has a natural gas boiler and a centrifugal chiller rejecting heat to a cooling tower. Using heat recovery in this configuration requires exhaust from the hotel rooms to be centrally ducted back to the main air handling system. In this model, the main air handling system has an outdoor air ratio of 0.207. The supply air temperature setpoint is controlled by an outdoor air reset schedule that varies the supply temperature between 12.8ºC at an outdoor air temperature of 26.7ºC and 18.3ºC at an outdoor air temperature of 15.6ºC. The archetype model provided has a sensible wheel with 50% effectiveness and with all energy recovery modelling parameters set to CAN-QUEST defaults. An enthalpy heat core, an energy wheel and a reverse flow unit were also considered in the analysis.

The simple payback period is shorter than the equipment lifetime for the enthalpy heat core, the energy wheel and the reverse flow unit starting in climate region 5, where the sensible heat in the exhaust stream increases from 137.8 to 181.9 kW. The energy savings are remarkably consistent across all three technologies modelled: enthalpy heat core (sensible/latent effectiveness of 0.68/0.56), energy wheel (sensible/latent effectiveness of 0.72/0.62), and reverse flow (sensible/latent effectiveness of 0.87/0.67). This consistency in the results, despite increases in the rated heat recovery performance, suggests that the heat recovery devices are being controlled to reduce their heat recovery capacity and avoid overheating of the supply air. Because of this control, the effectiveness of the heat recovery devices is not determined by the choice of equipment, but rather is limited by the relatively low supply air temperature of 18.3ºC. Since the return air temperature is close to 22ºC, the system will likely bring in additional outdoor air for “free cooling” of the mixed air stream (which is 79.3% return air and 20.7% outdoor air at the design flow rate) during much of the year. Changing the main system over to a dedicated outdoor air make-up system with 100% outdoor air and adding four-pipe fan-coils to the common areas and corridors for additional temperature control in these zones would eliminate this problem and allow the system to better take advantage of heat recovery on exhaust air.

Small Hotel

The Small Hotel model uses a packaged constant volume system to serve the common areas and corridors in the building. The hotel rooms are served by packaged terminal air conditioners (PTACs). The constant volume system provides tempered air with a maximum supply temperature of 21.1ºC and has an outdoor air fraction of 0.226. The supply temperature in this system is controlled according to the cooling demand of a single control zone. The supply air is heated by natural gas and cooled by direct expansion cooling. Additional heating is provided by electric heating coils in the zone terminals. In contrast to the Large Hotel model, the main system does not provide outdoor air to the in-room systems. Each in-room

PTAC system is modelled with its own outdoor air intake. In order to model heat recovery the system type for the in-room systems was changed in CAN-QUEST from PTAC to packaged single zone (PSZ), as CAN-QUEST does not support heat recovery on PTACs.

PTACs are usually small vertical or horizontal units built into the wall or under the window. As such, only sensible and enthalpy heat core units are considered for the PTAC systems. The following energy recovery configurations were modelled in the small hotel: sensible heat core in the PTACs and no heat recovery in the main system; enthalpy heat core in the PTACs and no heat recovery in the main system; enthalpy heat core in the main system; energy wheel in the main system; and reverse flow in the main system.

Payback periods are shorter than the equipment lifetime in all of these configurations. The enthalpy heat core in the PTACs has the shortest payback periods with a maximum of 8.1 years in climate region 4.

Since the heating coils in the PTACs are electric, the cost savings on space heating are higher when heat recovery is added to the PTACs than when it is added to the main system which uses natural gas for supply air heating. Adding energy recovery to the main system, which has 615 L/s of outdoor air flow, leads to energy savings comparable to those achieved by adding energy recovery to all of the individual PTACs, which have a combined outdoor air flow of 1,000 L/s. However, the cost savings that arise from adding energy recovery to the main system are much lower.

The building type and usage are remarkably similar to the large hotel, but the energy savings are much higher. The key differences between the two models are 1) that the main system is able to supply air at a higher temperature (21.1ºC in the small hotel and 18.3ºC in the large hotel) and is therefore able to recover more energy from the exhaust stream and 2) that each individual room has its own HVAC unit. Since each room has its own HVAC unit, the HVAC unit can maximize heat recovery as possible on a room-by-room basis.

