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Assessment of ambient loop-coupled GSHP and WWHP systems in a cold-climate institutional/residential development

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Abstract

Six potential heating and cooling systems were simulated in a large (44-storey) proposed institutional/residential development on a Canadian university campus: a base case including natural gas boilers and a water-cooled chiller; an ambient loop (AL) coupled with conventional equipment (natural gas boilers and cooling tower); an AL-coupled wastewater heat pump (WWHP) system; a hybrid WWHP-conventional AL system; an AL-coupled ground-source heat pump (GSHP) system; and a hybrid GSHP-conventional AL system. The hybrid WWHP-conventional system and the two GSHP systems outperformed the base and conventional AL systems on all fronts, providing energy savings and greenhouse gas (GHG) emissions reductions while also costing less to operate on an annual basis than the base or conventional AL systems under both 2019 and 2030 energy pricing. Of the six systems investigated, the hybrid GSHP-conventional system had the lowest energy use, produced the least GHGs, and cost the least to operate under 2019 and 2030 price schemas. While the results of the simulation mediate towards the adoption of a GSHP-based system for this institutional/residential development, annual cost savings and GHG emissions reductions must be balanced against upfront costs, available energy resources, and logistical concerns such as the construction of a borehole field.

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1. Introduction

Residential and commercial buildings in the US account for approximately 13% of all greenhouse gas emissions [1]. Since most of the buildings that will exist in 2030 have already been constructed, the majority of opportunities to reduce GHG emissions in buildings in the coming decades will come from improving the efficiency of existing building systems and from the electrification of fossil fuel-based space and water heating equipment. Ambient loop (AL) systems, also known as ambient loop heat pump (ALHP) systems, are a relatively clean and efficient substitute for conventional space heating and cooling systems, allowing for flexibility in the choice of coupled auxiliary heating and cooling equipment. Using a planned cold-climate institutional/residential development as a test case, this paper will investigate the performance of ambient loop systems paired with conventional equipment (natural gas boilers and cooling tower), wastewater heat pumps (WWHPs), and ground-source heat pumps (GSHPs). Annual energy usage, greenhouse gas (GHG) emissions, and energy costs will be compared, and recommendations will be made for system selection.

In an ambient loop system, refrigerant is circulated throughout a building at 8-25°C, with water-to-water or, more frequently, water-to-air heat pumps serving to 'upgrade' the energy in the ambient loop at-zone and provide heating or cooling to individual areas of the building [2] [3]. The simultaneous discharge of heat to and extraction of heat from the loop in different zones serves to maintain/moderate loop temperature; for this reason, ambient loop systems are well suited to buildings with simultaneous heating and cooling loads.

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Ambient loops are also ideally suited to make use of low-temperature waste heat (e.g., from wastewater, minewater, or industrial discharge), and do not suffer from transmission losses to the same extent as conventional hot/chilled water systems [3].

Soil and urban wastewater, both of which maintain relatively constant year-round temperatures in the 10-25°C range, present promising heat sources/sinks for ALHP systems [4] [5] [6]. In a wastewater heat pump (WWHP) ambient loop system, ambient loop temperature is maintained via heat exchange with urban wastewater. Although institutional-scale WWHP systems have been implemented in a number of buildings worldwide – for example, the Rechts der Isar Medical Centre in Munich, Germany and Okanagan College in Kelowna, Canada – heating and cooling with wastewater remains relatively uncommon in North America, and there exists a substantial underutilized energy resource [7] [8]. A 2009 Canadian study suggested that an area with a population of 100,000 could produce 300,000 GJ of recoverable heat per year, enough to heat 3,000-5,000 single-family homes, while a 2013 Swiss study estimated that cooling Zurich's wastewater by 1°C would correspond to a continuous delivery of 10 MW [6] [9]. An ALHP system which uses the earth as a heat source/sink is referred to as a ground-source heat pump (GSHP) or geo-exchange ambient loop system. GSHP systems share many advantages – including relatively high system coefficients of performance (COPs), and a high energy efficiency and decarbonization potential – with WWHP technology, but are better established in North America [10]. In this paper, WWHP modeling is conducted using Microsoft Excel and coupled thermodynamic plugins, while GSHP modelling is conducted in HyGCHP, a TRNSYS-based software module for analyzing hybrid geothermal systems. Subsequent sections of the report detail the characteristics of the analyzed building development, as well as the building energy model, ALHP system simulation methodology, and comparative results for the six systems under analysis.

