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Thermal Storage Below House Basement

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1. Introduction

The IEA Heat Pump Center Newsletter, Energy Efficient Buildings: Heating and Cooling Technology Roadmap indicates that heat pumps used in conjunction with thermal energy storage could result in energy savings (Taylor, 2011). In cold climates, technology limits render air-to-air heat pumps not economically operable all year long. A common residential heat pump "heating mode" outside temperature limit is about -10 °C, while January's mean temperature is -9.5 °C in Montreal, with a 7 °C daily standard deviation (ASHRAE, 2009). The heat pump is inoperable economically about 10 % of the year, or 15% of the heating season, when it is most required.

Generally speaking, thermal storage does not save energy. It shifts peak demand to another period. But coupling heat pumps to thermal storage could make a heat pump more efficient compared to exchanging heat with ambient air and could also make it operable all year, thus saving energy. This is the rationale behind ground sources heat pumps. However, a water filled tank buried under a building below frost level could serve as a thermal storage. This paper describes a method for simulating thermal loads of a residential building and evaluates the impact and interest of a buried water tank as a storage medium connected to a heat pump and solar collectors in Montreal, Canada.

This paper first provides basic figures so as to determine the order of magnitude of the reservoir to be considered for storage, and then it describes the residential building to be modeled along with the proposed system. The building is modeled with three different options for HVAC systems: baseboard heating, air-to-air heat pump and water-to air heat pump, with thermal storage. Results are then presented and discussed.

2. Basic steady state average calculations

Before any dynamic thermal modeling is carried-out, a basic study has been undertaken to determine the order of magnitude of the volume required for storage. In this calculation average values were taken for all conditions therefore leading to overall energy balances. The amount of energy required to heat a typical residential house in Canada is about 15 000 kWh (Oliver et Groulx, 2012). For a recently built house this figure reduces to 12,000 kWh. Using a heat pump with a COP of 3, the energy required by the heat pump in the latter case would be 8 000 kWh.

Assuming a water temperature of 40°C in a well insulated tank of 100 m^3 at the beginning of the heating season, the energy stored in the reservoir if one cools it down to zero would be 4 800 kWh provided no gain or loss from the boundaries. Therefore, the reservoir would freeze without incoming energy during the fall and winter. An array of 5 solar panels of 2.97 m^2, tilted at 60 ° in Montreal, is supposed to be used to provide energy between the begining of October and May. During this period, it would receive about 700 kWh m^{-2}. With a conversion efficiency of 35%, this would lead to a maximum heat recovery of about 3,700 kWh.

Finally, during the fall, with insulated vertical surfaces, the losses to the ground – with $U = 2\ W\ m^{-2}K^{-1}$ – could roughly be assumed, by use of an average temperature difference between 40 °C and 10 °C, for a surface area of about 67 m^2, to reach an order of about 1,000kWh. During winter, it is assumed, for the purpose of dimensioning, that the temperature difference is close to 5^oC. Furthermore, if phase change can be tolerated up to 50% in the 100 m^3 reservoir, the amount of latent energy that can be further extracted is about 4,800 kWh. Thus, this suggests that an insulated buried water reservoir of 100 m^3 could be large enough to cover the heating requirements of a recent residential building in Montréal, if coupled to a heat pump and 5 solar panels.

3. Residential Building Model

Evaluating buildings energy consumption through computer simulation is evolving rapidly. A novel approach uses Google SketchUp 3D® (Google, 2011) and free TRNSYS3D plugin (Transsolar, 2011) to define geometry and components of a building, such as exterior and interior walls, roof, ceilings, floors, windows, etc. This plugin models multi-zone building and exports radiation and geometry models to TRNSYS Simulation Studio (TRNSYS, 2011). Modeling of the building by using the TRNSYS3D plugin defines multiple zones. In this case, the basement was modeled in two different zones: one below ground and the other above ground. The rest of the building consists of a first floor and an attic. Fenestration is added to generated surfaces. Each generated surfaces types is defined as exterior wall, ceiling adjescent, roof, etc. The modeled building is a single-family home is located in Montreal, Quebec, Canada. Its footprint is 7.5 m by 9 m, the longer side oriented on the East-West axis. The basement and ground floor are both 3 m high and the inhabited attic is 5 m high at its gable. Windows are located all around the building, as shown in figure 1.

