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Energy Performances of Geothermal Heat Pumps Operating in Cold Climates

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ABSTRACT

The low-temperature ground-source heat pump (**GSHP**) systems make use of the solar energy stored in the Earth's crust. They are efficient alternatives for heating and cooling institutional and residential buildings in cold climates. Several institutional and residential **GSHP** systems have been implemented in Eastern Canada during the last two decades. This paper reviews five of them, mainly focusing on the systems' configurations, the ground thermal behaviour vs. the outdoor temperature, and overall energy experimental performances.

1. INTRODUCTION

The GSHP systems use the shallow ground as a heat source for heating institutional and residential buildings. During the cooling dominated periods, the sensible and latent heat removed from the buildings is stored in the ground and then partially recovered during the next heating season. In the case of large institutional buildings, the GSHP systems offer opportunities to save additional primary energy since the heat recovered from zones requiring cooling can be transferred to zones with simultaneous heating demands. They also allow using other free, inexhaustible and ecological energy sources, such as photovoltaic and thermal solar, engine cooling and combustion gases, and building exhaust air. The GSHP systems are highly efficiency, ensure a high and more uniform level of comfort and a higher level of consistency in the power demand of buildings. However, today, the main issue concerns optimizing their mechanical design and controls strategies in order to reduce the capital costs and thus increase their market acceptance in cold climates. This paper reviews a number of institutional and residential GSHP systems implemented and experimented in Canada during the last two decades. The reported results mainly focus on the systems general layouts, the geothermal fluid temperatures versus those of the ambient air, and annual energy consumptions and performances.

2. INSTITUTIONAL GSHP OPEN-LOOP SYSTEM

The open-loop GSHP systems use the groundwater as a heat and sink source. They are among the most efficient heating and cooling HVAC concepts applied in small and large buildings located in cold climates. Such a system has been implemented in a Canadian office building toward the end of the 90's (Nichols and Langlois, 1990).

2.1 System description

The office building HVAC system contains a hot (~ 50 ˚C) and a cold water (~7 °C) closed-loops operating year-round (Figure 1). Both hot and cold water flows are mixed within decentralized terminal units to supply heating and cooling to the building indoor air-conditioned spaces.

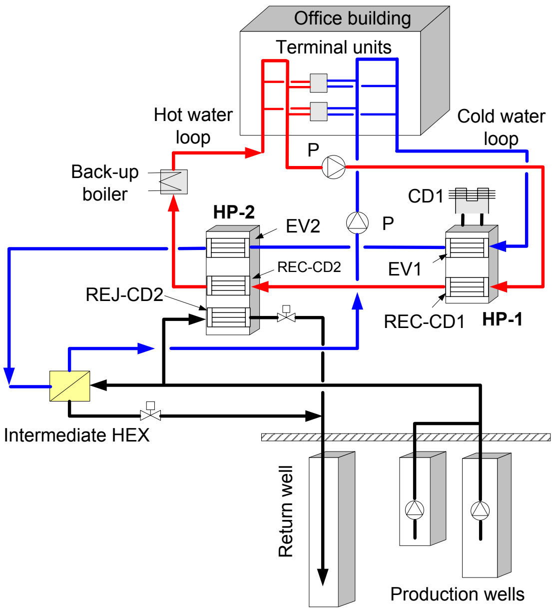


Figure 1: Open-loop GSHP system with artificial cooling charge. CD: outdoor air-cooled condenser; EV: evaporator; HP: heat pump; HEX: heat exchanger; REC-CD: heat recovery condenser; REJ-CD: heat rejection condenser; P: water circulation pump

An open-loop GSHP system has been coupled with the building HVAC system. It includes two production wells (85.4 and 99 m deep, respectively) and one return well (173 m deep) groundwater wells, and two non-reversible heat pumps (HP-1 and HP-2). The heat pump HP-1 (350 kW of nominal cooling capacity) contains one reciprocating compressor, one evaporator (EV1) and two condensers. The evaporator EV1 recovers heat from the building cold water loop by cooling it from 12 to 7 °C. The first condenser (REC-CD1) heats, as the first stage, the water flowing through the building hot water loop. The excess heat is rejected by the aid of the outdoor air-cooled condenser CD1. The heat pump HP-2 (210 kW of cooling capacity) contains two reciprocating compressors, one evaporator (EV2) and two condensers. The evaporator EV2 recovers additional heat from the building cold water loop by further cooling it from 7 to 1.6 °C. This process provides an *artificial* cooling charge allowing recovering heat from the groundwater that enters the intermediate heat exchanger (HEX) at around 8.3 °C and 20 L/s. By recovering heat from the groundwater, the cold water is reheated up to 7 °C prior returning to the building closed-loop during the heating dominated periods. After the intermediate HEX, the cold water at 7 °C enters the building where recovers internal heat gains and, finally, returns at 12 °C to the inlet of the evaporator EV1. The condenser REC-CD2 heats, as a second stage, the water circulating in the building hot water loop and the second (REJ-CD2), rejects the excess heat into the groundwater during the cooling season. Finally, the 810 kW back-up electrical boiler provides, as a third heating stage supplemental heat to the hot water loop, when required. During the cooling dominated seasons, the groundwater bypasses the intermediate HEX in order to absorb heat from the rejection condenser (REJ-CD2). After this heat transfer process, the groundwater is injected into the return well.

2.2 Experimental results

As can be seen in Figure 2a, the groundwater temperature at the open-loop GSHP system inlet was constant at around 8.3 °C over the entire year, while the average outdoor air temperatures varied between minimum -29 °C (in January) and maximum 32 °C (in June and July). In the winter heating mode, the groundwater entering the intermediate HEX was hotter than the cold water coming from the building closed-loop, artificially cooled up to 1.6 °C by HP-2 prior entering the heat recovery heat exchanger. In this way, significant amounts of geothermal heat have been recovered from the groundwater allowing contributing at increasing the temperature of the hot water closed-loop up to 45-50 °C (Figure 2b). On the other hand, in the summer cooling mode, the groundwater temperature was much lower compared to the outdoor air temperature (see Figure 2a) which provided higher heat pump cooling energy efficiencies compared to those of conventional air-to-water systems.