2. Development characteristics and energy model

The proposed development will be located in downtown Toronto, Canada, on the campus of Toronto Metropolitan University (formerly Ryerson University). The development will consist of a 15-storey podium (including 14 teaching storeys and one mechanical floor) and an adjacent 44-storey residential tower. The podium is slated to contain: retail areas; a café; a science gallery; a dining hall; conference space; lecture theatres; active learning classrooms; study rooms; and computer, physics, chemistry, and biology labs. The tower will contain student residences. Key parameters of the development are given in Table 1.

Table 1. Characteristics of proposed building development

Development type	Institutional/residential
Floor area	62,297 m^2 (702,850 ft^2)
Volume	339,195 m^3 (11,978,565 ft^3)

Building energy modelling was performed in eQuest by a consulting firm employed by the University, with the podium-tower development being modelled as 204 separate zones. Table 2 gives peak demand and annual loads for heating and cooling, as per the eQuest model. The development is slightly heating-dominated both with respect to energy peaks and with respect to overall load.

Table 2. Development energy usage

	Value
Heating peak	5,765 kW
Cooling peak	5,564 kW
Annual heating load	8,415 MWh
Annual cooling load	7,268 MWh

The development experiences almost year-round heating/cooling loads, with 0 annual no-load hours. Heating loads occur 8,715 hours a year (99.49% of the time) and cooling loads 8,758 hours a year (99.98% of the time), with the development having simultaneous heating and cooling demands for 8,713 hours each year

(99.46% of the time). The presence of simultaneous heating and cooling loads over most of the year renders the development well-suited to an ambient loop system.

The proposed development is to be located in a densely-developed downtown area. This presents an opportunity with respect to WWHP implementation, as the site is adjacent to substantial untapped wastewater resources, but a challenge with respect to GSHP implementation, as a large borehole field would be required to meet the development's heating/cooling loads and available space is limited.

3. Modelled heating and cooling systems

Six systems were modelled supplying the development's heating and cooling needs: a base case with natural gas boilers and a water-cooled chiller (no AL); an ambient loop coupled with conventional equipment (natural gas boilers and cooling tower); an AL-coupled WWHP system; a hybrid WWHP-conventional AL system; an AL-coupled GSHP system; and a hybrid GSHP-conventional AL system.

Modelling for the base case and the two WWHP systems was performed in Microsoft Excel using the XSteam and Psych plugins, while modelling for the two GSHP systems was performed in HyGCHP. Weather data used in air- and sewer-temperature correlations while modelling the conventional and WWHP systems was obtained from Environment Canada (Toronto weather station 6158355).

3.1. Base case (natural gas boilers and water-cooled chiller)

Under the base case, the development's space heating demands are met by natural gas boilers, while its space cooling demands are met by a water-cooled chiller. A constant 75% boiler efficiency was assumed, an industry-standard value as per the work of Kwiatek et al. [11]. Water-cooled chiller performance data was obtained from a reputable manufacturer, and is shown in Table 3. Two 3,285 kW chillers were required to meet the development's cooling needs.

Table 3. Water-cooled chiller operating parameters

% Load	Input power (kW)	COP
100	866.3	3.792
90	782.1	3.781
80	703.3	3.737
70	628.8	3.658
60	557.6	3.536
50	486.4	3.378

3.2. Conventional ambient loop

The conventional system model consists of: *(1)* a boiler model, *(2)* a cooling tower model, and *(3)* a heat pump model, integrated with a variable-flowrate ambient loop. Ambient-loop flowrate was set to 4.8×10^{-5}(m^3/s)/kW (2.7 GPM/ton) of net heating/cooling demand and ambient-loop power draw to 0.349 kW/(kg/s) (22 W/GPM), both industry-standard values, the latter drawn from ASHRAE 90.1 [12]. As in the base case, boiler efficiency was kept constant at 75%.