The average sensible heat in the exhaust stream for the PTACs ranges from 0.9 kW in climate region 4 to 2.2 kW in region 8, and the average sensible heat in the exhaust stream for the main system ranges from 18.9 kW in region 4 to 47.6 kW in region 8. Heat recovery is cost effective across all climate regions in all of the energy recovery technologies modelled. The use of enthalpy heat core devices in the PTACs shows shorter payback periods than the sensible heat core devices due to the improved energy recovery performance. The energy wheel and the enthalpy heat core show roughly equivalent payback periods.

Long Term Health Care

The Long Term Health Care archetype model has two packaged single zone (PSZ) systems with natural-gas fired heat and direct expansion cooling. Baseboards connected to a hot water loop served by a natural-gas fired boiler provide additional zone heating. The systems are operated 24 hours a day, seven days a week. System 1 has an outdoor air ratio of 0.226 and system 2 has an outdoor air ratio of 0.308. Each system provides a constant flow of supply air with the temperature for each system set by its control zone. The supply air and outdoor air flow rates are specified at the zone level in the CAN-QUEST model at 6 and at 2 air changes per hour respectively, which appears to reflect the rates specified by the CSA standard Z317.2-10 for patient rooms in a Class A facility. It should be noted that the system type chosen for the NECB archetype is no longer considered to be typical in health care facilities. Depending on the area served, most facilities now use a VAV system in order to reduce the airflow when possible (see, for example, the Advanced Energy Design Guide for Small Hospitals and Healthcare Facilities, ASHRAE, 2007). Reductions in the supply air flow rate will lead to reductions in the fan and reheat energy. Many systems in health care facilities are also designed to provide 100% outdoor air.

Since long term health care facilities typically have high outdoor air flow rates, they lend themselves well to energy recovery systems. However, they also tend to have strict limits on cross contamination. In cases where cross contamination is not acceptable, heat pipe and heat core energy recovery units must be used. Heat pipes, sensible and enthalpy heat cores, energy wheels and reverse flow units were all analysed in this study. It is important to note that careful attention to the interplay between the baseboards (which are prioritized to meet heating loads first by CAN-QUEST) and the air handling system was required to ensure that the system operation reflected real world behaviour.

Annual energy savings are high for all energy recovery technologies modelled across all six climate regions. The annual energy savings increase with the performance of the energy recovery system modelled. The simple payback periods are shorter than 5 years for almost all of the technologies modelled.

The main exception is the heat pipe, which has long payback periods in climate regions 4 and 5. Unlike the other technologies, the heat pipe is modelled without capacity control. A tilted heat pipe system would likely offer better performance as it could be better controlled to minimize overheating in the shoulder seasons. For the long-term health care facility, with its relatively high outdoor air flow rates and 24/7 operation, maximizing the energy recovery performance is the most cost effective option over the lifecycle of the equipment. The reverse flow unit has the best performance on annual energy savings and with an expected lifetime of 30 years is likely to yield the highest lifecycle cost savings. In applications where cross leakage needs to be minimized, the enthalpy heat core unit provides the best cost-benefit performance.

Large MURB

In the Large MURB, a ten-storey building, each thermal zone is modelled with its own water-source heat pump system. The water-source heat pump loop is heated by natural gas-fired boilers and cooled by a fluid cooler. There is also a single packaged constant volume system with direct expansion cooling and natural gas-fired heating that serves the central zone containing the corridors, elevators and service areas. As the physical space allowed for the systems in MURBs tends to be restricted, a heat core is the most appropriate energy recovery technology. Both sensible and enthalpy heat core devices were modelled. The results show that excellent energy and cost savings are achieved across almost all climate regions for both sensible and enthalpy heat cores.

As is the case for the Small Hotel, the ability of each system to maximize energy recovery as needed depending on the heating or cooling needs of the single thermal zone that it serves leads to high energy consumption and cost savings. The enthalpy heat core is able to recover more heat and shows increased space heating savings. Reduced static pressure in the enthalpy heat exchangers leads to lower fan energy and reduced cooling energy relative to the sensible heat exchange systems. Note that these savings are achieved with relatively low levels of heat in the exhaust air. The average heat per system in the exhaust air ranges from 4 kW in climate region 4 to 10.4 kW in climate region 8. The crossover to a payback period that is shorter than the life of the equipment (15 years) occurs between 4 kW in climate region 4 and 5.4 kW in climate region 5.