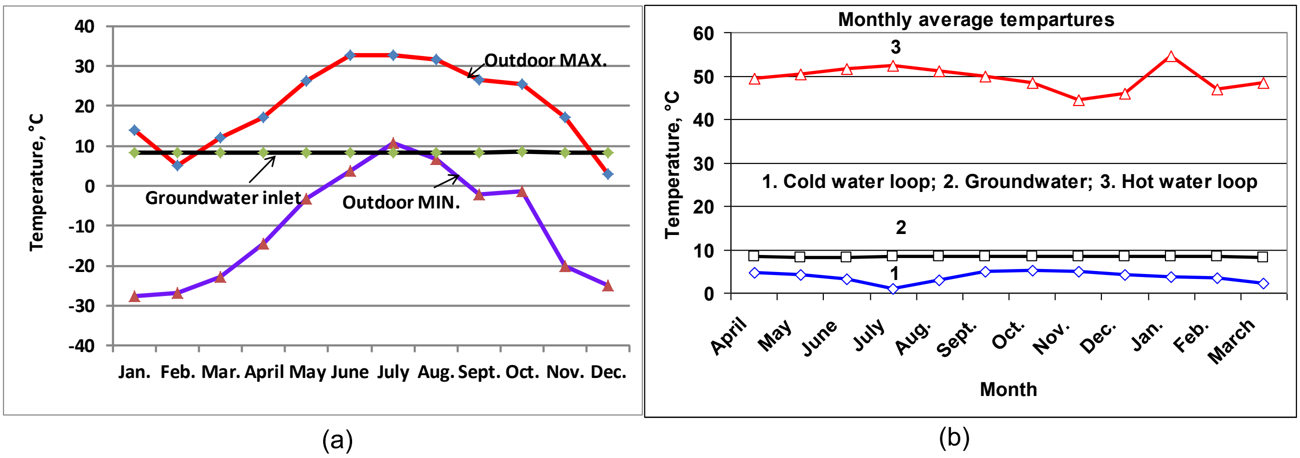


Figure 2: Open-loop GSHP system installed in a cold climate office building; (a) groundwater monthly average inlet temperatures vs. minimum and maximum outdoor air temperatures; (b) monthly average temperatures of groundwater and cold and hot water closed-loops. AVRG: average; MIN: minimum; MAX: maximum

The heat pumps HP-1 and HP-2 ran 18% and 94% of the year time, respectively, and assumed together 71% of the total annual electrical energy consumption of the entire GSHP system. The combined annual coefficient of performance (SCOP) of both heat pumps, defined as the total thermal energy supplied by both heat recovery condensers (REC-CD1 and REC-CD2) divided by the total electrical energy consumed by all heat pump compressors and groundwater pumps, was 2.8. The groundwater pump ran 100% of the time and the back-up boiler absorbed 14.8% of the total electrical energy consumed. The specific annual electrical consumption of the building was 279kWh/m^2, i.e. 19 to 29% lower compared to two similar office buildings equipped with conventional HVAC systems. Figure 3 resumes the annual energy balance of the open-loop GSHP system. It can be seen that it has recovered 356 540 kWh/year of geothermal energy and that the total amount of thermal energy transferred to the building's hot water closed-loop attained 1 463 342 kWh/year. Because the initial cost of the open-loop GSHP system was of US$50,000 (1989) (including, well drillings and submersible pumps, intermediate plate heat exchanger, groundwater distribution network, valves, controls and accessories), the simple pay-back period has been estimated at 2.6 years.

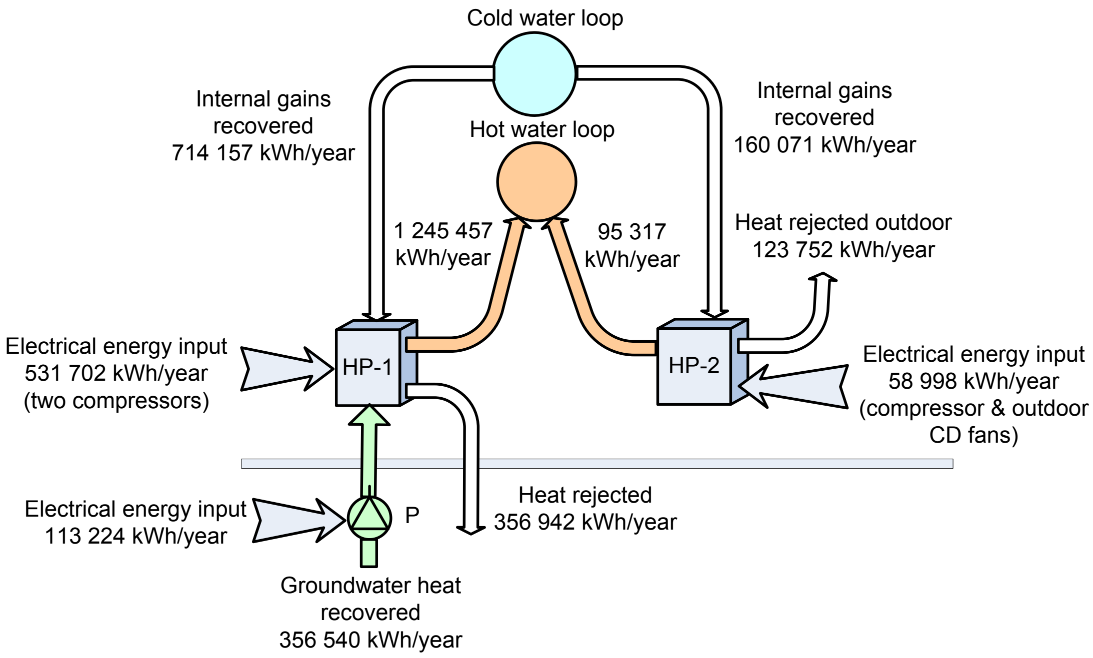


Figure 3: Annual energy balance of the institutional open-loop GSHP system

3. INSTITUTIONAL GSHP SYSTEM with HORIZONTAL GHEX

Another institutional GSHP system but with horizontal ground heat exchangers has been implemented in Canada in the earlier 90's. It managed multiple energy sources, as primary (electrical and fossil), renewable (geothermal and solar) and recovered (internal gains, engine & combustion gases), combined with sensible heat storage.