An open-loop cooling tower model was created in Microsoft Excel. XSteam, a MATLAB/Excel plugin, and Psych, a psychrometric plugin, were used to determine the thermodynamic properties of steam/water and moist air, respectively, under Toronto climatic conditions. In-zone water-to-air heat pumps were used to provide heating and cooling to individual building zones. Heat pump COPs for heating and cooling were drawn from TRNSYS. Table 4 shows the coefficients of performance used.

Table 4. Water-to-air heat pump operating parameters

AL Temperature (°*C*)	Heating COP	Cooling COP
-1.11	3.55	-
10	4.50	6.64
21.11	5.25	5.40
32.22	5.89	4.14
43.33	-	3.02

An open-circuit cooling tower was modelled as per the schematic in Figure 1 below. Temperature (T, in °C) and specific enthalpy (h, in kJ/kg-K) are modelled at each state point, along with the relative humidity (RH, unitless) and humidity ratio (ω, unitless) of the incoming and outgoing air. The specific enthalpy of air is denoted h_a (in kJ/kg-K), while the specific enthalpy of saturated liquid water and saturated water vapour are denoted h_f and h_g, respectively (also in kJ/kg-K). For air entering (State 3) and leaving (State 4) the cooling tower, both dry-bulb (T_{DB}) and wet-bulb (T_{WB}) temperatures are given.

Warm water entering the tower from the ambient loop (State 1) and cooled water returning to the ambient loop (State 2) share a single flowrate, $\dot{m}_w$ (in kg/s), with incoming makeup water ($\dot{m}_5$, in kg/s) compensating for evaporation such that mass balance is preserved. The tower is assumed to run only when there is a net demand for cooling. Further details for how makeup water rate and cooling tower air mass flowrate ($\dot{m}_a$, in kg/s) are determined on an hour-by-hour basis are given below.

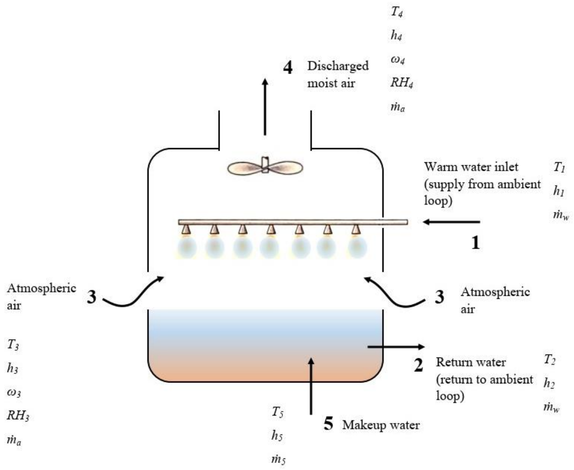

Fig. 1. Schematic of AL-coupled cooling tower (schematic adapted from [13])

Ambient loop flowrate ($\dot{m}_w$) was set to vary with net heating/cooling demand, with makeup water rate and airflow rate determined on an hourly basis as a function of ambient loop flowrate and the properties of supply (State 1) and return (State 2) water in the ambient loop.

For hours in which there is a net demand for cooling, state points were fixed as follows:

- **State 1:** The thermodynamic properties of the supply water from the ambient loop are determined by the amount of heat rejected by the building's water-to-air heat pumps. That is, $T_1 = (\dot{Q}_{cool})/\dot{m}_w C_{p1} + T_2$ where $\dot{Q}_{cool}$ is the heat rejected by all zones (in kW) and $\dot{m}_w$ and C_{p1} are the ambient loop mass flowrate (in kg/s) and specific heat capacity of the water in the ambient loop (in kJ/kg-K).
- **State 2:** Water at State 2 is at the *ambient loop temperature*, which, when there is net demand for cooling, is defined as being 5°C above the outdoor wet-bulb temperature. That is $T_2 = T_{AL} = T_{3WB} + 5°C$. (When there is a net heating demand instead of a net cooling demand, ambient loop temperature is held constant at 11°C.)
- **State 3:** State 3 is outdoor ambient air. Dry-bulb and wet-bulb temperatures from Environment Canada (Toronto weather station 6158355) were used to establish the state.
- **State 4:** State 4 is moist leaving air. The following assumptions were made to determine the properties of leaving air at State 4:

