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Energy Use of Ventilation Air Conditioning Options for Ground-Source Heat Pump Systems

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ABSTRACT

High outdoor ventilation air requirements can lead to significant increases in building energy use, thermal discomfort, indoor air quality problems, and litigation. Engineers often avoid ground-source heat pumps because of the perception that there are no acceptable methods for conditioning the ventilation air. However, this difficulty is currently a problem with all types of heating and cooling systems. Decisions may be based on system performance at design conditions without regard to seasonal energy consumption. A bin method for evaluating the energy use of outdoor air treatment systems has been developed and is described in a previous paper. Another paper was limited to the discussion of a four-story office building in a warm climate and five ventilation air system options. This paper extends the application of the evaluation procedure to two additional options in three different climates (Birmingham, St. Louis, and Minneapolis). In addition to the four-story office building, the discussion also includes an eight-classroom wing of a school. The results indicate fan energy requirements have a strong influence on annual energy consumption of conventional and heat recovery equipment. The calculation of the building balance point temperature is critical since most systems permit the outdoor air to displace cooling equipment energy when outdoor conditions are below the room set point conditions. Heat recovery systems saved little annual energy in cooling-dominated climates but were more effective in colder climates.

INTRODUCTION

Outdoor ventilation air treatment (cooling, heating, dehumidifying, and humidifying) equipment decisions are frequently based on performance at design conditions rather than on seasonal energy consumption. This biases the selection toward equipment that operates well under extreme conditions without regard to part-load performance. Part-load efficiency should have a strong influence upon equipment selection since most hours of operation occur during mild conditions. If capacity is a strong function of outdoor-to-indoor air temperature difference and/or humidity difference, part-load capacity will be moderate or poor. Additionally, fan energy use will be high if the static pressure losses across the coils, energy recovery elements, and associated filters are high. In these cases, annual fan motor energy consumption can offset heat recovery energy savings.

An analysis of a 32,000 ft^2 (3000 m^2) office building requiring 4000 cfm (1900 Lps) of outside air and a 9600 ft^2 (900 m^2) classroom wing requiring 2520 cfm (1180 Lps) were conducted using Birmingham, St. Louis, and Minneapolis weather data. Eight hours per day, five days per week occupancies were used. The seven options were (1) a total heat recovery unit, (2) a sensible heat recovery unit, (3) a direct expansion cooling/gas-fired furnace, (4) a water-to-water heat pump, (5) an air-to-air heat recovery heat pump, (6) a heat pipe heat recovery unit, and (7) a direct expansion cooling/electric furnace.

Figure 1 shows the seven options of ventilation air equipment in this analysis. The fan motor sizes shown are for the office system. The fan motors for the classroom wing are approximately 30% smaller.

An 80% effective rotary wheel was used for the total heat recovery system (HRU-wheel). It can add the heating and cooling capacity by recovery of both the sensible and latent energy from the exhaust air. This will reduce the coil size, the input power of the supplemental coil for cooling, and the