3.1. System configuration

The multiple energy-source GSHP system (Figure 4) was installed in one 11 426 m^2 school near Montreal, Québec (Eastern Canada) (Figure 4) (Minea, 2006). It includes 35 brine-to-air reversible heat pumps with total nominal cooling capacity of 568 kW. Eleven heat pumps provide heating and cooling to peripheral zones, and the others, to central areas of the building. All heat pumps are connected on a brine (20% water/methanol mixture) closed-loop linked to a two-section horizontal ground heat exchanger (GHEX) buried at 1.22 m and 1.82 m deep, respectively, in a humid grey/brown clay soil. Compared to a vertical ground heat exchanger, this horizontal GHEX is less expensive to install, but requires larger land area. A three-way valve allows alternate the geothermal fluid (brine) flow between the horizontal GHEX and a 100-m^3 sensible heat (water) concrete storage tank. In the heating dominated seasons, the excess heat accumulated inside the building closed-loop is periodically stored by means of the heat exchanger #1 and, then, supplied to the heat pumps, when required. A Diesel oil-fired back-up generator supplies power to the GSHP system at outdoor temperatures lower than -12 °C, i.e. during the winter peak demand periods, or in emergency situations. A glycol closed-loop allows recovering waste heat from both engine cooling fluid and combustion exhausted gases. The heat recovered is first stored inside the water storage tank through the heat exchanger #2 and supplied, via the heat exchanger #1, to the building closed-loop, when required (see Figure 4). Finally, a 618-m^2 passive solar wall recovers solar thermal energy for partially preheating the outdoor fresh make-up air. After the solar wall, a natural gas furnace supplies additional (back-up) heat to the outdoor fresh air, prior being uniformly distributed to the brine-to-air heat pumps. The initial cost of this GSHP system was 26% lower compared to an equivalent conventional HVAC system with central water chiller, induction terminals and cooling tower (Harouni, 2002). Such an initial cost reduction could be explained by the fact that the construction cost of the horizontal GHEX was almost equal to those of conventional cooling tower being eliminated.

3.2 Experimental results

At about 30 m far apart from the horizontal GHEX, the lowest (3.8 °C) and the highest (15 °C) temperatures of the undisturbed soil at 1.82 m depth have been recorded in April and toward the end of August, respectively (Figure 5a). In addition, while the minimum average temperature of the outdoor air (-29 °C) has been attained in January, the average temperature of the brine entering the building closed-loop never dropped below 0 °C (Figure 5b). This performance allowed all brine-to-air heat pumps operating in the heating mode to provide much higher COPs compared to conventional air-to-air heat pumps. By alternating the brine flow through the horizontal GHEX and the storage tank, the thermal capacity of GHEX has been enhanced by 20% from the second year of operation. This thermal behaviour improvement was achieved by avoiding unnecessary heat rejection to the ground by efficiently controlling the three-way valve according to the actual brine return temperature. During the heating dominated season (November to March), the horizontal GHEX has provided 39% of the building peak heating demand, while the heat pumps' seasonal coefficient of performance, defined as the ratio between the total heat supplied divided by the electrical energy consumed by the heat pumps (compressors and blowers), was of 3.56. Simultaneously, in the heating dominated season, a number of heat pumps, mainly located in the building core areas, operated in the cooling mode about 7.5% of the time. They recovered internal gains representing 16.8% of the total energy stored in the closed-loop with an overall cooling energy efficiency ratio (EER), defined as the total sensible and latent heat extracted from the building divided by the electrical energy consumed by the heat pumps (compressors and blowers), of 19.2. The heat recovered from the core zones has been thus stored inside the building closed-loop and then used as a heat source by the peripheral heat pumps simultaneously operating in heating mode. On the other hand, the highest temperature of the brine at the inlet of the building closed-loop was recorded in July was 28 °C, while the maximum outdoor air temperature attained 29 °C (Figure 5b). This result suggests that the horizontal GHEX was slightly undersized vs. the summer peak cooling demand.