Small MURB

The Small MURB is a smaller four-storey version of the Large MURB with eight dwelling units per floor, each served by a packaged terminal air conditioner (PTAC), surrounding a central core which is served by a packaged single zone (PSZ) system. As in the Small Hotel model, the PSZ system serving the core does not provide outdoor air for the dwelling units. The PSZ system uses natural gas-fired heat and direct expansion cooling. The PTACs use electric heat and direct expansion cooling. Sensible and enthalpy heat core devices were modelled for both the packaged single zone system and for the PTACs. The PTACs were changed to PSZ systems in CAN-QUEST as a work-around to allow for modelling of energy recovery. Given the small size of the packaged single zone system, energy recovery wheels and reverse flow devices were not considered. The results demonstrate annual energy savings across all climate regions for both sensible and enthalpy heat core units.

However, the energy cost savings are not sufficient to overcome the up-front capital costs in climate regions 4 through 6. The simple payback drops below 15 years in climate region 7a, where the sensible heat in the exhaust stream changes from 7.1 to 8.6 kW. The main reason that the payback is longer in the small MURB than in the large MURB (cost effective in climate region 5 and above) is that it is more expensive to add energy recovery to a PTAC ($2250 per unit) than to a water source heat pump system ($1950 per unit). Another reason is that the packaged single zone system serving the central core zones has a much smaller outdoor air ratio (0.10) in the Small

MURB than in the Large MURB (0.90). Even though the units bring in roughly the same amount of outdoor air, many water source heat pumps now have standard energy recovery options, whereas energy recovery in PTACs is still somewhat rare, and comes at more of a cost premium.

Large Office

The Large Office model uses a central VAV air handling system with a supply air flow rate of 52,000 litres per second and an outdoor air flow rate of 6,500 litres per second (cooling design outdoor air ratio of 0.125). Heating is provided by hot water coils connected to a natural gas-fired boiler and cooling is provided by chilled coils connected to a chiller which rejects heat to a cooling tower. VAV systems are controlled to supply air at a relatively low temperature, even in winter, to counterbalance thermal gains in interior zones. If the outdoor air fraction is low, and the return air temperature (i.e. 20ºC) is higher than the supply air setpoint (usually between 13 and 18ºC) it is often advantageous to bring in cold outdoor air to provide free cooling. With a low supply temperature, energy recovery opportunities are therefore limited to the coldest days of the year. However, appropriate control strategies which allow the supply air temperature to reset to higher temperatures can expand the operating range of energy recovery devices. One advantage of VAV systems from the perspective of energy recovery in winter is that in peak heating mode the system supplies air at flow rates close to the minimum outdoor air flow rates. This means that the outdoor air ratio can be much higher than the cooling design outdoor air ratio. Under these conditions, a much higher fraction of the heat in the exhaust air stream can be captured for re-use in the supply air stream.

Given the high supply and outdoor air flow rates, only the energy wheel and reverse flow devices are analysed. As in the case of the Long Term Health Care model, the energy wheel and the reverse flow unit show almost identical annual energy savings in the Large Office model despite having different energy recovery effectiveness. This suggests that energy recovery is limited more by supply air temperature control than by unit performance or by the available energy in the exhaust air stream. The energy wheel shows the shortest payback, and it crosses over to a period shorter than the equipment lifetime (15 years) between climate regions 5 and 6 where the sensible heat in the exhaust increases from 266 to 347 kW. Despite the high level of energy in the exhaust stream, the space heating savings are relatively small. In this case heat recovery appears to be limited by a system that is designed for a low supply air temperature and a low outdoor air fraction.

