

High-Performance Retail Store with Integrated HVAC Systems

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ABSTRACT

A new all-electric retail store located in Montreal, Canada, incorporates several design features to maximize the interactions between various building components. The two-story, high-performance, "green" commercial building is the result of an integrated energy design process and features ground-source heat pumps with radiant floors for space heating and cooling, improved building envelope, optimized natural lighting on the second floor, exhaust air energy recovery, and hybrid ventilation. A number of results, such as geothermal system operating parameters and building-specific energy performances, are presented. The final results show a specific annual energy consumption of 133.1 kWh/m² (12.4 kWh/ft²), while the reference building would be at 466 kWh/m² (43.3 kWh/ft²), for a reduction of 71.4%. Energy cost savings are CD\$ 24 per m² (CD\$ 2.22 per ft²).

INTRODUCTION

The commercial buildings in the province of Quebec consume more than 32.7 GWh of electrical energy annually, representing 18.5% (in 2001) of the total provincial annual consumption (MRNFP 2003). Reducing the energy consumption and minimizing the environmental impact of HVAC systems represent significant goals for building designers such as architects and engineers, especially in cold climates. Possible solutions involve ground-source heat pumps (GSHPs), radiant heating, natural ventilation, natural lighting, photovoltaic (PV) systems, passive solar heating, and optimized building envelopes. Some such solutions have been recently (2003) implemented in a high-performance retail store in Montreal, Canada. This store has a total sales open-space of 4 180 m² (45,000 ft²), including an 800 m² (8,500 ft²) storage area and

some administrative offices. The total cost of the project was CD\$ 6.1 M, approximately 33% of which accounted for the HVAC systems (CD\$ 482/m² [CD\$ 45/ft²]).

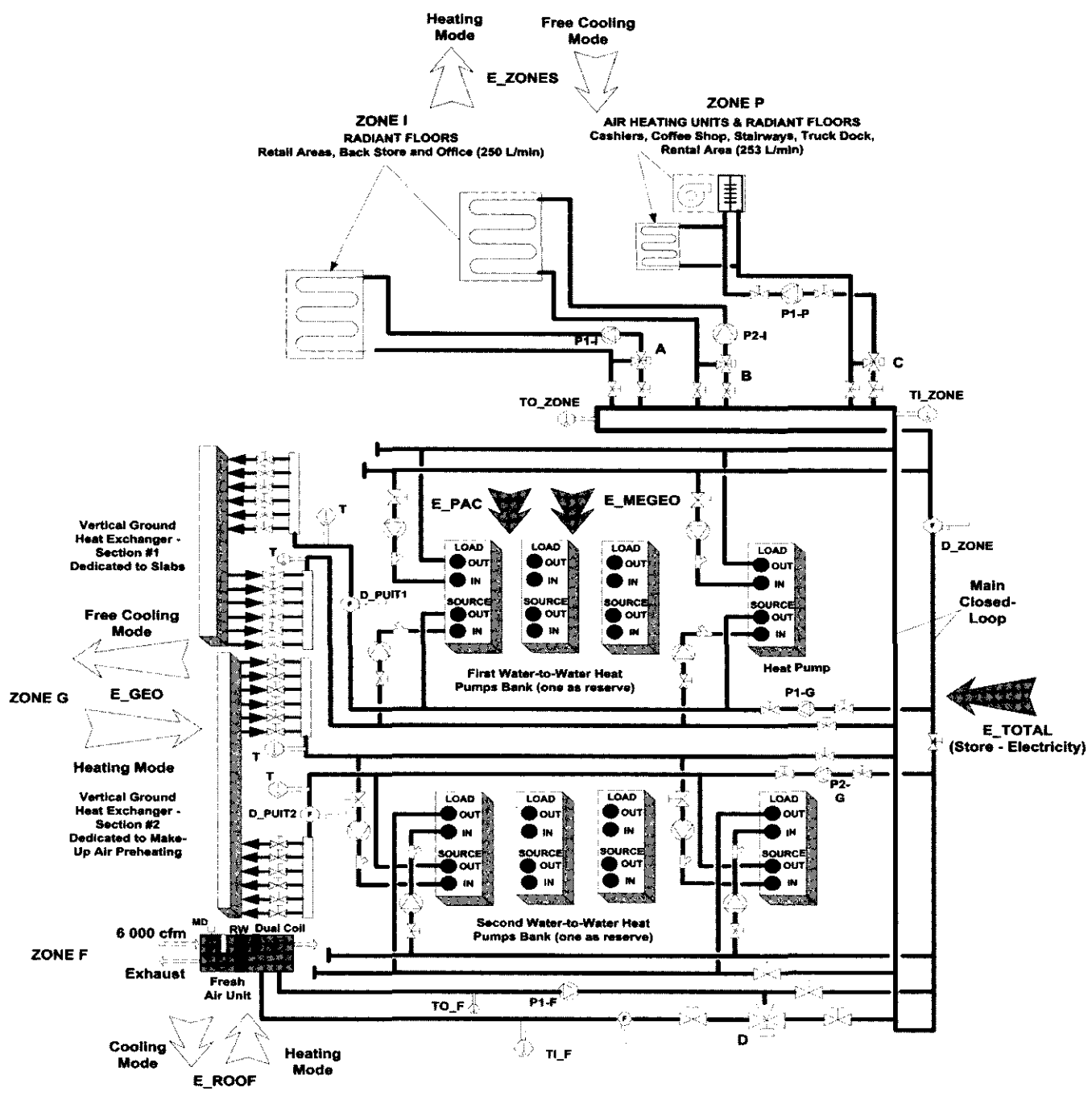
This commercial building, the first in Québec designed to meet Canada's C-2000 standard for high-performance buildings, has been awarded ASHRAE's 2005 Award of Engineering Excellence as the best project in all categories (ASHRAE 2005). It also has been awarded the AQME 2004 Energia Jury's Award (Charneux 2004a).