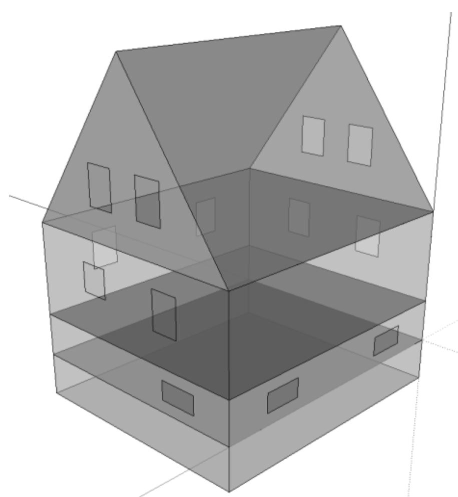

Figure 1: Google Sketchup 3D Model

The following step implies TRNSYS Simulation Studio to generate building files from TRNSYS3D, to be used in TRNBUILD (TRNSYS, 2011). This last application is used to define the materials and thermal performances of the building components, as well as HVAC systems to be simulated. TRNSYS Simulation Studio Multi-zone component (Type 56) is coupled to HVAC and energy related numerical models such as: heat pumps, thermal storage, solar collectors and ground coupling. Each component is defined using TRNBUILD module. The thermal resistance of the components such as external walls, windows, roof, mechanical equipment including ventilation, heating and air conditioning, as well as air infiltration and schedules of occupation are defined in TRNBUILD, as shown in table 1.

Table 1. Components description

Component	Description	R-value [m^2KW^{-1}]
Exterior wall	Fiberglass, 200 mm	5.3
Ceiling	Fiberglass, 270 mm	7.1
Window	Double glazed, 13 mm air	0.3
Concrete wall	Expanded polystyrene, 50 mm	1.8

The natural air infiltration rate of the residential building is set to 0.2 air-change per hour (ach) in accordance with experimental data (CMHC-SCHL, 2011). Ventilation is set at 280 l/s, with 0.2 outside air fraction mixed to the return air to the heat pump, resulting in the minimum value of 0.35 ach per ASHRAE 62.2 standard (ASHRAE, 2010). The heating temperature set point is 21 °C and cooling at 24 °C. The model is then imported within TRNSYS, as a multi-zone building (Type 56). Each surface is described by its azimuth and angle to the horizontal. The information generated by Trnsys3D includes solar zenith and azimuth as well as total and beam solar radiation on each surface modeled. It can also include shading that could be added to Google Sketchup 3D model. TRNSYS is used to simulate interactions between different numerical models. It is possible to use weather data from many locations on the globe and several components of renewable energy systems are available. Figure 2 shows the base model used by all three HVAC configurations.

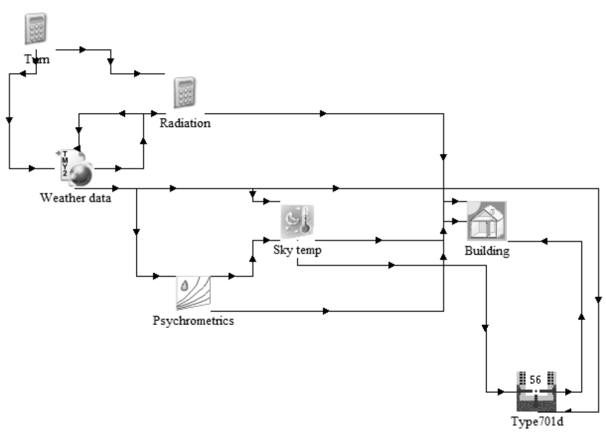

Figure 2: TRNSYS base model

The building is coupled to the ground by Type701d component, which is “Basement Conduction (interfaces with Type56)”. It models conductive heat transfer from the basement to the surrounding ground using a 3 dimensional finite difference model. The other components are used to define the environmental conditions.