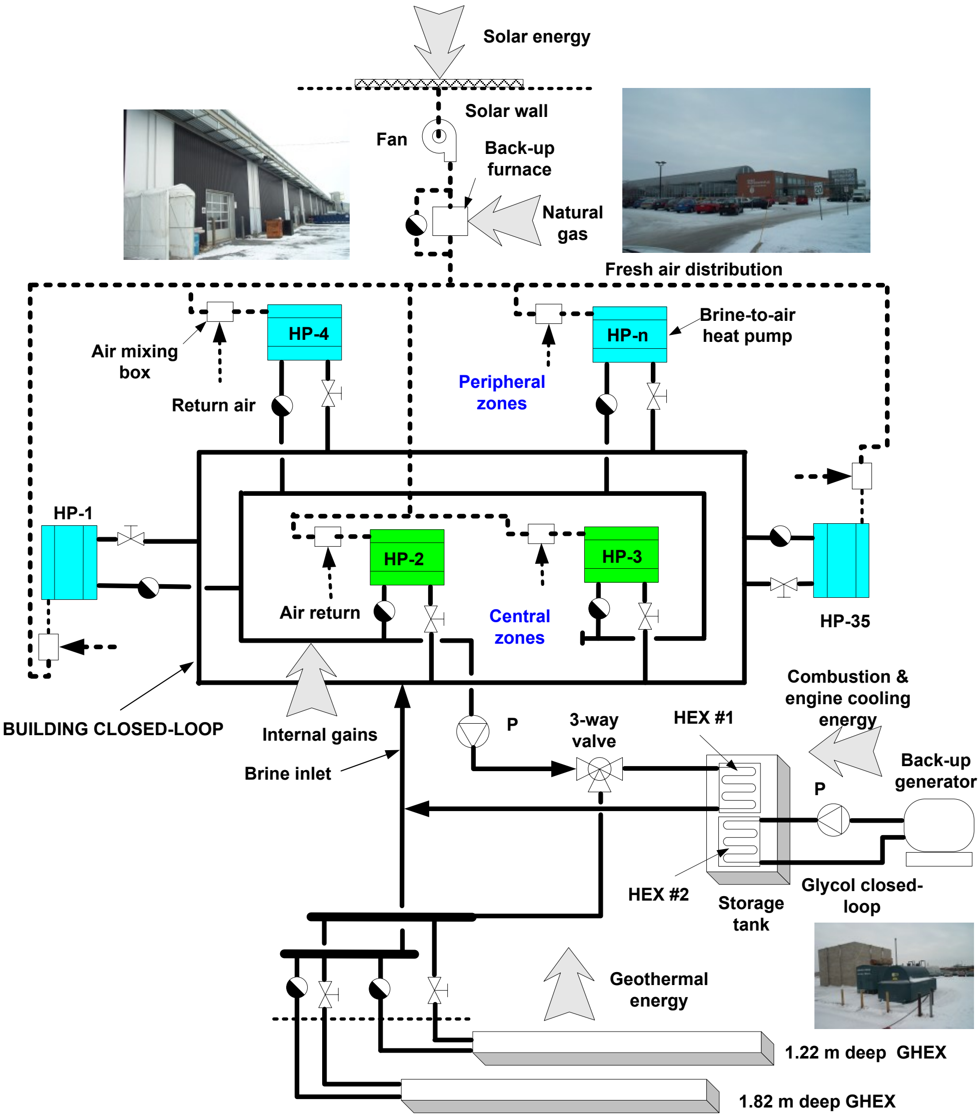


Figure 4: Multiple-energy source GSHP system with horizontal GHEX and thermal storage tank. HP: heat pump; P: circulating pump

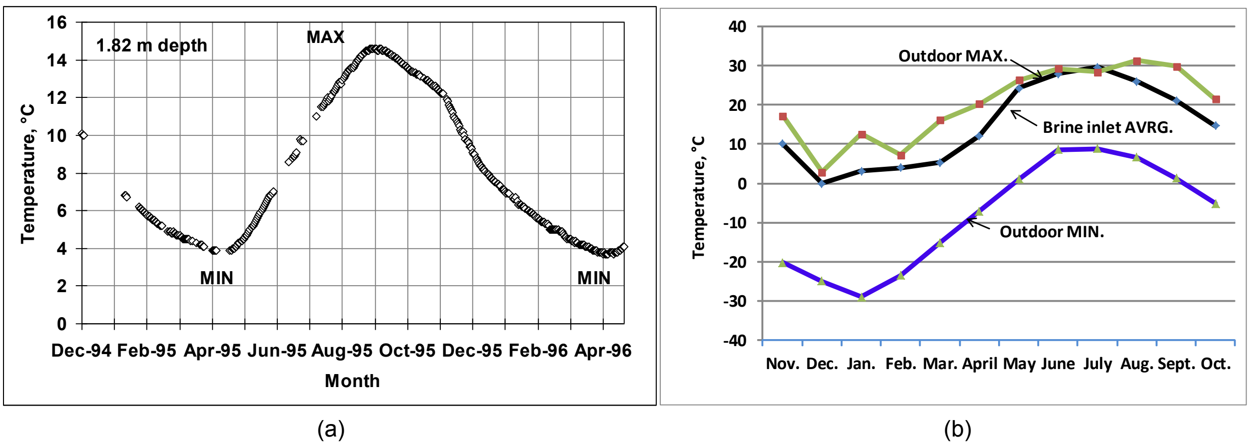
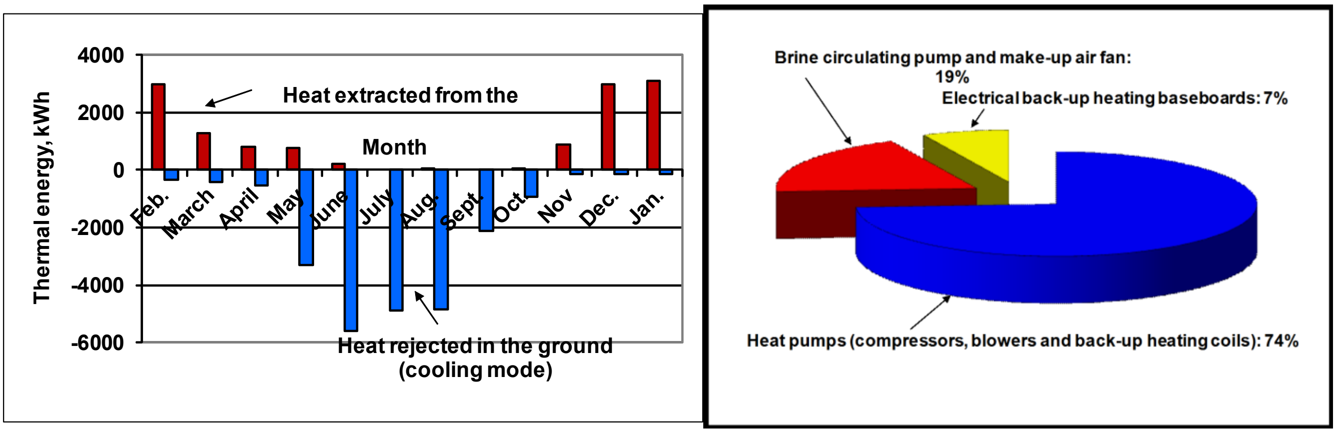