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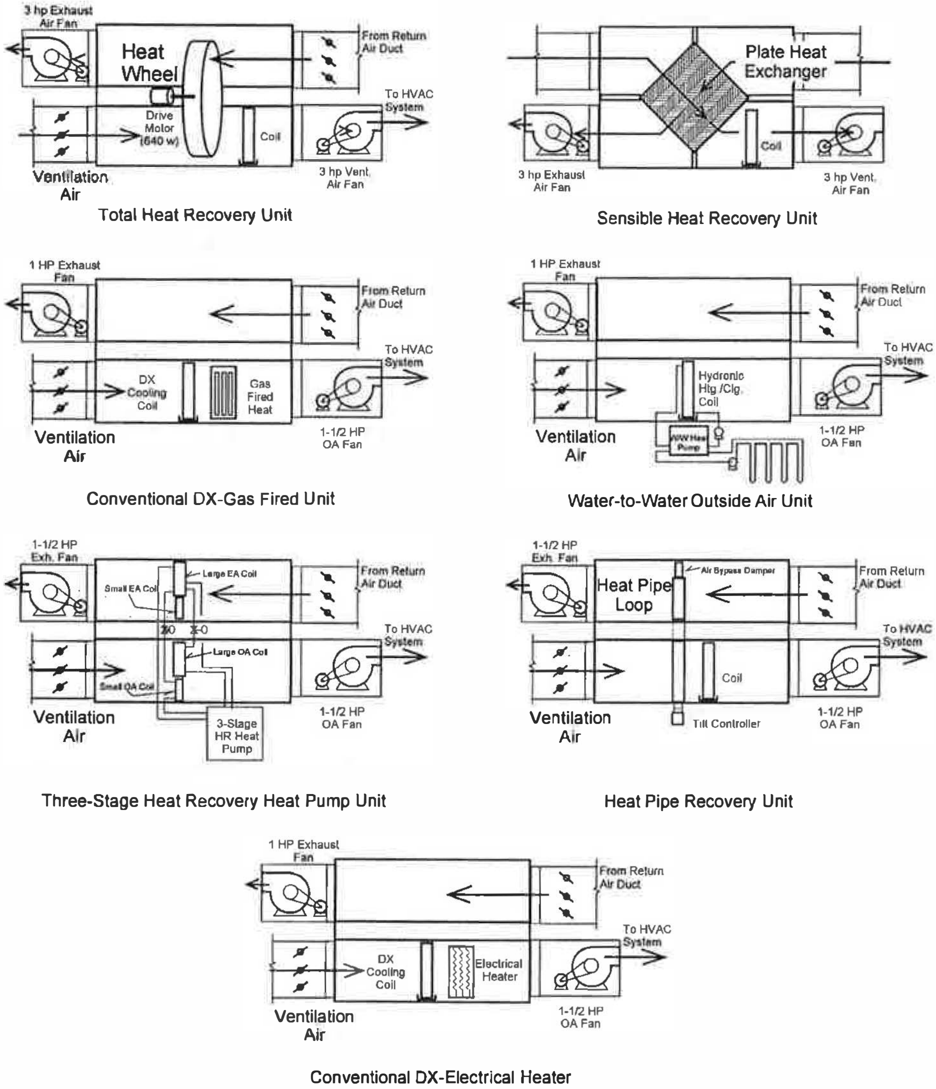

Figure 1 *Seven ventilation air treatment options.*

supplemental natural gas for heating. When manufacturer's sizing recommendations are followed, the required supply and exhaust fans are relatively large when compared to conventional ventilation air fans. Since both airstreams must pass through the heat wheel, the supply and exhaust fans must provide sufficient static pressure to overcome the friction of the HRU, filters, and duct. A small motor rotates the wheel (Venmar 1997). A 70% effective plate heat exchanger was used in the sensible heat recovery unit (PHE-HRU) analysis (Venmar 1996). Since it only recovers sensible heat, its capacity to supplement the cooling/heating and to reduce the coil size was smaller than the total heat recovery system.

A conventional vapor compression-direct expansion system combined with an equivalent 10 SEER cooling unit and an 80% AFUE gas-fired furnace was considered (Carrier 1995). The supply fan motor was sized to overcome the friction in the coil, filter, and duct. The exhaust fan motor is smaller than the supply fan motor since it does not have to circulate air through a coil. The water-to-water heat pump system (FHP 1997) power input includes the compressors, the two fans, and the auxiliary energy use of two loop pumps. The air-to-air heat recovery heat pump incorporates two conventional compressors (ARI 1997) and the two fans. The performance of the heat pipe (HP-HRU) was modeled using data from the manufacturer (HPT 1998). The conventional DX-electrical heating unit (DX-EH) used an electric furnace to supply heating and a vapor-compression cooling unit identical to the one used with the gas furnace. All units are centrally located with ductwork routed to the return air of the individual zones. For the office, the outdoor air unit was located on the roof with supply and return duct routed to a ducted system on each floor. The floor plans and ductwork are shown in Figures 2 and 3.

SEASONAL ENERGY EVALUATION PROCEDURE

A more detailed explanation of the evaluation procedure is presented in another work (Kavanaugh 1999). A summary is presented here.