The main innovative characteristics of the building's HVAC systems (Figure 1) are: geothermal liquid-to-liquid heat pumps combined with radiant slabs used for space heating and cooling, a hybrid ventilation system, PV panels coupled with an irrigation pump, solar panels for domestic hot water (DHW) preheating, rainwater recovery for toilet flushing, passive geothermal (free) cooling with radiant slabs, and exhaust air rotary wheel heat recovery. A building automation system (BAS) connected via the Internet to the Weather Channel Web site recovers weather forecasts and uses them to adjust the main operating setpoints. The PV panels (2 × 20 W modules) and solar DHW preheating system (4 × 3 m² flat panels) were excluded from this study as they are marginal energy producers, while the main focus of the study was grid energy demand and consumption levels.

BUILDING AND SYSTEM CHARACTERISTICS

The store, opened to the public in May 2003, is located in a cold climate region having a 99% heating design value of -21.7°C (-7°F) and 1% cooling design values of 28.3°C (83°F) dry bulb and 21.1°C (70°F) wet bulb (ASHRAE 2001a). These outdoor conditions correspond to climatic zone 6A (ASHRAE 2004). The building's wall and roof R-values are, respectively,

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Legend - RW: heat recovery wheel; TI: inlet temperature; TO: outlet temperature; P: pressure; F: flow meter; E: energy; GEO: geothermal; MEGEO: geothermal mechanical device; PUIT: borehole

Figure 1 Configuration of the GSHP system with radiant floor and geothermal free cooling.

6.2 m²·K/W (35 ft²·°F·h/Btu) and 7 m²·K/W (40 ft²·°F·h/Btu), more than twice the national and provincial code requirements. The windows are high-performance, double-glazed low-e glass with the shading coefficient optimized according to exposures (clearer on the north side than on the south side). They have a U-factor of 1.87 W/m²·K (0.33 Btu/h·ft²·°F). The overall building U-factor is approximately 0.43 W/m²·K (0.076 Btu/h·ft²·°F).