In order to better understand the energy recovery performance, further analysis of the Large Office model was carried out. In the CAN-QUEST model provided, the supply air flow rate is auto-sized to meet the peak cooling supply air flow rates, and the CAN-QUEST default of non-coincident peak cooling is chosen. This default means that the supply air flow rate is sized as if every zone in the building is calling for its peak cooling flow at the same time. An oversizing ratio of 1.15 is then applied. The resulting design flow rate in the model with no energy recovery is 53,494 L/s in climate region 5. With a minimum flow fraction of 0.3 in peak heating season, the lowest supply air flow rate that can be attained is 16,048 L/s. With an outdoor air flow rate of 6,500 L/s the highest outdoor air fraction will be 0.405. This way of sizing the system is not typical in the industry. The system would normally be sized to meet the peak cooling load for the building as a whole and not the sum of the peak cooling loads for each zone in the building. At coincident sizing, the design supply air flow rate drops to 40,158 L/s with a maximum outdoor air ratio of 0.540 at a minimum flow ratio of 0.3. If the minimum flow ratio is also allowed to drop from 0.3 to 0.2 the maximum outdoor air ratio increases to 0.809. The combination of right-sizing, activation of the central heating coil in CAN-QUEST, and a minimum flow setting of 0.2 increases the annual energy savings for all of the models. The simple payback periods are much shorter, with the energy wheel now showing a payback shorter than the equipment lifetime in all six climate regions and shorter than 5 years in climate regions 5 through 8. In climate region 6, the simple payback drops from over 10 years to shorter than 5 years.

Medium Office

The Medium Office model is largely identical to the Large Office model, with the exception that it is only two-storeys. The packaged VAV air handling system in the Medium Office model uses natural gas-fired heat and direct expansion cooling. Electric heating coils are used for zone reheat. The same supply air temperature reset schedule is used. It is not surprising to see that the results are much the same as those of the Large Office. The Medium Office was modelled with the supply flow rate sized according to the coincident peak building load, and the supply air temperature is allowed to rise to 18.3ºC in heating season. A minimum flow setting of 0.2 is used to boost the outdoor air fraction by lowering the supply air flow rate at the minimum flow settings and maximize energy recovery. Again, the energy wheel shows the shortest simple payback periods.

Full Service Restaurant

The archetype model is divided into two zones: the kitchen, and the dining room. Each zone is served by a constant volume, packaged single zone system using natural gas for heat and electricity for cooling. The dining room system has an outdoor air fraction of 0.223 with 620 litres per second of outdoor air. The system serving the kitchen is a 100% outdoor air makeup system that replaces 1944 litres per second of air exhausted from the kitchen. Additional zone heating is provided by electric baseboards. Kitchen exhaust, which tends to be laden with grease and soot, is limited to heat pipe and heat core exhaust air heat recovery applications which prevent cross contamination of the outdoor air stream. Heat pipes have historically been favoured, as they are easier to clean and have a longer service life than heat core units.

Dining rooms typically have high latent loads. They tend to be full at regular meal times with a high occupant load. The archetype model provided has a peak occupancy of 40 occupants in the dining room. In addition, the transmission of vapour from the kitchen to the dining room increases the latent load. With high latent loads, systems serving the dining room would be best served by sensible heat recovery devices, such as a heat wheel or a sensible heat core.

Significant maintenance is required for both the kitchen and dining room systems to maintain performance. Otherwise the build up of grease and other contaminants on the heat exchange surfaces degrades the heat transferred from the exhaust air stream. Annual maintenance costs are likely to be on the order of $1200. Due to the high level of maintenance and cleaning required, heat recovery wheels usually last only five to eight years in restaurants (as compared to fifteen years in other applications), which further increases the lifecycle costs for energy recovery. This high level of maintenance is required for both the kitchen and dining room systems, due to migration of airborne grease and other contaminants from the kitchen to the dining room.

The following configurations were modelled: heat pipe in the kitchen only; sensible heat core in both the kitchen and dining room; enthalpy heat core in both the kitchen and dining room; energy wheel in the dining room only; and reverse flow in the dining room only.

The energy savings are much smaller for those systems that add energy recovery to the dining room. Although modest energy savings are achieved by adding heat recovery to the dining room system in the colder climate regions the simple payback periods are longer than the expected lifetime of the equipment in the energy wheel and reverse flow applications.

The use of sensible and enthalpy heat core devices in the kitchen and dining room systems yields relatively high annual energy cost savings and the simply payback periods are less than 5 years in the climate regions 6 through 8 for the enthalpy heat core device. However, these cost savings are not sufficient to overcome the high lifecycle costs due to maintenance and frequent replacement of the heat core (every 5 years).