- Use bin data that include mean coincident wet bulb and are subdivided into four-hour increments to drive the energy calculation.
- Use psychrometric relationships to determine specific humidity from dry-bulb and wet-bulb temperatures for each bin temperature and for the indoor air conditions. (In the cooling mode, conditions used were 75°F [24°C] dry bulb and 63°F [17°C] wet bulb for bin temperatures of 67°F (19°C) and greater. For the heating mode, the indoor conditions were 70°F [21°C] with a relative humidity of 40% for Birmingham and 30% for St. Louis and Minneapolis).
- Find the sensible and latent capacities of ventilation air device(s) and resulting power and heat input requirement for each bin.
- Include fan heat as a sensible load and add a defrost penalty when ventilation air coil surface temperature is below the freezing point of water.
- Compute auxiliary equipment power and/or heat input requirement if primary device does not have adequate capacity (i.e., heat recovery devices).
- Calculate the heating/cooling loads for the building as a function of outdoor temperature in order to determine the balance temperature when internal loads balance heat losses and cooling is no longer required. (Since this balance temperature is often well below 55°F [13°C], the outside air will contribute to a reduction in the cooling requirement.)

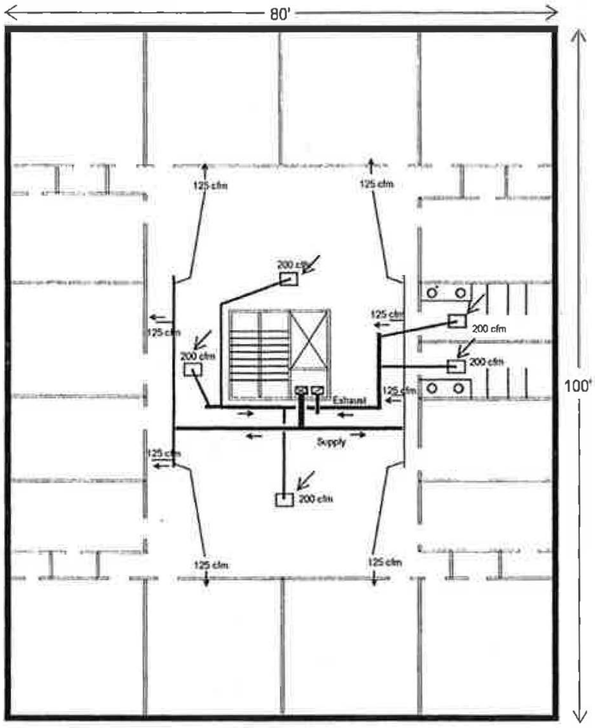

Figure 2 *Ventilation air ductwork for one floor of a four-story office building.*