The window system has been designed with a target of providing about 325 lux (30 fc) of general lighting through daylight to the second floor during an overcast day while minimizing glare during sunny days. The design solution includes a set of glazed continuous rows of different sizes and at different heights, located on the north and south exposures of the building as well as within a roof monitor. Daylight sensors shut down parts of the artificial lighting when it is not required. It was estimated that there will be enough daylight for nearly half of the building's yearly operating hours. Additionally, the artificial lighting has been designed with a power density of 1.3 W/ft² (14 W/m²), respectively, 48% and 13.3% lower than the Canada's Model National Energy Code for Buildings (MNECB) 1997 and Addendum g of ASHRAE Standard 90.1-2001 (Genest and Charneux 2005).

Main Hybrid Ventilation System

The 23,600 L/s (50,000 cfm) hybrid ventilation system involves large 1.2 by 1.2 m (3.65 by 3.65 ft) underground tunnels running along the building's perimeter and four 5,900 L/s (12,500 cfm) low horsepower propeller fans. In "natural" ventilation mode, the air flows through a bank of filters, underground tunnels, and vertical ventilation shafts before being delivered to the retail areas and storage spaces. It exits the building through a set of 16 motorized dampers located in the roof monitor. This system operates when the outdoor dry-bulb temperature is between 12.8°C (55°F) and 26.7°C (80°F) but only if the outdoor dew-point temperature is below 18.3°C (65°F) in order to prevent condensation on the cool concrete floors. It can be combined with slab radiant cooling that uses water directly fed from the geothermal exchanger when needed. The hybrid ventilation system supplies free cooling to the building for about 1,500 hours out of the 3,200-hour annual store opening time. At maximum airflow capacity, the hybrid ventilation system supplies 5.6 L/s·m² (1.11 cfm/ft²), or about four times more than the minimum outdoor air requirements set by ASHRAE Standard 62-2001 (ASHRAE 2001b). When the outdoor temperature is outside this range, the BAS activates the secondary dedicated outside air system (DOAS) ventilation system.

Secondary DOAS Ventilation System

The secondary ventilation system uses a roof-mounted DOAS to preheat (wintertime) or dehumidify (summertime) the outdoor air required for building operation when the outdoor temperature is outside the natural ventilation system

operating range. The DOAS is used at all times for sanitary exhaust. It includes variable-speed drives controlled with a CO₂ sensor in the exhaust airstream and a total heat recovery wheel (75% of thermal efficiency).

Heating and Cooling Radiant Slabs

In order to avoid traditional high energy consumption of HVAC fans, the building space heating and cooling system was chosen to be mostly radiant concrete floors with embedded cross-linked polyethylene (PEX) tubes. The slabs are used to provide both heating and sensible cooling to the building. It was designed to have a lot of exposed surface with minimal finish to reduce slab surface resistance and minimize the required fluid temperature in heating and cooling. A number of water-supplied unit heaters are used to provide heating to the vestibules and staircases.

The radiant slab concept for space heating and cooling allows an extension of the usual range of indoor temperatures for comfort from as low as 18.3°C (65°F) in winter to as high as 26.7°C (80°F) in summer, further reducing the heat losses and gains through the building envelope and the required capacity of the heat pump system.

GSHP System

Eight identical water-to-water heat pumps (having a total nominal cooling capacity of 80 tons) filled with HFC-407C are connected to twelve 175 m (575 ft) vertical boreholes (26 m/ton [79.2 ft/ton]). Since the heat pumps also supply the roof-mounted DOAS, a propylene glycol/water mixture (50% by volume and freezing point of -35°C [-31°F]) is used as heat transfer fluid in both geoexchange and building loops to prevent freezing. Even though propylene glycol is more viscous than other fluids and more difficult to handle in cold weather, its nontoxic, nonflammable, and noncorrosive properties were favored for this fully automated, operator-free installation. In order to prevent the U-tubes squeeze problem associated with below-freezing water supply to the geothermal wells and enhance the ground heat exchanger overall thermal performance, a bentonite-based grout was used as backfill material.