Figure 5: Multiple-energy source GSHP system with horizontal GHEX; (a) daily average temperatures of the thermally undisturbed ground at 1.82 m depth; (b) brine monthly average temperatures at the inlet of the building closed-loop versus minimum and maximum outdoor air temperatures. AVRG: average; MIN: minimum; MAX: maximum

Figure 6a represents the monthly heat extracted (in the heating mode) and rejected (in the cooling mode) from and to the ground by all heat pumps. During the entire year, the heat pumps (compressors, blowers and electrical back-up heating coils) assumed 74% of the total electrical energy consumption of the entire GSHP system (Figure 6b). The brine circulating pump and the outdoor air make-up fan consumed together 19%, and the building peripheral electrical back-up baseboards, 7%. Finally, the total building annual energy consumption, including electricity and natural gas (as supplementary heat for make-up air heating), was 0.69 GJ/m^2/year (192 kWh/m^2), i.e. about 8% lower than the average consumption of Québec's provincial schools heated and cooled by conventional systems (Minea, 2006).



(a) (b)

Figure 6: Multiple-energy source GSHP system with horizontal GHEX; (a) total amounts of heat monthly extracted and rejected from/to the ground by the horizontal GHEX; (b) share of the total annual electrical energy consumption of the GSHP system with horizontal

4. INSTITUTIONAL GSHP SYSTEM WITH VERTICAL GHEX

4.1 System description

A very simple GSHP system has been implemented in another secondary school located near Montréal, Québec (Eastern Canada) (Gastaldy, 2004). The design simplicity of this system allowed minimizing the construction and maintenance costs in addition to offering advantages such a smaller mechanical room, lack of noise and outdoor disturbances, losses in capacity in cases where one or several heat pumps would break down, as well as longer technical life of the heat pumps versus the conventional roof-top units. The two-story school (2 682 m^2 in total floor surface) for 220 students was equipped with a decentralized GSHP system with vertical ground heat exchanger linked to an inversed closed-loop (Figure 7). The ground heat exchanger includes 18 vertical boreholes, each drilled at 122 m depth. The pumping station circulates the geothermal fluid (brine) within the building geothermal closed-loop connected to 25 water-to-water heat pumps with nominal cooling capacities ranging from 2.6 to 35.1 kW for a total of 204 kW. Two passive thermal solar walls located on the east (51 m^2) and west sides (40 m^2) of the building, respectively, preheat the outdoor make-up fresh air during the winter heating dominated season. The second stage of the preheating assembly is a heat pipe-type heat exchanger that recovers heat from the building's exhausted air. After being mixed with the building's return air, the fresh outdoor air is heated, when required, by a 110-kW back-up electrical coil. The last preheating stage consists in a 35-kW brine-to-air heat recovery heat pump linked to the building brine closed-loop. The specific construction cost of this GSHP system, including the solar walls, labour, controls and administration costs, and the contractor's profits (5.2%) was US$176/m^2 (2002) while the specific drilling costs, including the ground HEX, geothermal fluid and accessories, was of US$43.3/m. The cost to build an equivalent conventional CVC system (roof-top cooling units) was evaluated and it would be lower than the actual cost of the geothermal system by 26.8% (Harouni, 2002).

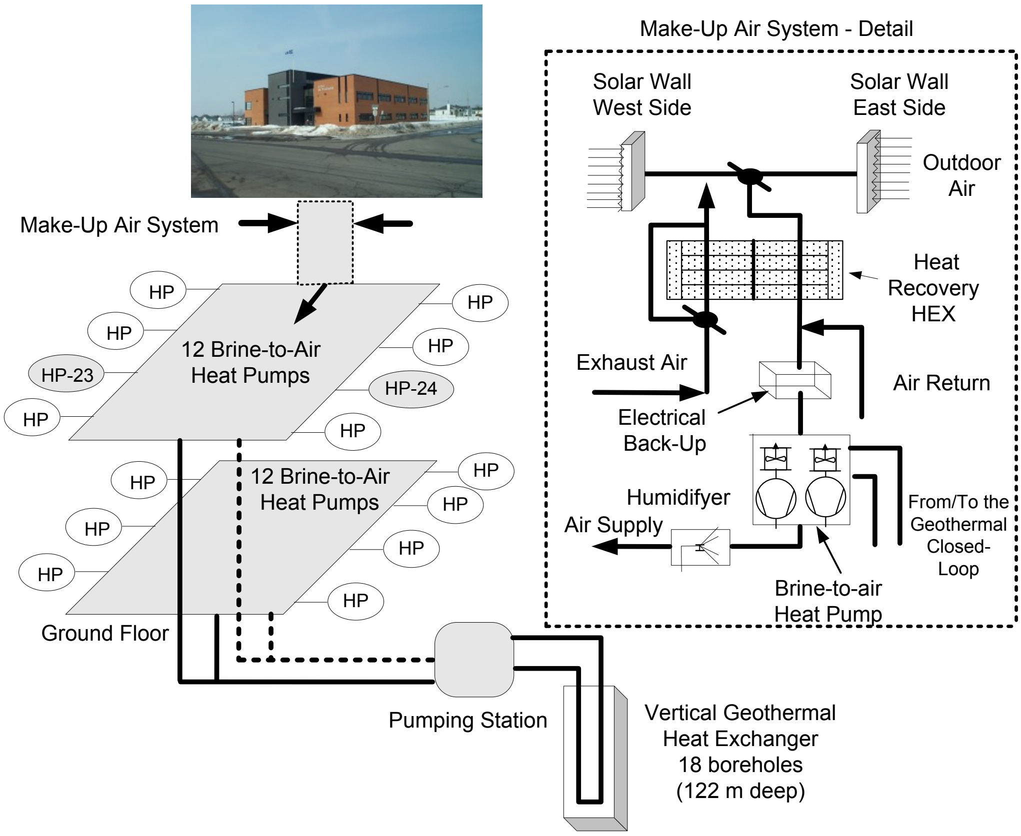
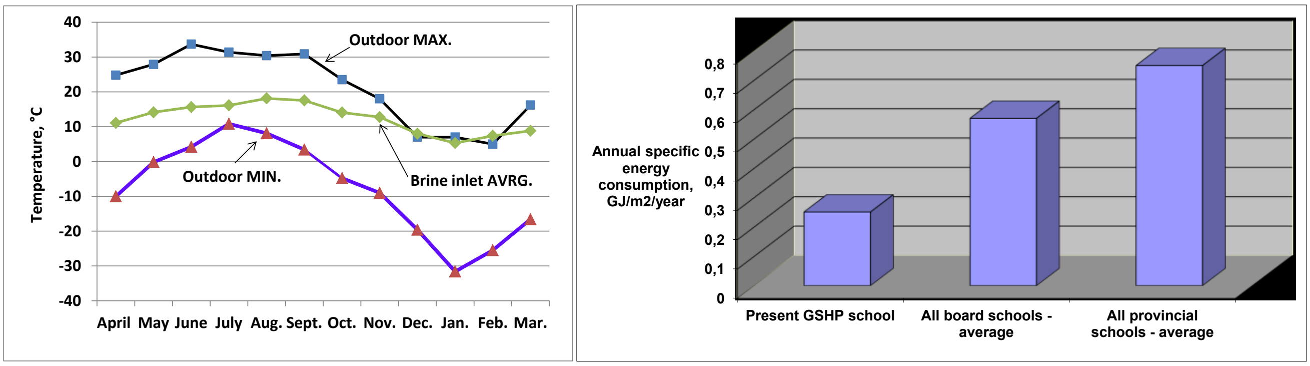