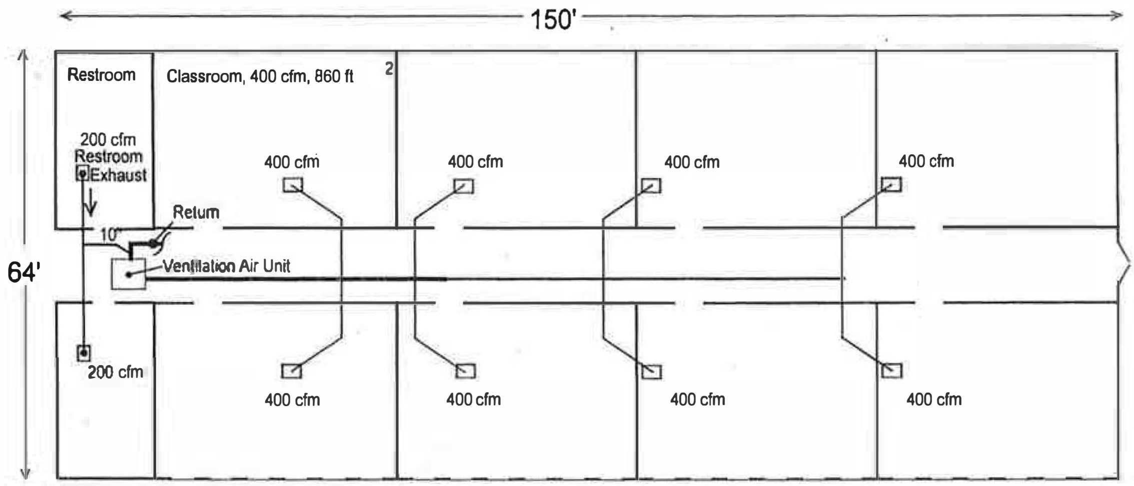

Figure 3 *Ventilation air ductwork for a classroom wing.*

- When outside air conditions are above the balance temperature and below indoor air temperature and/or specific humidity, the system has "free cooling" capability and will operate in an economizer mode. Therefore, equivalent cooling energy requirements are deducted.
- Sum electrical and heat input energy requirements for all temperature bins during occupied periods.

The need for weather data based evaluation is especially critical given the fact that heat recovery equipment performance is a strong function of the temperature and humidity *difference* between the ventilation air and the exhaust air. HRU efficiency (capacity ÷ power input) will decline significantly when outdoor conditions are moderate even though the effectiveness is constant. The input power to this type of equipment is primarily the fan motors, which is relatively constant with airflow requirement (unless bypass dampers and variable-speed drives are incorporated).

OFFICE BUILDING RESULTS

The results presented in this section follow the procedure outlined above using ASHRAE bin data (ASHRAE 1995). They are presented with and without the economizer. When the outdoor air temperature is between the indoor air temperature and the balance temperature, an economizer mode is incorporated that recognizes the reduction in cooling equipment energy input. The balance temperatures were 35°F (2°C) in Birmingham, 38°F (3°C) in St. Louis, and 42°F (6°C) in Minneapolis. In this mode of operation with the conventional DX-furnace system, the water-to-water heat pump, and the air-to-air heat pump, the cooling units simply cycle off and air continues to follow the same paths through the coils. However, the heat recovery units must be deactivated or bypassed or they will reheat the outdoor air that could be contributing to a reduction in cooling energy. Fan energy savings in the bypass mode are not significant unless variable-speed drives are installed on the fan motors. All evaluations consider the supply fan heat that reduces capacity in cooling but adds the capacity in the heating mode.

The results for the office building in Birmingham are summarized in Figure 4 based on utility cost of 7¢ per kWh for electrical and 50¢ per therm (0.5¢ /MJ) of natural gas. The analysis indicates the following.

- The conventional DX coil with a natural gas furnace is the least expensive outdoor air option to operate in Birmingham. The system had a significant benefit from the economizer mode operation because of the large number of hours between the balance temperature (35°F/2°C) and the indoor set point (75°F/24°C). Heating energy use was small since there were only 48 hours when the outdoor temperature was below the balance temperature in the 8:00 a.m. to 4:00 p.m. period.
- The total heat recovery unit was only slightly more expensive to operate. The small number of bin hours in which the outdoor temperature in this location was significantly below the indoor set point temperature limited the heating mode energy-saving potential of the HRU. All systems were cycled off at night when the air temperatures are more extreme. Also, the system did not benefit as much as the conventional equipment from the free cooling mode due to the added heat generated by the larger supply fan motor. However, the energy consumption at the extreme conditions was 40% of the DX-furnace in heating and 50% in cooling (Kavanaugh and Xie 1999).
- The costs to operate in order from the least to the most expensive of the remaining options are the three-stage heat recovery heat pump unit, the conventional DX-electrical heater unit, the water-to-water heat pump, the heat pipe heat recovery unit, and the sensible heat recovery unit.
- The economizer mode has significant impact on the results, and determination of the balance temperature is important to determine the level of impact.
- The method of preheating the ventilation air had little impact on operating cost in Birmingham because of the limited number of hours below the balance temperature.