The heat pumps are divided into two four-unit logical operating groups: one group is assigned to the radiant slabs and the unit heaters and the other group is assigned to the DOAS (Figure 1). The concept's originality is also seen in the existence of four main zones to which the heat transfer fluid flows: a peripheral zone (P), which includes unit heaters and provides heating/cooling to the cash registers, coffee shop, stairs, and radiant floors in highly glazed sales areas; an internal zone (I), which includes most of the radiant floors located in the sales areas, warehouses, and offices; a geoexchange zone (G), including two six-vertical-bores groups; and a DOAS zone (F). Zones P and I are piped in series to increase the water loop temperature differential. Finally, to take advantage of geothermal natural cooling whenever possible, dedicated circulating pumps (P1-G and P2-G) are operated to delay using the heat pumps in cooling mode until necessary.

System Control and Operation

Because the concrete floors have a slow response time to the heating and cooling demands, the BAS operates zones P, I, and G continuously during the heating season and most of the cooling season. Predictive logic based on weather forecasts automatically retrieved from the Internet corrects slab zone temperatures based on the actual outdoor temperature or the forecasted temperature to accelerate slab energy loading in advance of very cold or hot days.

In **heating mode**, when the outdoor temperature is lower than 12°C (53.6°F), zones I, P, and G are operational. Water pumps P1-I, P2-I, and P1-P are running, while valves A, B, and C modulate in order to keep each zone's water return temperature at their respective setpoints, following a ramp from 36°C to 20°C (96.8°F to 68°F) according to the outdoor temperature from -25°C to 15°C (-13°F to 59°F). Starting in mid-afternoon and until midnight, the weather forecast software overrides the outdoor temperature reading with the next night's low temperature forecast, thus adjusting the water supply setpoint accordingly.

The **natural ventilation mode** operates only if the outdoor dew point is lower than 16.7°C (62°F) and the outside temperature is between 12°C and 26.7°C (53.6°F and 80°F). During this mode, all heat pumps and circulating pumps are stopped. Cooling is provided by the hybrid ventilation system.

In **geothermal free cooling mode**, zones I, P, and G are operational while the heat pumps and zone F (the DOAS) are stopped. This mode operates to supplement the natural ventilation mode if the outdoor temperature is higher than 24°C (75.2°F). Between May and October and starting from mid-afternoon to midnight, it will also precool the slabs if the weather forecasts predict that the next day's high temperature will be above 20°C (68°F). Water pumps P1-I, P2-I, P1-P, and P1-G run continuously, and valves A, B, and C modulate in order to maintain the return temperature to each zone at 18°C (64.4°F). When the return temperature of the heat transfer fluid is higher than 15°C (59°F), the P2-G pump runs until the return temperature falls below 12°C (53.6°F).

The last cooling step is the **mechanical cooling mode**. It operates in replacement of the natural ventilation mode when outdoor temperature and dew point are higher than prescribed. Water pumps P1-I, P2-I, and P1-P are running, and valves A, B, and C modulate in order to maintain water return temperature to each zone at 13°C (55.4°F). A low limit prevents return water temperature from getting below indoor dew point.

Ventilation air is provided by the hybrid ventilation system and/or the DOAS (zone F). Both systems operate according to the store occupancy schedule, depending on the building mode. When operating in heating or mechanical cooling mode, the DOAS supplies treated outdoor air directly to the hybrid ventilation system, and the latter acts as the building air distribution system. The DOAS fans start at minimum speed and modulate in order to keep the indoor CO₂ level at 900 ppm without going below sanitary exhaust needs. During heating mode, pump P1-F and valve D operate to maintain supply air temperature between

22°C and 13°C (71.6°F and 55.4°F), ramped according to indoor air temperature (from 20°C to 26°C [68°F to 78.8°F]). During cooling mode, the supply air setpoint is fixed at 12°C (53.6°F) to provide dehumidification.

During the natural ventilation mode, the hybrid system operates in free cooling mode while the DOAS runs only the exhaust fan (at minimum speed) to provide sanitary exhaust. In this mode, the four propeller fans and the roof monitor dampers are operated in sequence to supply enough outside air to maintain indoor temperature at about 22°C (71.6°F).

RESULTS

The temperature of the geothermal fluid entering section #1 of the ground heat exchanger during a very hot period of a typical summer month (June 2004) has never exceeded 30°C (86°F) (Figure 2), while the temperature differences through the ground-source heat exchanger ranged between 3.5°C and 6.5°C (6.3°F and 11.7°F).