Three HVAC arrangements were simulated:

- A simple model with baseboard heating and air conditioning devices;
- An air-to-air heat pump;
- A water-to-air heat pump, coupled with a buried water tank and a solar collector.

The main objective of this simulation is to size a buried water tank thermal storage system that would be operational all year long. Humidification and dehumidification are not considered in this model because the latent heat is assumed to be the same in all three HVAC scenarios.

3.1 Simple model

The residential building HVAC system was first modeled with a baseboard heating, common in the Quebec province. During summer, air is cooled by a conventional device with an average COP of 3.0. The Ventilation Unit, a Type664 component in TRNSYS, was added to the Multi-zone building model. The air flow parameters are the same as for the other two HVAC scenarios described below. The simulation time step was set to 1 minute after several preliminary tests.

3.2 Air-to-air heat pump

In the second model, an air-to-air heat pump replaces the simple ventilation unit simulated previously. The simulation step time was also set to 1 minute. The ambient air temperature in the house is monitored on the first floor zone with Type698 component, which is a “Five-stage Room Thermostat - Multi-Zone Version”. A diverter (Type616) is used to split the ventilation flow into each zone. It is set to ensure temperature balances in each zone as much as possible. The performances of the heat pump (Type665) were taken from the examples included in TRNSYS. The cooling COP is between 2 and 3.3, while the heating COP is between 1.3 and 4.2. Two auxiliary heaters are added to the heating system and their set points are zone temperature below 19 °C for first stage and below 17 °C for both stages.

3.3 Water-to-air heat pump

In the model of interest, a buried storage tank is coupled to a water-to-air heat pump. Solar collectors are added to the system to raise the tank temperature in an effort to prevent freezing during the heating season. Figure 3 represents the connections between the main components of the water-to-air system.

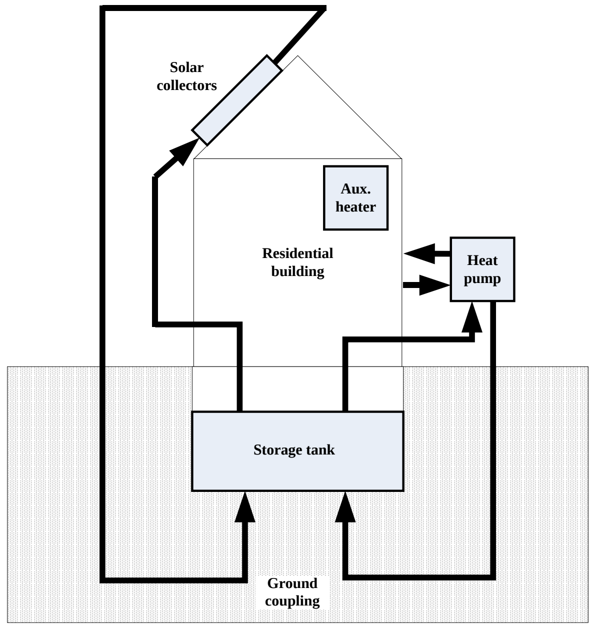

Figure 3: Water-to-air heat pump model diagram

The “Water-To-Air Heat Pump” (Type505b) component has COP between 3.2 and 7.5 for cooling mode, and between 3.6 and 6.2 in heating mode. The auxiliary heaters are controlled the same way as in the air-to-air heat pump model.

A “Flat Bottom Storage Tank” (Type531) component is used to model the thermal storage. The tank has the same footprint as the residential building; its depth is variable for different volumes: 1 m for 67 m^3, 1.5 m for 100 m^3 and 2 m for 133 m^3. Its top surface is located 1.5 m below ground, considered to be frost level. The storage tank inlet of the heat pump and the solar collectors are at the bottom, while the outlets are on top. The heat transfer fluid used for all components is the water contained in the storage tank. No heat exchangers are used between components.