Figure 7: GSHP system with vertical ground heat exchanger. HP: brine-to-air heat pump

4.2 Experimental results

During the one-year in field experiment, the GSHP system ran 28.7% and 14.5% of the time in the heating and cooling modes, respectively, mainly because of limited day occupation periods (9am to 5pm), students' statutory holidays and summer vacation and, also, because the HVAC system shuts-down during the night and on weekends. Under these operation conditions, the brine average temperature at the inlet of heat pumps varied between a minimum of 5 °C in the winter (while the outdoor air temperature dropped at -32 °C) and about 19 °C in the summer (whereas the outdoor temperature reached 30 °C) (Figure 8a). These results demonstrate that the ground HEX was properly designed (i.e. 10.8 m/kW of heat pump nominal cooling capacity). As a result, the heat pump's average seasonal coefficient of performance (SCOP) was approximately 4 (in the heating mode) and the seasonal energy efficiency ratio (SEER), 18.3 (in the cooling mode).



(a) (b)

Figure 8: (a) Brine monthly average inlet temperatures versus minimum and maximum outdoor air temperatures of the GSHP system with vertical ground heat exchanger; (b) comparison of the annual specific energy consumptions. AVRG: average; MIN: minimum; MAX: maximum

The outdoor make-up fresh air was completely preheated through the heat recovery system (see the make-up preheating system detail in Figure 7). The solar walls provided in average 6 kW of thermal energy with temperature ΔT of up to 22 °C. The heat pipe heat recovery heat exchanger provided 7 thermal kW with average temperature increases of 10 °C in the winter. On the other hand, the electrical back-up coil was energized at only 5% of its maximum capacity during about 1.2% of the time. Finally, the outdoor fresh air was preheated by the geothermal heat pump during 5.4% of the time, often operating at 50% of its maximum installed capacity. During one year of operation, the 25 brine-to-air heat pumps absorbed 31.2% of the building total electrical energy consumption. The indoor and outdoor lighting appliances came in the second place (15.8%), and the back-up heating (baseboards and fresh air back-up electrical coils) and air exhaust fans, in the third (10.15%). The brine circulation pump assumed 7.8% of the building total energy consumption, in spite of the fact that it has been overdesigned by 20% as compared to industry standards. The school's annual specific energy consumption was 0.251 GJ/m^2/year, whereas the average annual specific energy consumption of all provincial schools was 0.75 GJ/m^2/year (Figure 8b). This represents a reduction of 66.6%, making this school one of the most energetically efficient building in Canada. Finally, the total energy cost savings versus electrical and natural gas commonly used fro heating and cooling most of the provincial schools, were estimated at US$18 800/year (2004). Consequently, the simple pay-back period of the additional investment, as compared to the provincial average costs, would be 7.4 years.

5. GSHP SYSTEM FOR A LOW-ENERGY HOUSE

The energy consumption of the Canadian residential sector represents about 14% of the total national end use demand (2008), of which **over 50%** accounts for the space and hot water heating (Natural Resources Canada, 2010).