The free cooling by the radiant slabs was generally ensured with heat transfer fluid having temperatures varying from 10°C (50°F) to about 15°C (59°F) at the inlet of slab zones P and I (Figure 3). The control of the fluid supply temperatures efficiently prevented water condensation on the radiant slab surfaces.

During a typical winter month (January 2005), the heat transfer fluid returning from section #1 of the ground heat exchanger had temperatures varying between -2°C and -4°C (28.4°F and 24.8°F), which tends to suggest that this section of the ground heat exchanger was slightly underdesigned. The average temperature differential through the vertical ground heat exchanger was about 4°C (7.2°F) (Figure 4).

During the same period (January 2005), the heat transfer fluid was supplied by the heat pumps to the slab zones at average temperatures varying from 30°C to 40°C (86°F to 104°F) depending on the heating demand (Figure 5). The average temperature difference through the three zones was generally kept at around 10°C (18°F).

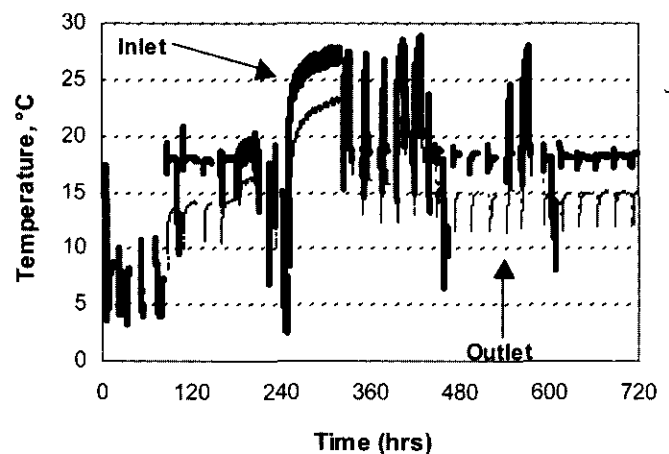


Figure 2 Geothermal fluid ground heat exchanger inlet/outlet temperatures, section #1, June 2004.

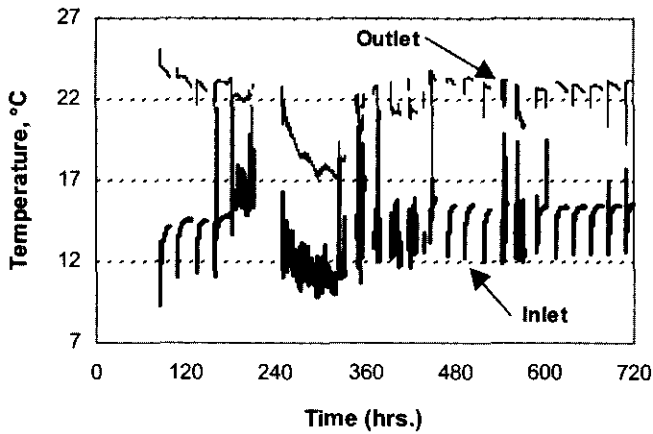


Figure 3 Radiant slab zones inlet/outlet temperatures, June 2004.

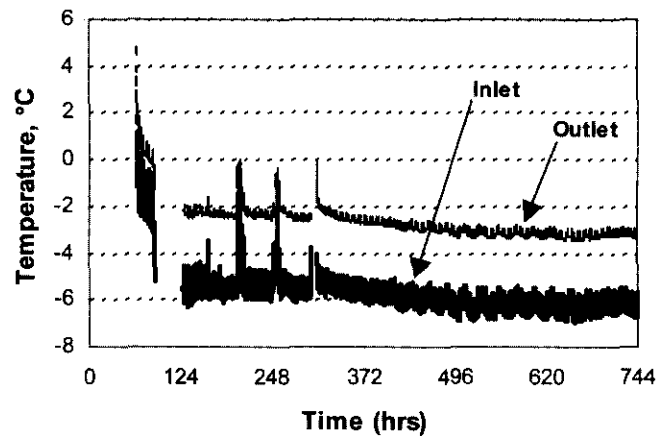


Figure 4 Geothermal fluid ground heat exchanger inlet/outlet temperatures, section #1, January 2005.