The storage tank component is coupled to “Soil Model for Buried Vertical Cylindrical Storage Tanks” (Type 707b) component. The soil model is cylindrical and the tank model is rectangular, but the soil model uses surfaces and lengths as dimensional parameters for conductivity heat transfer. Thus, the area and perimeter values of the tank were used regardless of the shape of the components. The mass of soil to be used as storage medium is calculated from the distance by which the soil temperature is considered undisturbed. This far-field distance is 10 m on around the tank and 10 m under it. The smallest node size for the finite difference calculations is 0.5 m. The U-value of the concrete tank is set to 6.9 $Wm^{-2}K^{-1}$. The mean surface temperature is set to 6.9 °C and amplitude of surface temperature of 11 °C (ASHRAE, 2009). The walls and floor of the thermal storage are simulated with and without an insulation of R-1.8. The system is schematically presented in figure 4.

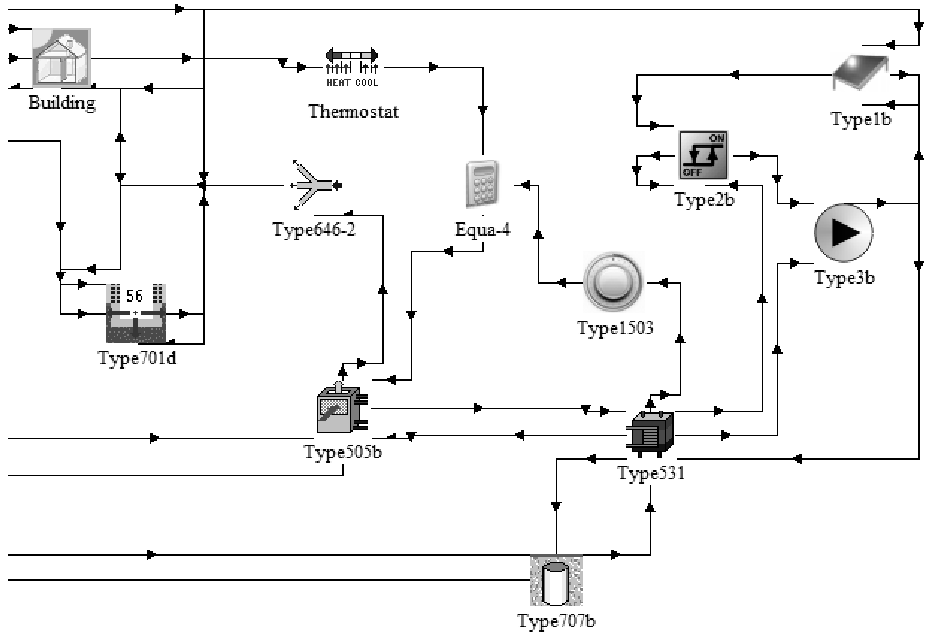

Figure 4: Water-to-air heat pump model in TRNSYS

The initial tank temperature value of the simulation is set to the final tank temperature of a first annual simulation. The surface temperature on top of the storage tank has been set to 20 °C to ease calculations, even though small oscillations exist in the buried portion of the basement. The top surface has a thermal resistance of R-3.6. The thermal properties of the soil are based on “heavy sand, below water table” with a density of 1,925 kg/m^3 (Kavanaugh et al., 1997), thermal conductivity of 2.4 Wm^{-1}K^{-1} and specific heat of 2.9 MJm^{-3}K^{-1} (or 1.5 kJ m^{-3}K^{-1}) (Sundberg, 1988). The tank water change per hour induced by the heat pump and the solar collector pump is about 0.01 per hour, taking about 100 hours to change the whole water volume. Considering this relatively low water flow rate compared to the storage volume, the heat transfer mode is assumed purely conductive, without convection. As shown in figure 3, the inlets are located at the bottom of the tank, while the outlets are on top.