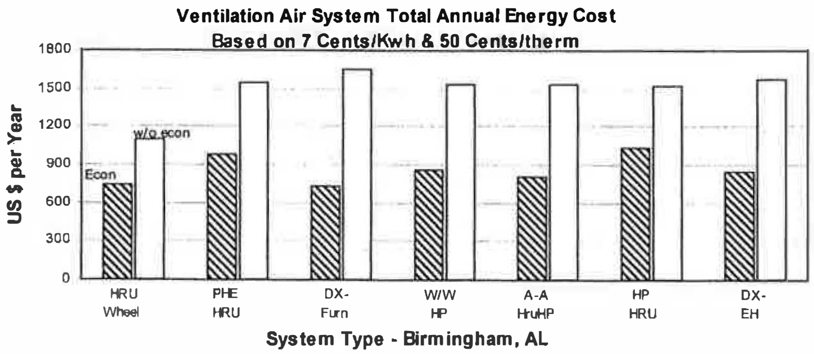

Figure 4 *Energy costs for ventilation air options in the Birmingham office.*

Figure 5 shows the evaluations for the office building in St. Louis. The analysis indicates the following.

- The total heat recovery unit was the least expensive option to operate. Although the larger fan heat contribution was present, the much greater number of hours in heating when the heat recovery mode was more effective offset this penalty.
- The sensible heat recovery unit, the conventional DX coil with a natural gas furnace, the water-to-water heat pump, and the heat pipe heat recovery unit were near the same cost to operate. The air-to-air heat recovery heat pump was only slightly more expensive to operate.
- The DX cooling-electrical furnace heater unit cost 200% to 300% more to operate compared to the other options.
- The economizer mode has significant impact on the results, and determination of the balance temperature is important to determine the level of impact.

Figure 6 shows the evaluations for the office building in Minneapolis. The analysis indicates the following.

- The effectiveness of the total heat recovery unit was more pronounced in this much colder climate. Additionally, the humidification benefits are evident with this method of evaluation. Humidification energy is required when the indoor air relative humidity falls below 30%. Total HRUs will transfer moisture from the exhaust stream to the ventilation air, which is extremely dry when outdoor temperatures are low.
- The other two heat recovery units were next to the lowest options in terms of operating costs with the heat pipe being slightly more effective.
- The costs in order from the least to the most of the remaining options are the water-to-water heat pump, the conventional DX-gas furnace, and the three-stage heat recovery heat pump unit.
- The DX cooling-electrical furnace heater unit costs 250% to 500% more to operate compared to the other options.
- The economizer mode impact was less pronounced in this climate.