    a. Temperature at State 4 was taken as the average of outdoor ambient temperature and supply temperature from the ambient loop. That is, $T_4 = \frac{T_1 + T_{3DB}}{2}$.
    b. Relative humidity at State 4 was assumed to be 20% higher than outdoor relative humidity, up to a maximum of 100%. That is, $RH_4 = RH_3 + 0.2$.

- **State 5:** Makeup water, which compensates for evaporation, is also treated as being at the same temperature as the ambient loop temperature.

With these relationships in place, the mass flowrate of air through the cooling tower was found through Equation 1:

$$\dot{m}_a = \frac{\dot{m}_1(h_{f1} - h_{f2})}{h_{a4} - h_{a3} + \omega_4 h_{g4} - \omega_3 h_{g3} - (\omega_4 - \omega_3) h_{f5}} \tag{1}$$

Note that when the system is in heating mode $h_{f1} = h_{f2}$ and therefore the mass flowrate of air is 0 and the cooling tower is off/bypassed.

Equation 2 below gives the mass flowrate of makeup water in kg/s:

$$\dot{m}_5 = \dot{m}_a(\omega_4 - \omega_3) \tag{2}$$

As with airflow through the cooling tower, the makeup water rate is 0 when cooling is not required. The boiler and cooling tower models were integrated to create a conventional system ambient loop model capable of meeting the complete heating and cooling demands of the proposed development. Once loads were extracted from the eQuest model, heat extracted from and rejected to the ambient loop were defined as follows:

$$\dot{Q}_{cool} = \dot{Q}_{in}\left(1 + \frac{1}{COP_C}\right) \tag{3}$$

Where $\dot{Q}_{cool}$ is heat rejected to the ambient loop (in kW), $\dot{Q}_{in}$ is cooling load (kW), and COP_C is cooling coefficient of performance (unitless).

$$\dot{Q}_{heat} = \dot{Q}_{out}\left(1 - \frac{1}{COP_H}\right) \tag{4}$$

Where $\dot{Q}_{heat}$ is heat extracted from the ambient loop (in kW), $\dot{Q}_{out}$ is heating load (kW), and COP_H is heating coefficient of performance (unitless).

We then define the **net heat rejected** (NHR) as cooling minus heating for a given hour:

$$NHR = \dot{Q}_{cool} - \dot{Q}_{heat} \tag{5}$$

NHR determines how much cooling must be provided by the cooling towers or (if negative) how much heating must be supplied by the boilers. Boiler energy use and cooling tower air mass flowrate and makeup water rate were set to ensure that NHR was always met. Cooling tower power draw was determined as a function of flowrate through the tower, using the minimum efficiency value set by ASHRAE 90.1, 3.23×10^{-3} (m^3/s)/kW (38.2 GPM/hp) [12].

3.3. WWHP-coupled ambient loop (including hybridization)

For the WWHP system, it is proposed that a wetwell – a structure which receives sewage for handling – be constructed to tap into one of the sewers adjacent to the university campus. Wastewater will be screened for debris, passed through a bank of shell-and-tube wastewater-to-water heat exchangers housed in an energy transfer station (ETS), and – once its energy has been extracted – returned to the sewer. The shell side of the heat exchanger will be wastewater, while the tube side will be clean (ambient loop) water. This system configuration will ensure that only clean water circulates on the university side of the heat exchanger. The fluid pressure will also be higher on the tube side of the heat exchanger to ensure that in the event of a rupture clean water enters the wastewater side, and not vice versa, though it should be noted that such an emergency is unlikely.

Although the WWHP system is capable of meeting the development's complete heating and cooling needs, a boiler plant and/or cooling tower(s) for may be retained for redundancy depending on local legislation and the preferences of the building operators. Regulations regarding redundancy may differ depending on the exact configuration of the WWHP system.