The “Solar Collector, Quadratic Efficiency” (Type1b) component is used to warm up the storage tank. It is based on AET Glazed Flat-Plate solar collector, model AE-32E. Its performances are Y-Intercept of 0.655 and a slope of -6.37 Wm^{-1}K^{-1}, with an area of 3 m^2. The pump flow rate is set to the lowest manufacturer’s recommended flow rate of 0.03 l/s. Two arrangements of 1 and 5 solar collectors are modeled, coupled in parallel. To avoid frequent start-stop cycling, the collector’s pump starts when the temperature difference between the storage tank and the outlet of the collector reaches 10 °C and stops when it is lower than 2 °C. The pump also stops when the outlet temperature reaches 100 °C. The collectors are installed due-South at a 45° angle.

The control strategy of the heat pump is that if air temperature in the house gets below 18 °C, the 1st stage auxiliary power is triggered and the heat pump stops. If the temperature of the house drops below 16 °C, the 2nd stage auxiliary power is triggered to reinforce the 1st stage, and the heat pump is still off. To prevent damaging the pump, a freezing protection system is installed: if the tank temperature reaches 0 °C (Type1503), the heat pump shuts down and the auxiliary power triggers on.

4. Results and discussion

The simple residential model annual energy consumption is 15,800 kWh of heating and 600 kWh of cooling, which would be exchanged by the heat pump with the storage tank. For the water-to-air heat pump model, a total of twelve simulations were executed with: three tank volumes (67 m^3, 100 m^3 and 133 m^3), coupled with one and five solar collectors, with and without insulation. Figure 5 presents the tank average temperature profiles for the three tank volumes, insulated, with 5 solar collectors.

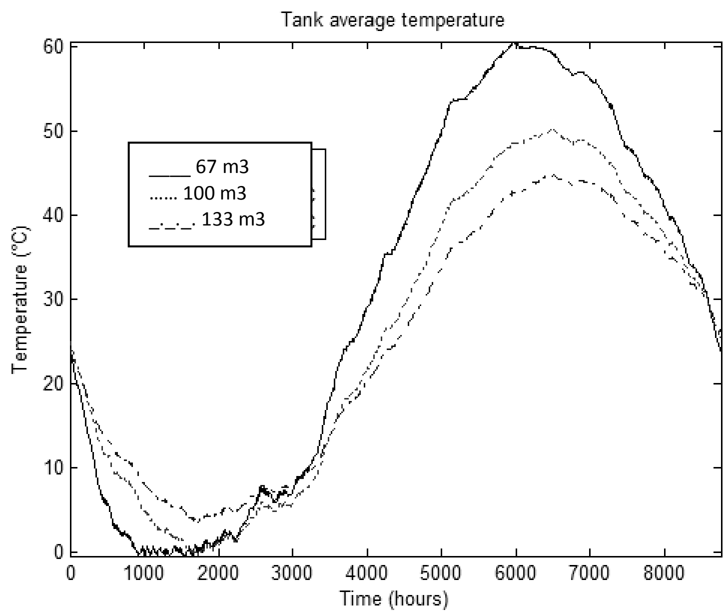

Figure 5: Insulated tank temperature profiles, with 5 solar collectors

The heat pump extracts heat from the storage tank during heating seasons and stores heat during cooling seasons. Obviously, the small tank temperature rises higher than the large one during summer, but also cools down faster during the heating season. The amplitude of temperature variation is also larger for the small tank, freezing in winter and getting close to 60°C during summer. On all simulated arrangements, only the 100 m^3 and 133 m^3 insulated tanks coupled with 5 solar collectors avoided freezing all year long. The freezing protection triggers auxiliary power for all the other arrangements. Table 2 shows auxiliary power consumption for each simulation.