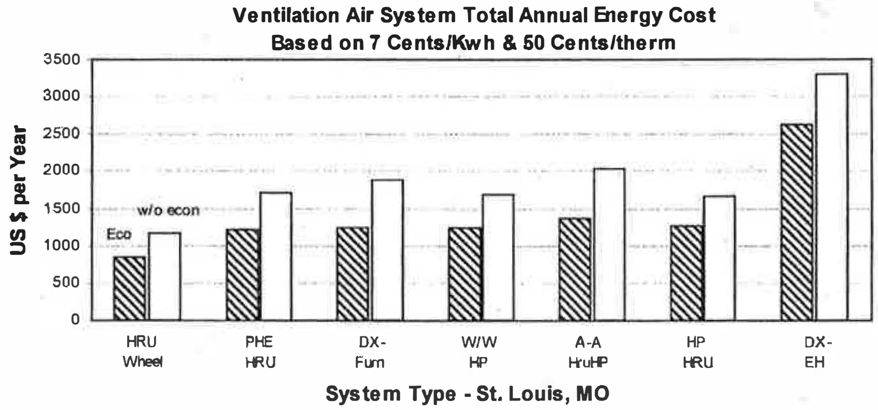

Figure 5 *Energy costs for ventilation air options in the St. Louis office.*

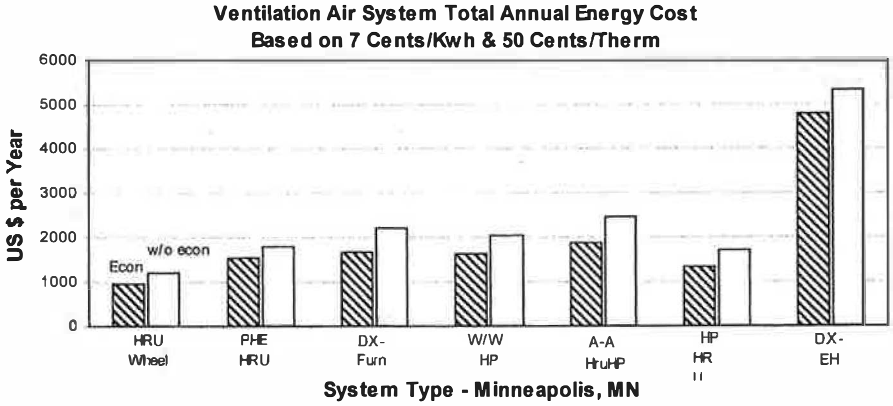

Figure 6 *Energy costs for ventilation air options in the Minneapolis office.*

SCHOOL CLASSROOM RESULTS

For the school, the evaluation is based on eight classrooms with a total area of 6100 ft^2 (560 m^2) with 20 students and a teacher per classroom. They are occupied eight hours per day, five days per week. The total outdoor airflow rate is 2520 cfm (1180 Lps), which is derived from ASHRAE Standard 62-1999 (ASHRAE 1999).

Each classroom has an individual unit to handle its own space cooling/heating load. The system uses a central unit to treat the outdoor air to the internal conditions. The outdoor air is delivered to the classrooms through a central ductwork. The same procedure used for analyzing the office building is applied to find the energy consumption of the classrooms.

Figure 7 shows the evaluations for the office building in Birmingham. The analysis indicates the following.

- The conventional DX coil with a natural gas furnace is again the least expensive outdoor air option to operate in Birmingham.
- However, the air-to-air heat recovery heat pump and the water-to-water heat pump have the second and third lowest predicted energy use. The primary reason for the improvement in energy efficiency relative to the other options was the smaller fan and pump motors for the short duct and piping networks.
- The costs in order from the least to the most of the remaining options are the total heat recovery wheel, the heat pipe heat recovery unit, the conventional DX-electrical heater unit, and the sensible heat recovery unit.
- The economizer mode has significant impact on the results, and determination of the balance temperature is important to determine the level of impact.
- The method of preheating the ventilation air had little impact on operating cost in Birmingham because of the limited number of hours below the balance temperature.

Figure 8 shows the evaluations for the school in St. Louis.

- The annual operating cost of the water-to-water heat pump is the lowest, but the total heat recovery unit and the heat pipe heat recovery unit used only slightly more energy for the classroom wing. The effectiveness of the HRUs in the more extreme heating climate begins to offset the added fan energy consumption.
- The costs in order from the least to the most of the remaining options are the conventional DX coil with a natural gas furnace and the sensible heat recovery unit.
- The conventional DX-electrical heater unit is significantly more expensive to operate than any of the other options because of the added heating requirement of the climate.