3.3.1. Sewer temperature correlation and wastewater energy estimation

Sewer temperature and flow data were received from Toronto Water for several sites in the Greater Toronto Area. In order to estimate available wastewater energy in a manner consistent with the Toronto outdoor air temperatures provided by Environment Canada (and because temperature data was available only for the August-October 2018 period), it was necessary to determine a correlation accounting for the relationship between sewer temperature and: *(1)* outdoor dry-bulb temperature, and *(2)* time of day.

Sewer temperature fluctuates seasonally with outdoor air temperature, with average sewer temperatures being higher in summer and lower in winter. Additionally, sewer temperature varies predictably within a 1-2°C window throughout the day; temperatures are lowest around 7AM-8AM and rise steadily towards a high point in the late morning/early afternoon (11AM-2PM). Temperatures then drop steadily until they reach another low point around 5PM-6PM, before climbing towards their highest point around midnight. While there is considerable day-to-day variation in the exact shape of the sewer temperature curve, this general pattern of two peaks and two valleys holds true throughout the year.

The flows from Sewer MH101, Site 005 were used to generate a correlation between wastewater temperature, seasonal outdoor dry-bulb temperature, and time of day according to the following method:

- A fifth-degree polynomial trendline was generated to represent variation in wastewater temperature as a function of time of day ("Correlation A").
- Mean daily ambient temperature and mean daily wastewater temperature were correlated using a line of best fit ("Correlation B").
- To capture the effect of seasonal variation, the x^0 value of the fifth-degree polynomial (y-intercept) was replaced with the estimated mean daily wastewater temperature as determined from Correlation B.
- An offset of +0.6°C was applied to reduce error.

RMSE between estimated sewer temperature and recorded sewer temperature under this method ("Correlation C") was 0.73. The maximum modelled wastewater temperature was 25.6°C, while minimum modelled wastewater temperature was 19.6°C, values consistent with most urban sewersheds [4] [5] [6]. The coefficients of the line of best fit used are shown in Table 5 below.

Table 5. Coefficients for sewer temperature correlation

x^5	x^4	x^3	x^2	x^1	x^0
9.593×10^{-6}	-0.0005	0.00804	-0.03230	-0.16591	$f(T_{DB})$

Where:

$$x_0 = \overline{T_{sewer}} + 0.6 = f(T_{DB}) = [0.1041 \times T_{DB} + 22.634] + 0.6 \quad (6)$$

The estimated temperature profile was paired with a full year of actual flow data from a different monitoring site (103-119) to generate a complete temperature/flowrate profile.

Maximum available sewer energy (i.e., energy available if the entire sewer flow is utilized) was calculated according to Equation 7 below:

$$\dot{Q}_{sewer} = \dot{m} \times c_p \times \Delta T \tag{7}$$

Where $\dot{m}$ is the mass flowrate of the sewer, c_p is the specific heat capacity of water (wastewater), and ΔT is the inlet-outlet temperature difference across the wastewater side of the heat exchanger, here taken to be 3°C due to municipal safety limits on wastewater temperature.

A 5°C difference between water and wastewater streams was assumed – that is, ambient loop temperature was taken to be 5°C higher than the sewer temperature in the cooling season and 5°C lower than the sewer temperature in the heating season. The lowest available sewer energy at any point during the year was found to be 5,416 kW (occurring in late March), sufficient – once heat pump efficiencies are taken into account – to meet the complete heating and cooling demands of the proposed development.

3.3.2. Hybrid WWHP-conventional ambient loop

As has been mentioned above, it is estimated that the energy content of available wastewater resources near the proposed development – estimated based on the flowrate of a comparably-sized sewer and sewer temperature-outdoor air temperature correlations based on other Toronto sewers – is capable of meeting the heating and cooling demands of the development. However, for the sake of comparison, a hybrid WWHP-conventional ambient loop scenario is also presented.