Table 2. Auxiliary power energy consumption (kWh)

	Insulated Tank			Uninsulated Tank		
Nb. of collectors	67 m^3	100 m^3	133 m^3	67 m^3	100 m^3	133 m^3
1	6,700	6,600	6,500	7,300	6,800	6,400
5	1,000	0	0	2,900	1,800	1,200

The electricity consumption to heat the residential building would be larger from auxiliary power than from the heat pump. Considering this, a larger tank volume definitely helps energy savings, so does insulating the tank. Each solar collector injects yearly about 2,700 kWh of thermal energy to the tank, but the increased tank temperature also increases losses to the ground. The heat exchanged with the ground has a negative balance because the mean water temperature is higher than that of the surrounding ground most of the year, as shown in table 3.

Table 3. Heat exchanged with surrounding ground (kWh)

	Insulated Tank			Uninsulated Tank		
Nb. of collectors	67 m^3	100 m^3	133 m^3	67 m^3	100 m^3	133 m^3
1	-100	-50	20	-750	-250	150
5	-1,500	-1,600	-1,700	-4,400	-4,200	-4,100

Three different tendencies can be analyzed from this table. The first involves arrangements of one solar collector, with and without tank insulation. The smaller annual temperature variation of the larger tanks reduces heat losses to the ground, even gaining heat from the ground for the 133 m^3 tanks. The second tendency is for the five solar collectors' arrangements for insulated tanks. The larger tanks are losing more heat to the ground than the small ones. This can be due to the fact that the proportion of surfaces in contact with the ground is more important than the temperature difference. The last tendency is for five solar collectors arrangements with uninsulated tanks. This time, the heat losses decrease with larger tank volumes. Even if the surface is bigger for larger volumes, the temperature difference with the ground is more important for smaller tanks. This behavior cannot be modeled with a simple average energy balance such as that presented in section 2.

For the arrangements with 5 solar collectors, the energy saved by insulating the tanks is more important than the annual energy gain of one solar collector. The energy savings that can be generated with heat pumps and solar collectors are lowered by the electricity required to operate mechanical equipments. Based on Hydro-Quebec's residential rate of 7.5 ¢/kWh, table 4 shows the electricity cost required to keep the building within comfort zone, including energy required from auxiliary power, to operate the heat pump and the solar collector pump:

Table 4. Modeled electricity costs ($/year)

	Insulated Tank			Uninsulated Tank		
Nb. of collectors	67 m^3	100 m^3	133 m^3	67 m^3	100 m^3	133 m^3
1	620 $	620 $	610 $	650 $	630 $	610 $
5	360 $	320 $	320 $	450 $	400 $	370 $

There is virtually no economy between the 100 m^3 and 133 m^3 insulated tanks with 5 solar collectors' arrangements. Using this 100 m^3 tank arrangement, figure 6 compares the heat transferred from the heat pump to the water tank, solar collectors' heat gain and the ground losses.

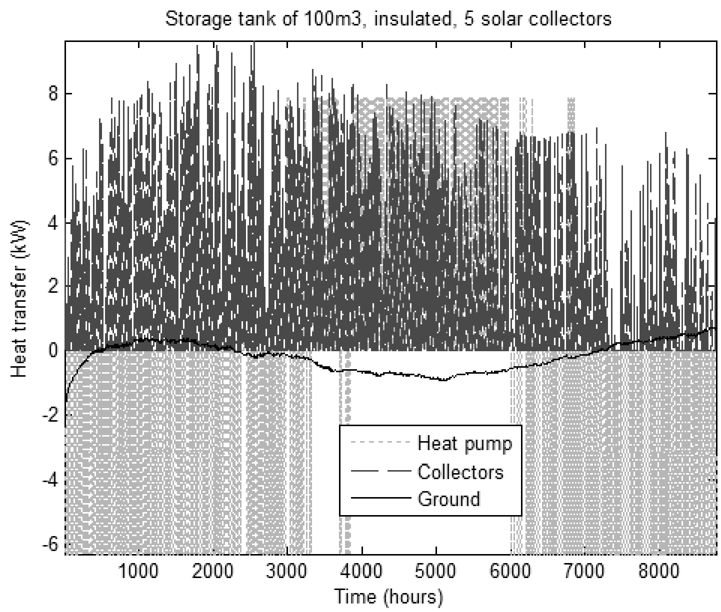

Figure 6: Heat pump, ground and solar collector heat transferred to the storage tank