The heat pipe, with a longer service life of twenty years, is able to achieve significant energy cost savings in all climate regions apart from region 5. The region 5 climate model is based on the Windsor weather file and the region 4 climate model is based on the Victoria weather file. The demand for space cooling is much higher in Windsor than in Victoria, and heat pipe heat recovery increases the space cooling demand by adding heat to the incoming outdoor air stream. This increase in space cooling has more of an impact on the region 5 Windsor model than on the region 4 Victoria model, because Windsor has a much higher space cooling in summer than Victoria which has a milder climate. Given the high levels of heat in the exhaust stream, use of a heat pipe system that could be “turned off” in summer would be highly recommended.

Quick Restaurant

The archetype model for the quick restaurant is much the same as that for the full service restaurant. A slightly lower exhaust air flow rate of 1,557 litres per second is used in the kitchen, and a smaller occupant load of 13 people is assumed for the dining room. As the dining areas in fast-food restaurants tend to have much more variable and less predictable occupancy patterns and thus lower latent loads an enthalpy heat exchanger might be more suitable. As in the Full Restaurant above, the following configurations were modelled: heat pipe in the kitchen only; sensible heat core in both the kitchen and dining room; enthalpy heat core in both the kitchen and dining room; energy wheel in the dining room only; and reverse flow in the dining room only. Modelling the sensible and enthalpy heat core devices in the kitchen only was also considered. However, as the bulk of the heat recovery and up-front capital cost is on the kitchen system, this change was not found to yield qualitatively different results.

The results show that heat recovery on the dining room system is not cost effective. The annual energy cost savings are too small to make up for the high capital and maintenance costs in all climate regions. As in the case of the Full Service Restaurant archetype model (with baseboards), heat pipe recovery on the kitchen exhaust yields significant lifecycle cost savings in all climate regions apart from region 5. The sensible heat in the exhaust air on the kitchen system ranges from 48 kW in region 4 to 121 kW in region 8.

Primary School

Schools tend to have relatively high outdoor air flow rates due to the high occupancy rates of classrooms and auditoriums, and the high activity levels in gymnasiums. A common design in new schools is to provide partial cooling. When providing partial cooling, ventilation air is cooled and dehumidified to a setpoint of 13ºC, but the system is not sized to meet the full cooling load at peak cooling conditions. It may be sized to meet only 30% of the peak load, however the school remains relatively comfortable as the air is dehumidified relative to the outside air. With this design strategy, it often makes sense to maximize energy recovery as higher performance improves comfort at peak cooling conditions, and energy wheels or reverse flow energy recovery technologies are often recommended.

The Primary School archetype model is a single storey building served by three air handling systems. One is a large constant-volume air handling system serving the bulk of the building with a supply air flow of 17,000 litres per second an outdoor air fraction of 0.258. The other two are much smaller single zone systems serving a small gymnasium and a cafeteria respectively. The system serving the gymnasium has an outdoor air fraction of 0.504 and the system serving the cafeteria has an outdoor air fraction of 0.431. All three systems have natural gas-fired heating and direct expansion cooling. Additional zone heating is provided by hot water radiators served by a natural gas boiler. The supply air temperature is controlled to meet the needs of the warmest zone with a maximum setpoint of 25ºC. Additional zone heating is provided by hot water baseboard heat

Energy recovery technologies analysed for the primary school include the sensible heat core (in the smaller two systems only), the enthalpy heat core (in all three systems), the energy wheel (in all three systems) and the reverse flow (in all three systems). The enthalpy heat core analysis was separated into two pieces: enthalpy heat core in the two smaller systems; and enthalpy heat core in the larger system only. This provides a clearer picture of which system is driving the energy consumption and cost savings. The simple payback periods show that energy recovery on the two smaller systems is only cost effective in climate regions 7a, 7b, and 8, after the sensible heat in the exhaust stream rises from 25 to 30 kW.

Energy Recovery in the large system, with 78 kW of sensible heat in region 4 and 197 kw of sensible heat in region 8, is cost effective for all of the energy recovery technologies analysed in all six climate regions. The reverse flow technology has short payback periods in the colder climate regions 6 through 8 and may well offer the best long term savings with its higher performance and longer expected service life of 30 years.