5.1 System description

A low-energy house, known as Eco Terra home, has been equipped with a GSHP system and other energy efficiency devices aiming at reducing the annual electrical energy consumption in a typical Canadian cold climate environment. Eco Terra house is a 234 m^2 (including a 90-m^2 basement), two-storey, factory built wood-framed modular detached home located near Montréal, Québec (Eastern Canada) (Figure 9) (Chen et al., 2007; Candanedo et al., 2008). About 30% of total south façade area of the house is glazed with triple-pane, argon filled, low-emissivity windows. A 2.86-electric kW roof south facing 57.2 m^2 building-integrated photovoltaic/thermal system (BIPV/T) converts light directly into electricity. The home draws power only as needed and excess power is fed back to the utility grid. The outdoor air is heated in the process by absorbing a portion of the solar energy that falls on the BIPV/T system. Some of this energy is used to dry clothes, preheat domestic hot water via an air-to-water heat exchanger (except in the winter) or actively heating the thermal mass of a ventilated concrete slab for night use. The thermal energy stored is passively released from the top surface of the slab into the living space. The preheated water is stored inside a domestic hot water (DHW) tank where it is further heated by the heat pump desuperheater (DSH). A second back-up electrical DHW tank then rises the hot water temperature up to 60°C prior supplying the consumers. The cold water coming from a well is first heated by a drain water heat recovery (HR) device, prior entering the preheating DHW storage tank. Finally, a heat recovery ventilator HRV recovers heat from the outgoing, stale household air and uses it to preheat the incoming, fresh outdoor air. During the cooling season, it removes the heat from the incoming air and transfers it to the intake air (Doiron, et al., 2007; Chen et al., 2007; Candanedo et al., 2008).

At the home site, the depth of overburden is of 14.4 m followed by bedrock, and the static level of the water table is at 1.8 m depth. Below 10 m, the ground temperature remains practically constant at around 8.5°C. The ground vertical HEX consists of a sealed loop of high-density polyethylene pipe containing liquid brine (25% by weight water/methanol mixture) circulating inside two vertical series U-tubes inserted into two boreholes of 87.5 m deep each drilled at 5 m apart. The 10.5 kW (nominal cooling capacity) two-stage (using R-410A as refrigerant) brine-to-air geothermal heat pump is the main house heating system. It has been sized to meet 60% of the design heating load and about 85% of the annual heating energy requirement of the highly insulated low-energy house.

5.1 Experimental results

The low-energy house has been monitored during four years (2008-2011) and five consecutive winters. The house has been unoccupied in 2008 as well as during the first eight months in 2009, then fully occupied until 2011. The lowest outdoor dry temperature (-35.1 °C) was recorded on January 2009 (Environment Canada). The GSHP system provided heating in the winter and cooling in the summer. As could be seen in Figure 10, during the years when the house has been unoccupied (2008), partially occupied (2009) or fully occupied (2010 and 2011), the heat pump has extracted from the ground 14 to 20 times more heat amounts in the heating modes than it has rejected in the cooling modes. A part of the thermal energy transferred to the ground during the summer cooling operating modes has been stored being available to be extracted in the winter for heating purposes.

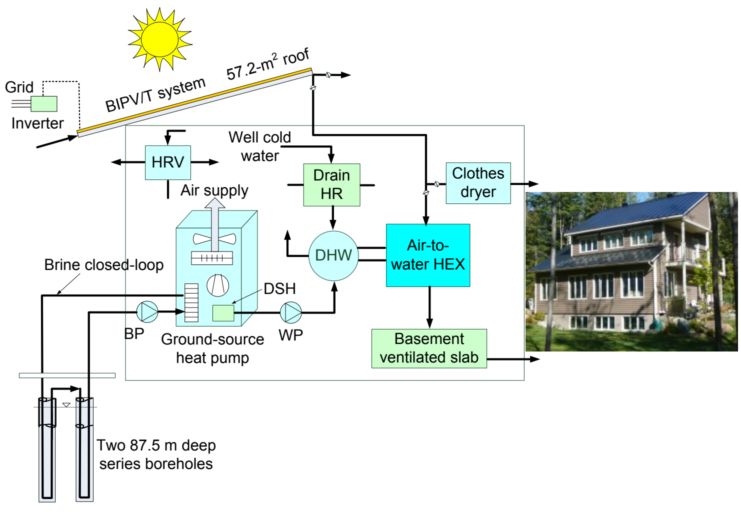


Figure 9: Schematic of the HVAC system of Eco Terra low-energy house; BP: brine pump; DHR: drain heat recovery; DHW: domestic hot water tank; DSH: desuperheater; F: air fan; GSHP: ground-source heat pump; HR: heat recovery; HRV: heat recovery ventilator; HEX: heat exchanger; WP: pump (Minea, 2007; Minea et al., 2009)

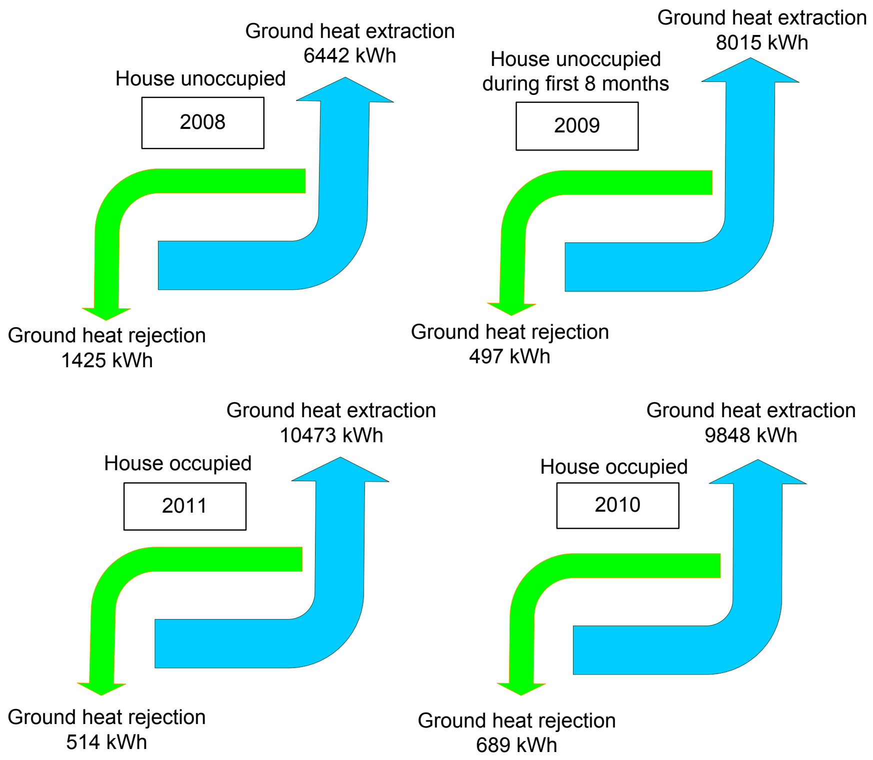


Figure 10: Annual heat rejection and heat extraction from the ground during the four consecutive years