Under the hybrid scenario, it is assumed that wastewater resources are *not* sufficient to meet the demands of the development, so conventional equipment – namely, natural gas boilers and a water-cooled chiller – is reintroduced to make up the deficit, with wastewater remaining the first source of supply to the ambient loop. It was assumed under this scenario that there would be enough year-round flow to ensure constant supply for a single shell-and-tube heat exchanger; heat exchanger specifications were provided by the manufacturer. At full capacity, this shell-and-tube heat exchanger operates with a wastewater flowrate of 0.057 m^3/s and clean water flowrate of 0.028 m^3/s.

3.4. GSHP-coupled ambient loop (including hybridization)

In the two GSHP-coupled ambient loop scenarios (full geo-exchange and hybrid GSHP-conventional system), the ambient loop is paired with a ground heat exchanger. Modelling for the two GSHP-coupled scenarios was performed in HyGCHP, a module based on TRNSYS (Transient System Simulation Tool) used for analyzing hybrid geothermal energy systems. The parameters used in both simulated scenarios are given in Table 6 below.

Table 6. HyGCHP simulation parameters

Ground temperature (at mid-bore depth)	13.9°C	**Ambient loop fluid**	Propylene glycol
Drilling depth	91.4 m	**Minimum fluid temperature**	-7.78°C
Bore spacing	6.10 m	**Pump power per 100 tons of peak block load**	7,457 W
Header depth	1.80 m	**Fraction of pressure drop attributable to GHX**	0.55
Center-to-center half distance	3.80 cm	**COP heating**	3.42
Borehole radius	5.70 cm	**EER cooling**	15.6 MBH/kW
Ground thermal diffusivity	0.10 m	**Fan operation**	Continuous
Ground thermal conductivity	5.68 W/m^2-K	**Performance curves**	Default
U-tube size	25 mm	**Heating EAT**	21°C
Grout thermal conductivity	4.54 W/m^2-K	**Cooling EAT**	24°C

3.4.1. Hybrid GSHP-conventional ambient loop

The final scenario simulated was a hybrid GSHP-conventional ambient loop. As in the hybrid WWHP-conventional ambient loop scenario, rejection of heat to and extraction of heat from the thermal reservoir (in this case, the ground rather than wastewater) remains the first order of supply, with conventional equipment – in this case, a single cooling tower – making up the remainder of the development's demand. In the hybrid GSHP-conventional scenario, the borehole field is sized to meet heating demand.

4. Energy, cost, and GHG comparison

Natural gas and electricity prices used in estimating energy costs for the six heating/cooling systems are shown in Table 7. 2019 and 2030 prices are derived from Toronto Metropolitan University's *Carbon Reduction Roadmap* (2021) [14]. It should be noted that natural gas costs are extremely volatile; 2022 natural gas costs are substantially higher those of 2019, reflecting current sociopolitical conditions. With respect to electricity pricing, the University is a Class A consumer under the Ontario regulatory structure, meaning that it pays a global adjustment (GA) factor based on the percentage of the province's electrical demand for which it is responsible during the top 5 draw hours every year; costs given in the *Roadmap* are therefore not simple marginal energy costs, but rather reflect estimated global adjustment.

Table 7. Factors used in calculating energy costs [14]

	Natural gas cost (*$CAD/kWh*)	Electricity cost (*$CAD/kWh*)
2019	0.0286	0.1517
2030	0.0595	0.1566

Canada's 2021 *National Inventory Report* for greenhouse gas sources and sinks provided the factors used to calculate greenhouse gas emissions associated with: *(1)* electricity consumption from the Ontario grid, and *(2)* the burning of natural gas; these factors reflect 2019 conditions [15]. For electricity consumption, the average emissions factor ("AEF"), which represents the simplest measure of the grid's GHG intensity, was used. GHG emissions factors are shown in Table 8 below.

Table 8. Factors used in calculating greenhouse gas emissions [15]

	GHG intensity
Natural gas	1,899 gCO_2eq/m^3
Electricity AEF 2019	30 gCO_2eq/kWh

A comparison of annual energy use, GHG emissions, and energy costs for the six modelled systems is given in Table 9 below.