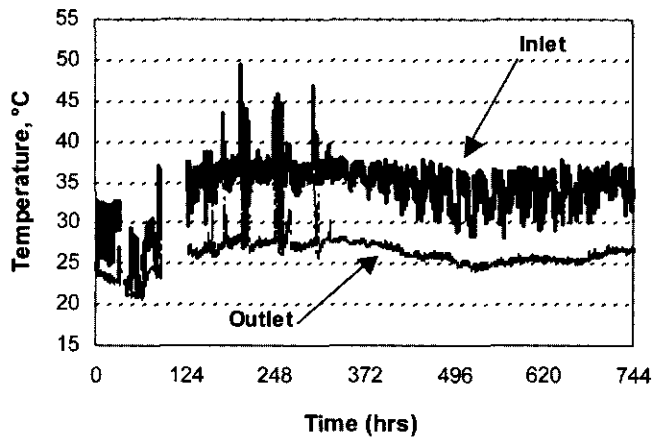


Figure 5 Radiant slab zones inlet/outlet temperatures, January 2005.

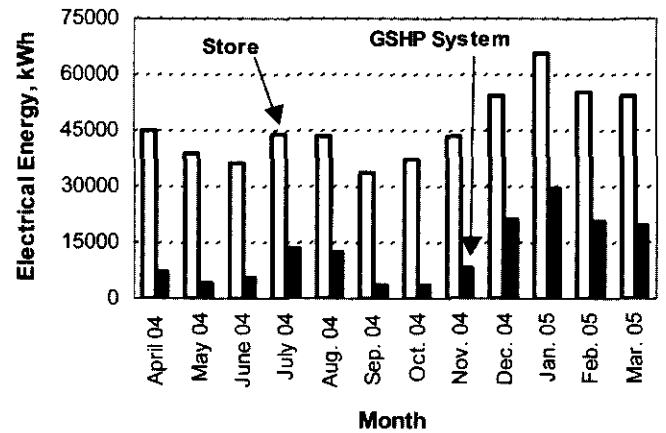


Figure 6 Monthly energy consumptions of the store and the GSHP system.

Energy Consumption

The monthly energy consumption profile of the GSHP system (heat pumps and all circulators) shows that during the winter, the GSHP system was responsible for between 35% (March) and 44% (January) of the store's total. During the summer, it assumed between 28% (August) and 31% (July) of the store's energy consumption (Figure 6).

The specific annual consumption of the entire store was 133.1 kWh/m² (12.4 kWh/ft²) per year, of which the geothermal system assumed 40 kWh/m² (3.7 kWh/ft²) per year, or 30.09%. The most important energy consumer of the building was the lighting system, with about 71 kWh/m² (6.6 kWh/ft²) per year, or 53.31% of the total store energy consumption. Compared to the main heating system (geothermal) and to the lighting, the peripheral baseboard electrical heating (with about 2.77%) and the DOAS system (4.29%) were almost marginal energy consumers (Figure 7).

Compared to an all-electric reference building designed according to MNECB (which would have a simulated energy

consumption of 466 kWh/m² per year), these data show a reduction of 71.4% in annual specific energy consumption for the store (Table 1). This represents a total reduction of 1,391 MWh per year in electrical energy consumption. For this project, the MNECB reference building HVAC system includes an electrical boiler with air-cooled chiller supplying distributed fan coils, a lighting density of approximately 26.9 W/m² (2.5 W/ft²), and a total building U-factor of 0.60 W/m²·K (0.106 Btu/h·ft²·°F).

This result was obtained after a long commissioning process aimed at fine-tuning all components of the system and their control sequences. Compared to three other documented high-performance buildings (a secondary school, a retail store, and an office building) the specific energy use of the new retail store during the second year of operation was on the same order of magnitude (Table 1 and Figure 8). The energy savings compared to the appropriate reference building were about twice as much.