Secondary School

The Secondary School archetype model has six packaged constant volume systems with natural gas-fired heating and direct expansion cooling. Two of the systems serve multiple zones and four single zone systems serve the gymnasium, the auxiliary gymnasium, the cafeteria and the auditorium. As in the primary school model, additional zone heating is provided by hot water radiators connected to a natural gas-fired boiler. The outdoor air flow rates are relatively high with outdoor air ratios ranging between 0.27 and 0.51 and outdoor air flow rates of up to 6,300 litres per second. The average heat lost in the exhaust stream per system is between 102 kW in region 4 and 257 kW in region 8.

Since all six of the systems in the Secondary School are fairly large with high outdoor air flow rates (the smallest of the four single zone systems has a supply flow rate of 1,800 L/s and an outdoor air flow rate of 800 L/s) only the higher performance enthalpy heat core, energy wheel and reverse flow technologies were analysed. All six systems were modelled together as the smallest system has a minimum of 40 kW of sensible heat in its exhaust stream in climate region 4 which is larger than the 25 kW threshold observed for the Primary School. Excellent energy consumption and cost savings are observed for all energy recovery technologies in all six climate regions.

The energy wheel has payback periods of 5 years or less in all six climate regions, and the reverse flow system has payback periods of shorter than 10 years in climate regions 6 through 8. The high outdoor air flow requirements lead to short payback periods in all six climate regions.

Warehouse

It is often difficult to get energy recovery into warehouses, as they have relatively low outdoor air requirements and they seldom have proper ventilation systems. Many warehouses are ventilated by infiltration of outdoor air through louvres or dampers coupled to an exhaust system on the other side of the building. Space heating is provided by gas-fired unit heaters to maintain temperature setpoints and space cooling is seldom provided. Packaged rooftop units tend to use heat core or energy wheel technologies, but the incremental capital cost may be quite high if it includes the addition of an entire ventilation system.

The Warehouse archetype model provided has a single heating and ventilating system that provides 100% outdoor air at a flow rate of 1,346 litres per second. The maximum supply air temperature is 48.9ºC. The sensible heat in the exhaust stream ranges from 41 kW in climate region 4 to 104 kW in climate region 8. Natural gas-fired unit heaters are used to heat the warehouse.

In this 100% outdoor air application with no requirement for space cooling, energy recovery provides short payback periods across all climate regions for the enthalpy heat core and energy wheel. Although all three technologies show comparable annual energy savings, the sensible core, with its lower energy recovery performance, is not as cost effective.

The energy wheel has a lower incremental capital cost than the enthalpy heat core and the highest performance of the three technologies modelled. It has a simple payback period shorter than five years in all six climate regions.

DISCUSSION AND CONCLUSIONS

The addition of heat recovery to thirteen NECB archetype building energy models was analysed and exhaust air heat recovery systems were found to provide short simple payback periods in all 13 of the NECB archetype buildings modelled. A summary of the simple payback periods is shown in Figure 1 below. For the Big Box Store, Small Hotel, Long Term Health Care, Large and Medium Office, Full and Quick Restaurant, Primary and Secondary School and Warehouse models, a payback period that is shorter than the equipment lifetime is observed in all six Canadian climate regions. The Large Hotel, and Large MURB have a payback period longer than 15 years in climate region 4. The Small MURB has a payback period longer than 15 years in climate regions 4 through 6. In all but one model, the Small MURB, the payback periods are shorter than the equipment lifetime in climate region 5 with more than 3000 Celsius heating degree days. If costs associated with building elements that last the lifetime of the building (e.g. electrical upgrades, structural elements, or ductwork which last longer than the lifetime of the main HVAC and heat recovery system itself) are removed from the analysis, the simple payback periods are shortened and the use of heat recovery systems becomes even more favourable. Heat recovery has a payback shorter than the equipment lifetime in all climate regions for the Large MURB and in climate regions 6-8 for the Small MURB.

The results indicate that the amount of sensible heat in the exhaust air stream is not a reliable metric for predicting the cost benefit performance of exhaust air heat recovery systems. The sensible heat threshold varies widely from building to building, and ranges from 1 kW in the Small Hotel to 182 kW in the Large Office. Excluding the buildings with self-contained systems serving single dwelling units (the Small Hotel, and the Small and Large MURB) exhaust air heat recovery is cost effective above a threshold of 25 kW in the Primary School model and above 35 kW in the Big Box Store Model.