There is not much heat transferred to the ground in winter because the temperature difference between the ground and the tank is small. In summer it rises, but still stays far below the cooling requirements. The annual energy transferred to the ground is marginal in comparison to the two other factors. The large heat transfer values at the beginning of the simulation can be caused by the fact that the ground temperature profile is based on Kasuda correlation. The initial tank temperature of 25 °C gets in contact with the colder ground temperature, increasing heat transfer. Using custom ground temperature profile would have been more accurate in these conditions. This problem was not as obvious for the systems with one solar collector, since the initial tank temperatures were 0 °C.

A problem with the simulation time step, Δt, was encountered. With Δt = 1 hour, the room temperature fell below the auxiliary heaters set point, so the heat pump stopped. The simulation operates as if the compressor runs for the step time period and also stops for the same period of time when the room temperature gets to the set point. This implies that surface heat transfer, infiltrations and fresh air intake happens for 1 hour without heating sources. Lowering to Δt = 5 min, the temperature was more even throughout the simulation, but still showed instabilities. The ideal time step would have to be as low as 5 seconds to avoid all instability but Δt = 1 min was found to provide similar solutions.

Also, the air-to-air heat pump was based on manufacturer's catalog data supplied with the TRNSYS model. Consequently, the low temperature limit of the model was at -5 °C, rather than -10 °C commonly encountered for Quebec's air-to-air heat pumps. The refrigerant used in the component was not specified, but temperature of -5 °C and below occurs about 1,700 hours per year (20% of the time) and it occurs when heating is mostly required. Moreover, temperatures of -10 °C and below occur about 1,000 hours per year (11% of the time).

The annual energy consumption and electricity cost for sensible heat for the three HVAC options modeled are represented in table 5.

Table 5. Electricity consumption comparison

HVAC option	Annual Consumption (kWh)	Heating/Cooling Electricity Bill ($/year)
Baseboard and air conditioning device	16,400	1,250 $
Air-to-air heat pump	13,500	1,150 $
Water-to-air heat pump with thermal storage and solar collector	3,200	250 $

The baseboard model showed the most important annual energy consumption. The advantage of a heat pump can be measured by a 2,900 kWh energy economy, but the auxiliary power supplied by the heat pump is of 11,500 kWh with cold temperatures, which is over evaluated because of the previously stated air-to-air heat pump component discrepancy. The water-to-air heat pump system with 100 m^3 of water buried under the residential building and 5 solar collectors showed the best energy consumption, with 13,200 kWh of energy economy compared to baseboard model.

5. Conclusions

A residential building located in Montreal, Quebec, Canada has been simulated with :1) a baseboard and air conditioning model; 2) an air-to-air heat pump; and 3) a system composed of a water-to-air heat pump, coupled with a water storage tank buried under the house and solar collectors. For the third system modeled, a freezing protection is added to the control strategy to avoid damaging the circulation pump. No partial freezing was allowed within the reservoir.

To avoid freezing during heating period, the size of the thermal storage was set to 100 m^3, coupled with five standard size 1.2m x 2.4m solar collectors. The ground coupling showed favorable results with insulation around the tank of R-1.8. The annual energy balance on the storage tank was 9,000 kWh extracted from the heat pump, 10,500 kWh gain from solar collectors 1,500 kWh net lost to the surrounding ground. The sum of heat pump heat transferred to water, solar collectors' useful gain and heat transferred to the ground equals -5 kWh, deemed acceptable.

Even though the annual bill is lower with the water-to-air heat pump system, the use of solar collectors to avoid freezing in the heating period and the size required of the thermal storage would make this option economically. Moreover, certain sanitary considerations should be accounted to avoid proliferation of microorganisms.

6. References

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7. Acknowledgment

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