Table 1. Comparison of High-Performance Buildings

Building Type and Main Characteristics	Specific Annual Energy Consumption		Annual Energy Saving
	Actual (Real)	Reference (Conventional)	-
	kWh/m ²	kWh/m ²	%
Father Michael McGivney, Secondary School , Ontario, Canada. 17,657 m ² . GSHP system with 20 heat pumps (410 tons). 360 wells (62.6 m deep). DHW service and heating/cooling ventilation air with heat pumps. Heat pipe type heat recovery unit (517 kW) (ASHRAE 1998).	148 (130 elec. + 9 nat. gas)	352	42
BigHorn Home Improvement Center , Colorado, USA. Hardware retail store and warehouse. 3,940 m ² . Smart envelope design and PV system. Reduced lighting load. Retail area: hydronic radiant floor heating with natural gas. Warehouse: solar collector and gas radiant heaters (Torcellini et al. 2004).	124.3	296	42
Cambria Office Building , Ebensburg, PA, USA. 3,205 m ² . GSHP system. Underfloor air distribution system. Heat recovery ventilators. 18 kW PV system. Daylighting and motion sensors. Additional wall and roof insulation. High-performance windows (Torcellini et al. 2004).	115.8	322	36
Mountain Equipment CoOp , Montreal, Canada. 4,180 m ² . Retail store. GSHP system (80 tons). 12 vertical wells (175 m deep). Hybrid ventilation system and DOAS with heat recovery wheel. Space heating and sensible cooling by radiant floor. Geothermal free cooling. Daylighting. Solar panels for DHW preheating with PV panels. Central DDC system retrieving weather forecasts from the Internet (Genest and Charneux 2005).	133.1	466.0	71.4

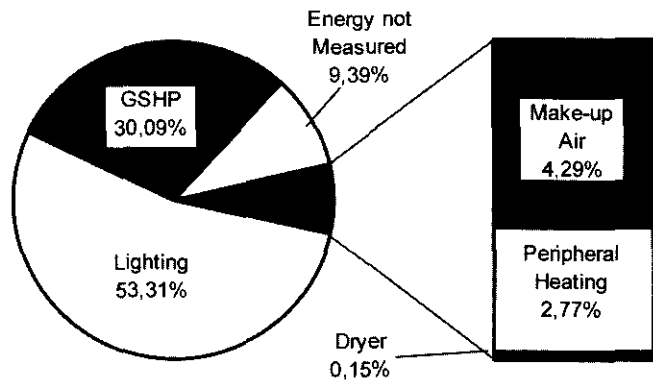


Figure 7 Store annual electric energy consumption distribution.

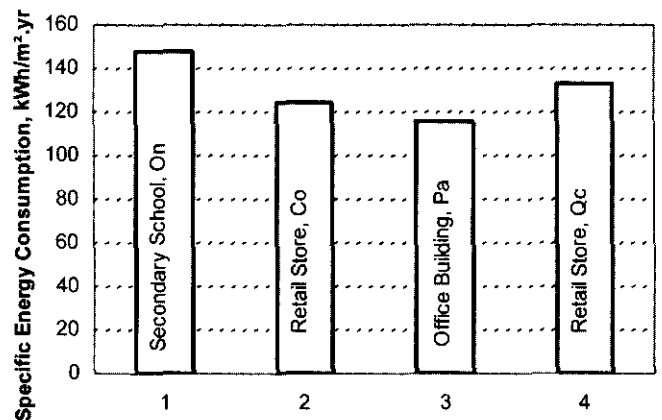


Figure 8 High performance buildings comparison (see Table 1).

The additional costs of the HVAC systems are estimated at CD\$ 475,000. The store's annual energy costs were reduced by more than CD\$ 100,000 (or CD\$ 24 per m²). Consequently, the simple payback period is estimated at about 4.75 years.

Because the indirect emission factor for the electrical energy distributed in Québec (almost 100% hydroelectricity) is 0.00122 kg of CO₂ per kWh, the actual greenhouse gas emissions were reduced by 1.7 metric tons of CO₂. However,

compared with a 75% efficient electrical thermal plant (using natural gas), the reductions in greenhouse gas emissions would amount to 360 metric tons per year (with an emission factor for natural gas of 0.2 kg of CO₂ per kWh).