Table 9. Comparison of annual energy use, GHG emissions, and energy costs for the six modelled systems

System	Energy use (*MWh*)	GHG emissions (*tonnes*)	Cost (*$CAD*, 2019)	Cost (*$CAD*, 2030)
Base	13,193	2,118	$630,450	$987,149
Conventional AL	9,566	1,236	$689,332	$897,107
WWHP	5,711	171	$866,423	$894,409
WWHP-conventional	6,007	589	$582,861	$681,656
GSHP	3,261	97	$494,646	$510,623
GSHP-conventional	3,218	96	$488,123	$503,889

The AL-coupled WWHP system provided a meaningful reduction in annual energy use as compared to the base case (57% reduction) and the conventional ambient loop (40% reduction), as well as significant greenhouse gas (GHG) emissions reductions (92% as compared to base case, 86% as compared to conventional ambient loop); however, under 2019 energy pricing, it was more costly to operate than either the base case (37% higher cost) or conventional AL (26% higher cost) systems. By 2030, the AL-coupled WWHP would provide slight costs savings as compared to the base (9% lower cost) and conventional AL (0.3% lower cost) systems.

By contrast, the hybrid WWHP-conventional was cheaper to operate than the base and conventional AL systems under both 2019 and 2030 energy costs. When compared to the base case, it provided 8% cost savings under 2019 pricing and 31% savings under 2030 pricing; when compared to the conventional AL system, it provided 15% cost savings under 2019 pricing and 24% savings under 2030 pricing. However, GHG emissions were significantly (243%) higher than for the pure WWHP system, and energy use slightly (5%) higher.

Of the six systems studied, the two GSHP systems – and particularly the hybrid GSHP-conventional system – performed best on all metrics (energy use, GHG emissions, 2019 energy costs, and 2030 energy costs). The hybrid GSHP system had an annual energy use of 3,218 MWh, only 56% of the energy used by the WWHP system and less than a quarter of the energy used by the development under the base case. Due to the offsetting of natural gas emissions, GHGs were significantly lower than in the base case for all four renewable-based systems (the hybrid and non-hybrid WWHP and GSHP systems). The hybrid GSHP system produced only 96 tonnes of GHGs annually, about 5% of the GHGs produced by the conventional system and 56% of the GHGs produced by the WWHP system.

The natural gas boilers were the largest energy consumer for the base case and conventional AL systems. For the WWHP AL system, heat pump electrical consumption represented the largest share of energy consumed, slightly edging out electrical consumption by the AL pumps. In the hybrid WWHP AL system, the boilers were again the largest energy consumers, representing the relative inefficiency of natural gas boilers. For the two GSHP systems, electrical draw by the heat pumps represented the majority of energy used.

5. Conclusion

The results of this investigation mediate towards the selection of a GSHP-based system for the proposed campus development, as the two GSHP-based systems had the lowest energy usage and GHG emissions of the systems studied, as well as the lowest costs under both 2019 and 2030 energy prices. However, it should be noted that this analysis had numerous limitations. Upfront costs and capital expenditures were not considered, nor were return-on-investment or the larger economic viability of the systems under study. The implementation of WWHP systems requires the cooperation of municipal authorities, who control access to city wastewater, while GSHP systems require large borehole fields which are often difficult to build in urban areas and whose construction can slow the development process.

In addition to the practical and economic concerns involved in the implementation of WWHP and GSHP systems, the current analysis was limited by the software used. HyGCHP is a software intended for simplified analysis of geo-exchange and hybrid geo-exchange systems; a more detailed analysis would use TRNSYS or equivalent software to analyze both the WWHP and GSHP configurations.

While a more complete analysis remains for future work, it is certain that, as carbon pricing in Canada continues to rise, the economic feasibility of heat pump systems such as those studied in this paper will increase and their implementation will become more widespread. By providing preliminary evidence for the viability of GSHP- and WWHP-based systems in a proposed campus development, the present study suggests two plausible alternatives to conventional heating and cooling; this is particularly significant in light of the underutilization of WWHP systems in Canada. Although it is not possible to draw broad generalizations from the results of this paper, the economic and environmental benefits of GSHPs and WWHPs for the institutional/residential development under study suggest that these types of heating and cooling systems may be worth investigating in other large institutional or residential buildings in Canada, particularly when climatic conditions and wastewater availability resemble the present scenario.

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