Those models which show the highest energy cost savings (see Figure 2) and shortest payback periods are those with winter design supply air temperature setpoints above 21ºC and with outdoor air fractions above 0.2. The Large Office model, despite having a high level of sensible heat in the exhaust air stream, shows poor performance on heat recovery. Increasing the outdoor air fraction in winter in the Large Office model by right-sizing the design supply air flow rate to 15% above the coincident peak, and by reducing the minimum supply air flow setpoint from 0.3 to 0.2 was found to dramatically improve the energy recovery potential and decrease the payback period from 10 years to 3 years in climate region 6. The outdoor air ratio was increased from 0.125 to 0.15 as the supply air flow rate was decreased from 52,000 to 40,300 litres per second.

In climate regions 5 and 6, heat recovery on the smaller systems in the Primary School has a simple payback period longer than 15 years. These systems have an average supply air flow rate of 1000 litres per second with an outdoor air ratio of 0.47. The systems in the Big Box Store have an average supply air flow rate of 3,200 litres per second and an outdoor air ratio of 0.27. The simple payback period in this model with an energy wheel is 6.4 years in climate region 5 and 4.6 years in climate region 6.

In climate region 4, heat recovery remains cost effective in most of the archetype models. However, the payback period is longer than 10 years for the Big Box Store, the Large Hotel, the Large and Medium Office buildings and the Small and Large MURBs. Shorter payback periods are seen in the Long Term Health Care model, the Primary and Secondary Schools, the Full Service and Quick Restaurants and the Warehouse. The last three models have 100% outdoor air systems, while the first three models have high supply air flow rates of over 10,000 litres per second. In addition, the Primary and Secondary Schools are modelled without cooling, and the Long Term Health Care building is in operation 24 hours per day.

Climate Zone	4	5	6	7a	7b	8
Big Box Store Energy Wheel	12	6.4	4.6	4.2	3.5	2.5
Large Hotel Enthalpy HX	25	3.4	2.6	2.8	2.0	1.2
Small Hotel PTACs Enthalpy HX	8.1	5.7	4.2	3.8	3.1	2.2
LTHC Reverse Flow	5.6	4.5	3.6	3.2	2.8	2.1
Large MURB Enthalpy HX	18	12	8.8	8.2	7.1	5.8
Small MURB Enthalpy HX	335	40	17	12	8.7	4.6
Large Office Energy Wheel	11	3.9	2.6	2.3	1.9	1.2
Medium Office Energy Wheel	11	5.2	3.7	3.1	2.7	1.8
Full Restaurant Heat Pipe	6.5	8.2	6.4	5.0	4.6	3.4
Quick Restaurant Heat Pipe	7.2	8.5	6.8	5.3	4.8	3.5
Primary School Energy Wheel	1.6	1.1	0.9	0.8	0.7	0.5
Secondary School Energy Wheel	5.0	3.5	2.8	2.5	2.2	1.6
Warehouse Energy Wheel	4.3	3.6	2.8	2.4	2.1	1.5

Payback Period	> 15	8-15	5-8	2-5	0-2	Years

Figure 1: Simple payback period by archetype and climate zone

A number of the building energy models required careful attention to the control and operation of the HVAC systems and energy recovery units in order for the full heat recovery potential to be realized. These results indicate that careful attention to the design and operation of HVAC systems is required to ensure that heat recovery equipment delivers on its promised energy consumption and cost savings.

For single dwelling units in large multi-unit residential buildings, the results suggest that heat recovery can be cost effective in climate regions 5 through 8 with more than 3000 Celsius heating degree days. Heat recovery is also found to be cost effective in the Small Hotel model (which has electric heat) in Canada's mildest climate region 4, with less than 3000 Celsius heating degree days.