CONCLUSION

A new retail store built in Montreal involves several innovative features ensuring high-energy performance and BAS

capabilities, taking into account outdoor weather forecasts. The store features a GSHP system combined with radiant floors used for space heating and sensible cooling (taking advantage of geothermal free cooling), a hybrid ventilation system, and a DOAS equipped with exhaust air heat recovery, assuming 34.4% (45.8 kWh/m²/year) of the store annual energy consumption. The lighting system uses 53.3% of the total annual energy consumption. During the first heating-dominated season (January), the geothermal system consumed 44% of the total store energy consumption; this percentage dropped to 31% during the summer (in July). Although the store's specific energy consumption is on the same order of magnitude as three other high-performance commercial and institutional buildings (133.1 kWh/m² per year), several improvements have been made in order to optimize the GSHP system operating parameters and lighting schedules.

REFERENCES

- ASHRAE. 2005. Energy savings design wins prestigious award. *ASHRAE Insights* 20(2):1–2. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 2001a. *2001 ASHRAE Handbook—Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 2001b. *ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 2004. *ANSI/ASHRAE/IESNA Standard 90.1-2004, Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- ASHRAE. 1998. *Operating Experiences with Commercial Ground-Source Heat Pumps Systems*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- Charneau, R. 2004a. Control strategies for retail GSHP systems. Pageau Morel and Associates, Building Consultants, Montreal, Canada.
- Charneau, R. 2004b. Le bâtiment vert: Mountain Equipment CoOp, ASHRAE Symposium, Québec.
- Genest, F., and R. Charneau. 2005. Creating synergies for sustainable design. *ASHRAE Journal* 47(3):16–21.
- Minea, V. 2005. Retail store geothermal heating and cooling with radiant floor. Hydro-Quebec Technical Report.
- MRNFP. 2003. L'énergie au Québec. Ministère des Ressources naturelles, Faune et Parcs, Québec.
- Torcellini, P.A., R. Judkoff, and D.B. Crawley. 2004. High-performance buildings: Lessons learned. Buildings for the future (supplement). *ASHRAE Journal* 46(9):S4–S11.

DISCUSSION

Paul Torcellini, Senior Engineer, National Renewable Energy Laboratory, Golden, CO: (1) How was the slab insulated? (2) Were there any construction issues with getting the slab insulated?

Frederic Genest: The ground floor slab (slab on grade) was fully insulated underneath with a 100 mm (4 in.) thick insulating concrete (lightweight concrete matrix with insulating aggregates within) totaling an R-value of at least 1.06 m²·°C/W (6.1 ft²·°F·h/Btu). The insulating concrete was chosen due to the construction schedule, which required workers to work on the ground floor before the slab was poured.

Joe Huang, Staff Scientist, Lawrence Berkeley National Laboratory, Berkeley, CA: Are the heating and cooling loads balanced in the ground-source heat pump? If not, is there a danger of the ground loop getting progressively cooler over time and degrading the heating COP?

Genest: Due to the predominately cold climate and the natural cooling occurring during the mid-seasons and most of the summer, the annual heating and cooling loads are not balanced. However, this was taken into account when sizing the ground-coupled heat exchanger. Also, the site had a rather good ground water flow. Consequently, we do not expect any degradation of performance over time.

Klaus Haglid, President, Haglid Engineering, Ridgewood, NJ: This was a very good presentation. It raises the bar for energy efficient buildings and represents good out-of-the-box energy engineering. It would be interesting to attribute exact energy savings for each mechanical energy savings measured.

Genest: Unfortunately, the only sources of comparison available are the values obtained from the energy simulation when done for the reference building. For lighting, the reference has a total annual consumption of 95 kWh/m² (8.8 kWh/ft²), compared to 71 kWh/m² (6.6 kWh/ft²) as measured. For the HVAC systems (which includes the heat pumps, all pumps, the hybrid ventilation system, and DOAS), the reference has a total annual consumption of 329.2 kWh/m² (30.6 kWh/ft²), compared to 49.4 kWh/m² (4.6 kWh/ft²) as measured. Water flows to the ground-source exchanger, slabs zone, and DOAS were measured, but the data obtained are unfortunately unreliable and cannot be published.