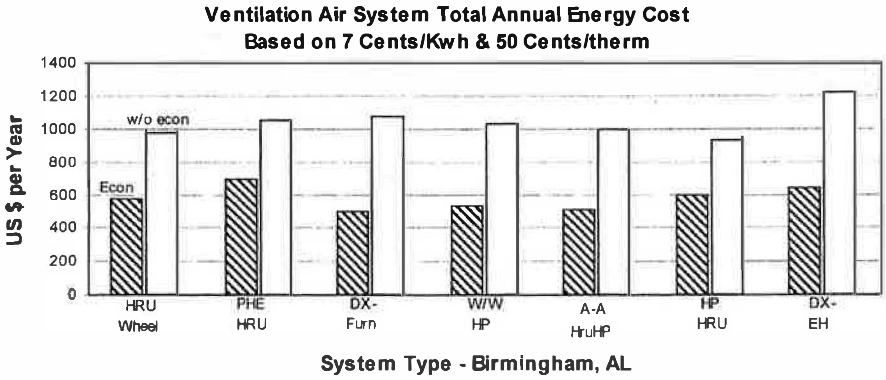

Figure 7 *Energy costs for ventilation air options in the Birmingham school.*

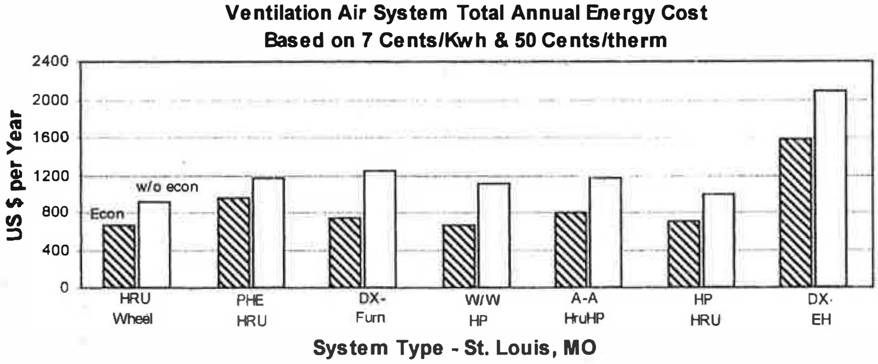

Figure 8 *Energy costs for ventilation air options in the St. Louis school.*

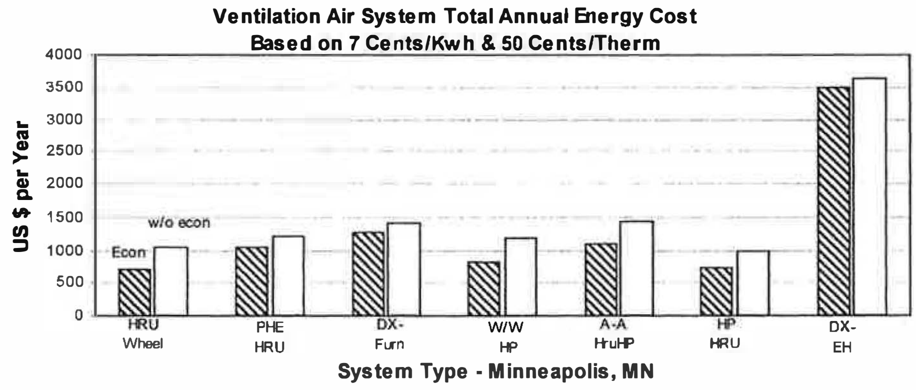

Figure 9 *Energy costs for ventilation air options in the Minneapolis school.*

Figure 9 shows the evaluations for the school in Minneapolis.

- The annual operating cost of the total heat recovery unit is the lowest, but the heat pipe heat recovery unit and the water-to-water heat pump used only slightly more energy for the classroom wing.
- The sensible heat recovery unit and the air-to-air heat recovery heat pump were next in terms of energy use. The difference in their effectiveness when compared to the total HRU was the added energy for humidification in the heating mode. The costs to operate in order from the least to the most expensive are the conventional DX coil with a natural gas furnace to the DX coil with the electric furnace.
- The conventional DX coil with a standard natural gas furnace costs more to operate in this cold climate than most of the options.
- However, the conventional DX-electrical heater unit cost 300% to 500% more to operate than the other options.

SUMMARY

The difference of energy consumption for the various options was surprisingly small with the exception of the electric furnace in cold climates. This is a result of the fact that fan energy of heat recovery units and low capacity of heat recovery units tend to offset the energy savings of this type of equipment during extreme outdoor conditions. However, heat recovery systems offer more benefit in colder climates such as Minneapolis. The another important benefit was derived from the use of untreated ventilation air in the "free cooling" mode when cooling was required and outdoor air temperatures were below indoor temperatures.

- Evaluation of ventilation air systems should include seasonal energy use of all fans, pumps, drive motors, compressors, and furnaces.
- Fan energy is significant portion of annual ventilation air system energy consumption.
- Heat recovery units, which may be effective at reducing energy use when outdoor conditions are extreme, can consume more energy on an annual basis than conventional equipment if ancillary equipment (fans, pumps, etc.) energy use is high.
- In order for heat recovery or conventional ventilation air systems to be efficient, fan losses must be minimized and control strategies optimized.
- The economizer (free cooling) mode provides significant energy savings with both heat recovery and conventional ventilation air systems, especially in warm and medium climates. Some options required additional ductwork and/or additional controls to allow this mode of operation.
- The balance temperature of the building has significant impact on the amount of free cooling energy savings and should be carefully calculated.
- Humidification energy should be considered when the introduction of dry outside air results in unacceptable indoor relative humidity levels (assumed to 30% in this analysis).

ACKNOWLEDGMENTS

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