In commercial kitchens, the cost benefit of adding heat recovery to kitchen exhaust is challenged by the increased cost of maintenance and by the shortened lifetimes of heat core heat recovery devices and

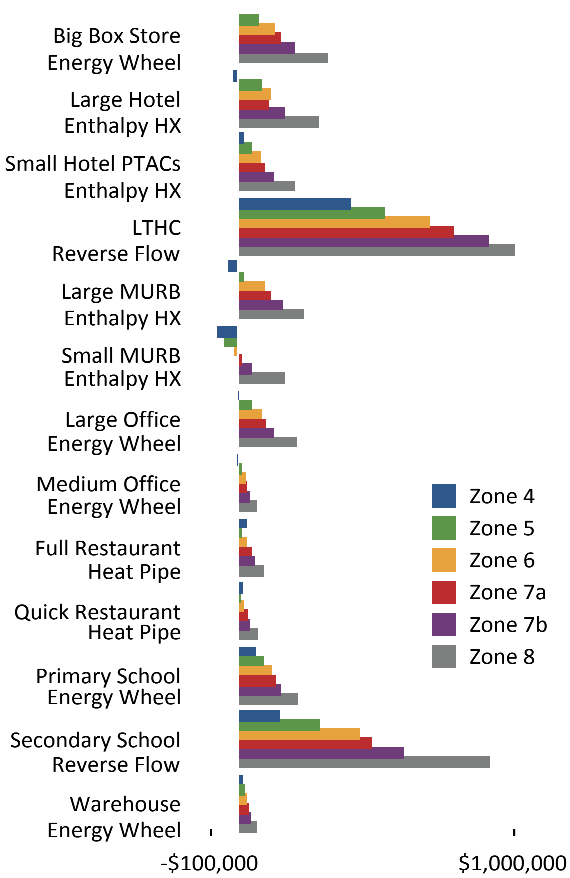

Figure 2: 15 year lifecycle cost savings by archetype and climate zone

energy wheels. Nonetheless, heat recovery on exhaust air using heat pipes, which have a longer service life, is found to be favourable across all climate regions.

Among the technologies studied, the energy wheel with a sensible effectiveness of 72% strikes a good balance between cost effectiveness and performance. Where energy wheels are not an option (either due to space restrictions or concerns with cross contamination), the enthalpy heat core, with a sensible effectiveness of 68% and a latent effectiveness of 57%, was found to outperform the sensible heat core with a sensible effectiveness of 56%. Enthalpy heat core devices tend to cost only marginally more than sensible core devices, but offer higher performance by recovering both latent and sensible heat. Reverse flow devices, which have the highest performance (sensible effectiveness of 87% and latent effectiveness of 67%) and highest cost of the heat recovery technologies studied, are only cost effective in those applications with the highest outdoor air flow rates and with a supply air heating setpoint above 21ºC. The shortest payback periods for reverse flow systems are seen in the Long Term Health Care and Secondary School models. Both of these models have high outdoor air flow rates and supply air heating setpoints of 25ºC.

A significant finding of this study is that heat recovery on exhaust air delivers high annual energy savings on space heating in all of the NECB archetype buildings in all of the NECB climate regions. However, the cost savings are challenged by the present-day low commodity pricing for natural gas. At the utility rates of $0.1128/kWh for electricity and $0.3449/cubic metre ($0.0328/ekWh) for natural gas used in this analysis, electricity costs more than three times as much as natural gas per equivalent kWh.

LIMITATIONS

The use of heat recovery may allow heating and cooling equipment to be downsized which would lead to additional up-front capital cost savings. The cost benefit of downsizing chillers, boilers, and heating/cooling coils, and other equipment has not been considered in this study.

The study relies on manufacturer's specifications for heat recovery performance. Field testing of different heat recovery devices to verify performance was not a part of this study.

The present study has not considered active humidity control. The NECB archetype models do not include humidification, and dehumidification is achieved in most models by cooling the supply air in the summer months to a temperature setpoint of 12.8ºC. It is possible that control of the humidity levels would affect the results presented in this study, and that changes in the results might favour the enthalpy heat recovery devices. Satellite exhaust has not been considered. Satellite exhaust systems that do not return exhaust air to the central air handling unit will diminish heat recovery performance by returning less exhaust air to the heat recovery system.

The cost analysis is simplified by considering only the current costs of energy. A more advanced analysis could be carried out that considers various models for electricity and natural gas price escalation. As noted in the Discussion above, a narrowing of the gap between electricity and natural gas prices would strongly tip the cost benefit analysis in favour of exhaust air heat recovery systems.

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