In spite of this apparent thermal unbalance, the ground has been able to fully recover its capacity from one heating season to another. This capacity recovery has been shown by the brine temperature entering the heat pump during the *last* and the *first* heating cycle of each year, respectively (Figure 11). It can be seen that the average brine inlet temperature at the end of each heating dominated season was about 6 °C and that it always reached 8.3 °C at the beginning of the next heating season. This validates the correct design of the vertical closed-loop heat exchanger that, among others factors, accounted for summer ground thermal storage and the groundwater movement. With such a geothermal heat source, the heat pump average coefficient of performance, defined as the thermal power supplied to the house divided by the heat pump's total electrical power input (compressor, blower and brine pump), was about 3.8. In the province of Québec (Eastern Canada), the average annual consumption of conventional houses with electrical heating baseboards ranges around 26 700 kWh/year (Natural Resources Canada, 2010). As could be seen in Table 1, the annual *net* electrical energy consumption (i.e. the electrical energy supplied by the grid minus the electrical energy produced by photovoltaic system) of the occupied low-energy house were 11 077 kWh in 2010 and 11 993 kWh in 2011, i.e. about 56.9% lower compared to the average consumption of conventional houses.

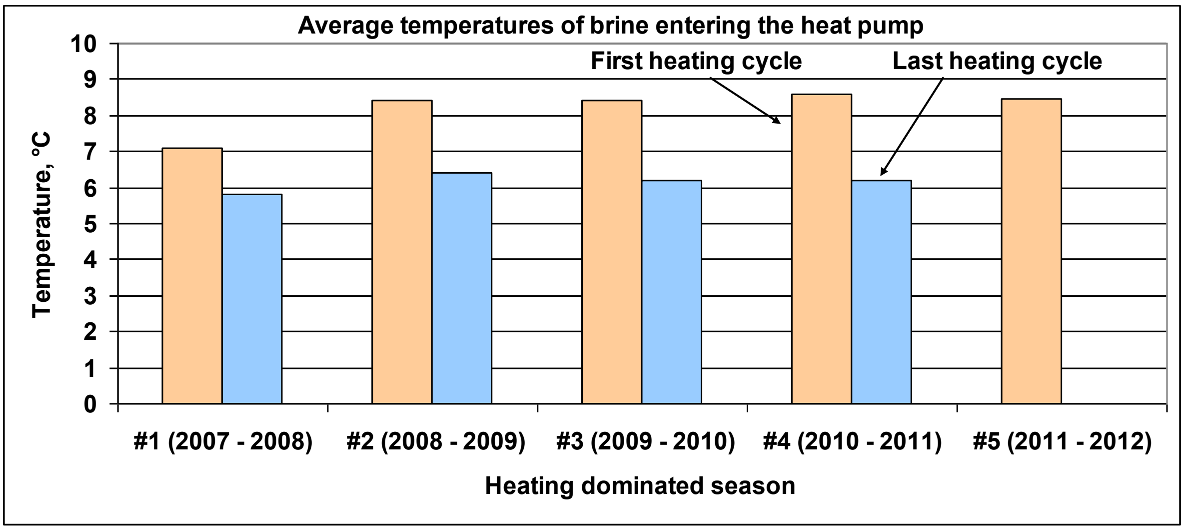


Figure 11: Brine average temperatures entering the heat pump during the *last* and the *first* of consecutive heating cycles

Table 1 – Net annual electrical energy consumption of the low-energy Eco Terra house

Year	status	Total *net* electrical energy consumption
-	-	kWh/year
2010	Occupied	11 077
2011	Occupied	11 993

Consequently, the house annual specific electrical energy consumption (vs. the total area) of the occupied house was 49.5kWh/m^2 in 2010 and 51.2 kWh/m^2 in 2011. The ground-source heat pump (compressor, fan and brine circulating pump) consumed 10.8 kWh/m^2 in 2010 and 9.9 kWh/m^2 in 2011 for both space heating and cooling, i.e. about 33% less compared to the initial performance target established at 15 kWh/m^2.

6. CONCLUSIONS

This paper reviews three institutional and one residential ground-source (GSHP) systems operating in the Canadian eastern cold climate. It mainly focuses on the systems' layout description and some of in field experimental results. The open loop GSHP system installed in an office building allows recovering energy from both building internal heat gains and the groundwater with a combined overall coefficient of performance of 2.8. The multiple energy-source GSHP system with horizontal ground heat exchanger installed in a Canadian school contributed at reducing the building annual energy consumption by 8% compared to average consumption of Québec's provincial schools heated and cooled by conventional systems. The building total specific annual energy consumption (electricity and natural gas) attained 192 kWh/m^2/year. The GSHP system with vertical ground heat exchanger, also installed in a second Canadian school, provides a specific annual electrical energy consumption of 0.251 GJ/m^2/year, i.e. 67% lower compared the Québec provincial average, and a simple pay-back period of 7.4 years. Finally, a multi-year validation of a vertical closed-loop ground-coupled heat exchanger installed in a Canadian low-energy house, integrating a brine-to-air heat pump, a building solar integrated electricity/heat generation photovoltaic system, a passive solar thermal storage, and exhaust air and sewage waste heat recovery devices, showed that that the ground entirely recovered its thermal capacity from one heating dominated season to another. The low-energy house reduced by 56.9% the annual electrical energy consumption compared to typical average houses located in the province of Québec that usually use electrical baseboards as unique heating devices.

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